WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Nitrogen Use by Crops and the Fate of Nitrogen in the Soil and Vadose Zone

A Literature Search

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Executive Summary

The Washington State Department of Ecology (DOE) and Washington State University (WSU) signed an agreement to generate a report describing the results of a literature review on the fate of residual nitrogen (N) in the soil and vadose zone. The main purpose of this review was to provide background information regarding nitrogen use by crops as well as the interactions between the soil water and nitrogen balances and crop water and N use. This information is to be applied primarily to management systems involving land application of processed water (municipal, food processing plants, livestock liquid manure), although the information should also be relevant to other issues of nitrogen management and nitrate leaching.

The focus of the report was to identify principles and not to provide quantitative guidelines for regulating land treatment systems (LTS) in the state. A large body of literature from outside of Washington State is relevant given the diversity of conditions in the state. However, direct application of this information to a specific LTS site, soil, weather, and crop for regulatory purposes is not possible nor is the purpose of this report to provide such specific information. Nevertheless, the general principles presented in this report plus a judicious and technically sound analysis for conditions in the state should allow regulators and managers to establish a reasonable first approach to the problem. Careful monitoring of crop nitrogen removal, soil nitrate accumulation, and leaching for several years should lead to an excellent database to refine the approach. Targeted field research focusing on management questions, complemented with computer simulations, would provide the specific information required for further progress.

Soil N content is the result of dynamic processes including several components. Fertilization and land application of organic wastes should provide N to supply crop demand while properly accounting for existing residual (inorganic) soil N, mineralization of organic N in the soil, as well as other possible sources such as N present in irrigation water. Crop N requirements and their temporal and spatial variation are reviewed in this report. Matching fertilization and/or organic waste application to these requirements is not easy. Year-to-year variation in climatic conditions influence crop N demand as well as the retention of inorganic N in the soil. In addition, there is uncertainty regarding the magnitude of N supplied by mineralization of soil stable organic matter, crop residues, and organic N applied with the waste. The N uptake efficiency of a crop also varies with management and environmental conditions.

The current state of knowledge shows that there is a good understanding of the processes and principles affecting the fate of nitrogen in the soil. However, there is little data from Washington that is suitable for this report. Partly this is due to the lack of research including all aspects of the complex and multifaceted N cycle. In many cases, researchers (or funding agencies) are interested in only specific aspects of the N cycle. For example, many studies emphasized determination of how much N was needed to increase yield, but did not measure crop N uptake, leaching, mineralization, etc. Many other studies measured N leaching, but did not measure yield or crop N uptake. As a result, there are very few comprehensive data sets.

The majority of the existing knowledge comes from studies conducted outside the region. Specifically, there have been many studies conducted in the midwestern, eastern, and more southerly regions of the U.S. A large number of the studies were conducted in a corn or corn-soybean cropping system. However, it is difficult to apply their results to Washington State due to differences in cropping systems and regional climates. The diversity of microclimates within the State promotes a large variety of crops and cropping systems. In addition, the overall regional climate is one of primarily winter rainfall (as opposed to growing season rainfall) with relatively cool nighttime temperatures. This affects the rate of the various processes of the N cycle. For situations in Washington State that have not been researched, we need to realize that models based on data from other locations are only approximate, but can serve as a good first approach in constructing best management recommendations.

We suggest that this report provides a basis for understanding the fate of nitrogen under a large number of crops and cropping systems. As far as we know it is one of the most comprehensive literature surveys conducted in this area. However, based on the issues discussed above, we caution that it will take a concerted effort to distill, apply, and verify the information summarized in the report to specific management situations in Washington.

General principles and recommendations based on the literature review are however given in this report. A comprehensive summary of these principles and recommendations is presented in the following paragraphs.

General Principles and Recommendations

- The agronomic rate as used in this document refers to the recommended rate of nitrogen addition to the soil that is needed to produce an expected yield, while minimizing adverse environmental effects. The estimation of agronomic rate must factor in nitrogen available to the crop throughout the growing season from all sources such as mineralization of organic residues and soil organic matter, residual inorganic nitrogen in the rooting zone and nitrogen from irrigation water. Agronomic rate and expected yield must consider all management, soil and climatic factors that will affect the crop's ability to meet the yield level.

- Under management conditions such as process water sprayfields the agronomic rate and the application rate of nitrogen may be different. Sprayfields may be managed to encourage removal of nitrogen from the system at levels above required crop uptake. This is accomplished through processes such as denitrification and excess nitrogen uptake by the crop. This may allow increased application of nitrogen above that normally considered as an agronomic rate to adequately supply the crop. However, whenever the application rate exceeds that agronomic rate, close attention must be given to the environmental consequences of this practice.

- All nitrogen applied to the soil (including ammonium and organic forms) will eventually be subject to transformation to nitrate (except for volatilization losses). The total transformation of organic to inorganic nitrogen may take a few weeks to a few years, depending on the nature of the organic waste.

- Nitrate moves readily with water in the soil profile and can reach groundwater if not taken up by crops or denitrified/volatilized. Other forms of nitrogen are less mobile.

- Organic or inorganic nitrogen applications that, on the average, exceed crop nitrogen uptake plus gaseous emissions (denitrification and volatilization) will accumulate inorganic N in the soil, which will be susceptible to leaching in nitrate form.

- Soil N that moves below the root zone will not be taken up by plants and will eventually leach to groundwater as nitrate. Denitrification may help to reduce nitrate loading to groundwater under some conditions. Steps should be taken to minimize movement of N below the root zone during the growing- or non-growing season.
  - Depth of the rooting zone varies depending on the crop and time in the season.
  - Management systems should be designed to minimize the levels of residual soil nitrate in any part of the soil profile during the non-growing season.

- Agronomic rates of N applied in accordance with the timing and amount of crop N demand will minimize the buildup of inorganic N.
  - Applying wastes so that inorganic N content is maximized at the times of maximum crop demand will result in the greatest amount of N removal. Waste applied substantially before or after maximum crop demand may result in buildup of inorganic soil N that will subsequently be susceptible to nitrate leaching.
- The use of winter cover crops can minimize movement of N deeper into the soil profile by taking up N from the rooting zone, storing it in the plant tissue, and eventually returning it to the soil surface after death of the cover crop. This will help to minimize N movement below the rooting zone of the subsequent crop during this traditional fallow period.

  - The use of winter crops does not imply that N can be applied above agronomic rates without increasing the amount of N leaching. The only nitrogen removed from the system corresponds to that contained in crop biomass removed from the field plus gaseous emissions. Cover crops temporarily store N from the root zone. This N is then available for plant uptake, leaching, or other transformations after the death of the cover crop if not harvested. If excess N is applied in one growing season, it must be offset by decreased N application in the following season to avoid residual N build up and subsequent nitrate leaching.

- The rate of organic N mineralization is affected by organic N source (i.e., kind of waste), soil and climatic conditions. While mineralization coefficients have been well established for manure-N, less is known about the mineralization coefficients of food processing or municipal processed water.
  - Application of N-containing wastes should be managed to minimize mineralization during periods when plants are not actively taking up N.

- Crops vary in their capacity to recover N, as influenced by their rooting depths, biomass production and capacity to store N per unit of biomass.
  - While statewide research data is not available on all crops covered in this review, national and international data provide baseline information on accumulation capacity, N uptake efficiencies, rooting depths and N harvest indices. As a starting place, we encourage monitoring of plant nitrogen removal at harvest (i.e., in grain or other harvested plant parts) and measurement of residual soil nitrogen - including deep soil nitrogen (below 1m). This will provide Washington-specific baseline data on the likelihood of nitrogen leaching under various waste disposal systems.

- Poor irrigation management and/or scheduling will prevent efficient N management and recovery. Components of the soil water balance that can be controlled must be managed to minimize leaching and runoff (e.g. deficit irrigation, frequent light irrigation).

- The N composition of the processed water should be determined before application because it will affect the timing of N availability and the susceptibility to N leaching. Inorganic ammonia or ammonium are immediately available for any of several paths including plant uptake, volatilization or conversion to nitrate. Organic N must be mineralized before it is available for these reactions.
  - Mineralization rates will likely vary between organic N sources (for example, manure compared to food processing waste), however once the mineralization characteristics are known, the same principles apply. Therefore, use of existing methods for predicting N loading from manure or biosolids should be adaptable to other types of wastes, once the N composition and mineralization characteristics are known.

- Maximizing nitrogen removal by crops will generally increase the risk of nitrate accumulation in the soil.

- An alternative method of nitrogen removal from the soil-plant system would be to encourage nitrogen pathways other than leaching and plant uptake. Volatile N losses as ammonia can be encouraged for ammonia/ammonium-rich wastes through surface applications without incorporation. However this approach may conflict with offsite odor and air quality concerns. Denitrification can be induced through irrigation management leading to temporary anaerobic conditions.

- Organic wastes applied during the non-growing season will partially or totally mineralize and nitrify before the next growing season. The fraction mineralized will depend on the type of waste and on the soil temperature and moisture conditions prevailing during this period. This will contribute to increasing nitrate-N in the surface soil. This nitrate will then be available to be transported down the soil profile. The depth that nitrates will travel in the soil before the next growing season will depend on the soil hydraulic properties and the volume and distribution of precipitation and water added to the soil by the land application method. Nitrates transported beyond the reach of roots of the crop to be grown during the following season will not be removed and will be available for transport to groundwater.

- Precipitation amounts and soil temperature fluctuate annually and are spatially variable. Soil characteristics are also variable throughout the state. Thus, applying organic wastes during the non-growing season has an inherent risk and requires close soil monitoring to establish the success of the operation in terms of avoiding N leaching. The use of winter cover crops helps to mitigate the problem but does not guarantee a solution. The use of storage facilities to minimize waste applications during the non-growing season is a safe alternative. The definition of how much risk is tolerable, the implementation of monitoring requirements, and the quantification of expected outcomes for non-growing season application of organic wastes for the array of soils, weather conditions and waste types involved is beyond the scope of this report.

1. OBJECTIVES AND METHODOLOGY

The Washington State Department of Ecology (DOE) and Washington State University (WSU) signed an agreement with the purpose of generating a report describing the results of a literature search on the fate of residual nitrogen in the soil and vadose zone. They agreed in the following statement of work: a) WSU will conduct a literature search on the fate of residual nitrogen in the soil and vadose zone, b) WSU will write a report describing conclusions and findings based on the literature search, including a list of references and recommendations for a possible future computer modeling and field studies based on the report.

More specifically, the purpose of this report is to provide background information regarding nitrogen use by crops and the interactions between the soil water and nitrogen balances and crop water and nitrogen use. This information is to be applied primarily to management systems involving land application of processed water (municipal, food processing plants, livestock liquid manure), although the information should also be relevant to other issues of nitrogen management and nitrate leaching.

The literature search was conducted using standard procedures including computer search of specialized databases, abstract indices, journals and book references at WSU and other libraries, and indirect search based on references already at hand. Bibliography available nationally and worldwide was included. Published and/or suitable information pertaining specifically to the State of Washington was rather scarce. Raw monitoring records or other similar data without formal interpretation could not be used within the context of this report. Fortunately, the basic processes affecting the fate of nitrogen in the soil and associated groundwater pollution problems are the same regardless of location. The wide range of weather and soil conditions across the state allowed us to utilize research from many national and international locations.

The literature search yielded a massive amount of information. This material was classified, read, filtered, re-read, and selected for inclusion in the report. The selected references are all included in the reference list. Based on the selected information, sections 2 to 8 of the report were prepared. Section 9 includes a brief description of field and computer simulation research that is required to "customize" the information found to the specific soils, weather, and typical organic waste characteristics and agricultural management practices prevailing in the state of Washington. Details required to conduct any of the research activities outlined in this section are beyond the scope of this report, but they can be provided to DOE upon specific request.

2. INTRODUCTION

There is a large body of information documenting nitrogen content of groundwater and surface waters in Washington State and the nation. The agriculture sector is often identified as an important contributor of nitrogen to groundwater. For example, studies in Nebraska, Illinois, Georgia, Texas, Florida, and Long Island have shown that groundwater under irrigated farming areas is generally higher in nitrate than from non-cropped or non-fertilized areas (Meisinger; 1976; Keeney, 1986).

A detailed study by Hubbard et al. (1984) in Georgia showed that nitrate-N concentrations under a center pivot area ranged from <1mg/L to about 133 mg/L, with a mean of 20 mg/L. In contrast, samples from adjacent forest sites had nitrate-N concentrations ranging from < 0.1 mg/L to just over 1 mg/L. Mean nitrate-N concentrations under the center pivot area were found to vary seasonally according to cropping and hydrologic patterns such that the mean values for March - May, June - August, September - November, and December - February were 7, 21, 27, and 21 mg/L respectively. The lower value for March - May indicated that winter rains leached most of the root zone nitrate-N beneath the wells by March, and that there was a 2 to 3 month lag between spring - applied N and its appearance in shallow groundwater.

In Washington State, high levels of nitrates have been found in the Pasco area. Water quality changes due to agricultural activities have been reported for the Yakima River since the 70's. Data for the period of 1971 to 1975 have shown that nitrate concentrations have increased from 0.45 mg/L in the upper Yakima basin to 0.71 mg/L at the middle and 1.86 to 2.53 mg/L at the lower Yakima basin (Peralta, 1997). This increase have been attributed to both point and non-point discharges (including agricultural return flows). The same trend is reported by US Geological Survey (1992), with the highest values found at the Sunnyside subbasin where a large number of dairies might be contributing to the enrichment.

In terms of groundwater pollution, Ryker and Jones (1995) has reported that, in the Central Columbia Plateau of Washington State, nitrate concentrations for 19% of 573 wells monitored exceeded the US EPA maximum contaminant level (MCL = 10 mg nitrate-N / liter) for drinking water. A significant concentration of the problem is located in the Quincy-Pasco area, where 29% of the wells monitored exceeded the EPA MCL.

The Washington State Department of Health reported that 3% of 6,500 well-dependent water systems tested exceeded the MCL at least once since 1985 (Stewart et al., 1994). The following counties had the highest percentage of wells exceeding the MCL: Benton (13.3%), Douglas (20.8%), Franklin (32.5%), Lincoln (17.6%), Walla Walla (23.9%), and Whitman (10%).

Not all agricultural activities have the same potential to contribute to N pollution. Irrigated and intensively managed cash crops hold a significant share. This is particularly true for crops with relatively shallow roots growing in light-textured soils (sandy to sandy loam). Large concentrations of animals in feedlots and dairy farms also create conditions for significant excess N in the soil system. These operations require special management to minimize nitrate pollution. This includes proper management of feedlots to minimize nitrification and leaching and application of the wastes to cropland at rates based on agronomic principles, including N needs of the crop. In managing nitrogen in agriculture is important to understand that nitrate leaching may be unavoidable under many agronomic conditions. Nevertheless, water and nitrogen must be carefully managed to minimize the groundwater pollution impact (Keeney, 1986).

Almost all variables involved in soil and crop management can influence N cycling and the accounting of N in the ecosystem. Consequently, understanding the effects of agriculture upon nitrate accumulation in groundwater must address all aspects of the nitrogen and the hydrological cycles. Dominant in any accounting is the total nitrogen required by the crop. Decision-making regarding N application to land must consider adjustments to crop requirements based on efficiency of N uptake (particularly in the case of production agriculture) and other aspects such as soil, climate, and management practices. Credits must be given for the amount of N derived from mineralization of soil organic N, manure, green manure, crop residues, or various types of wastes, plus that added through precipitation, foliar absorption of ammonia, biological N fixation, or nitrates in irrigation water.

The difference between the crop N requirement and the available soil N from the various sources described above is normally corrected by fertilization. However, a major problem exists in determining what constitutes sufficient fertilizer N. One must consider the crop, weather, soil properties, fertilization practices (carriers, time of application, rate, and placement), and N source (i.e., organic and inorganic). Also, many management practices can influence crop N uptake efficiency: tillage and crop residue placement, cropping systems, irrigation practices, weed control, and others. Consequently, this efficiency varies greatly.

The fact that N uptake efficiency is part of the decision-making process to quantify N application to crops is an indication that losses are an unavoidable element of the fate of N in agricultural systems, although some of this efficiency also accounts for N incorporated into soil organic matter. Quantitative effects of any given practice are often site-specific, but can be estimated through process-based computer simulation models. In practice, the best approach is to apply N according to field-calibrated soil tests. Although this is an empirical approach, when restricted to the area from which the field calibration was derived, it can provide reasonable estimates of minimum N requirements. Experience has shown that N applications based on such recommendations reduce nitrate leaching while maintaining yields. With continued research, well-calibrated soil test recommendations for N usage can provide the accounting needed to minimize nitrate leaching into groundwater (Power and Broadbent, 1989).

To understand the potential for N pollution from agricultural systems, it is important to develop a framework of analysis for evaluating the fate of N in the soil. For this purpose, it is important to understand the components of the N cycling, N balance, soil water balance, and the interactions among these components. The nitrogen and water balances interact to determine N transport in the soil and the magnitude of eventual N leaching below the profile explored by crop roots. The components of these balances are discussed in following sections.

2.1. Soil Water Balance

The water balance can be expressed as:

$$(P+I)-(ET+L+R)=\Delta_{wc}$$

where:

P = Precipitation

I = Irrigation

ET = Evapotranspiration

L = Leaching or deep percolation

R = Runoff

Δ_{wc} = Soil water content change for a given time interval

2.1.1. Precipitation

Precipitation is the principal source of water to the surface of the earth, and it is the basis for water supply to agricultural systems (Raudkivi, 1979). Precipitation can be either solid or liquid. Liquid precipitation comprises rainfall and drizzle while solid precipitation is mainly snow (Ward et al, 1990).

2.1.2. Irrigation

Irrigation is the artificial replenishment of the soil water when no or insufficient precipitation has occurred. This practice is oriented to sustain high-productive agriculture where natural precipitation is unable to do it. Irrigation water is supplied to agricultural lands usually from rivers, dams and reservoirs (from runoff) and groundwater.

2.1.3. Evapotranspiration

Evapotranspiration is a concept that involves *evaporation* of water from the soil surface, plants and residues and *transpiration* of water from plants. Evaporation is the process by which water is transformed from liquid to water vapor. It requires a source of liquid water and energy. The source of liquid water can be the soil water when the soil surface is wet and/or water intercepted by the crop canopy and residues. Interception is the amount of either precipitation or irrigation that does not reach the soil surface (Ward et al, 1990). It is retained by plant canopy and post harvest residues and is later evaporated away from those surfaces. It represents an addition to the evaporative losses. Transpiration is a form of evaporation where vapor escapes from within plants (Ward et al, 1990).

2.1.4. Runoff

Runoff is the portion of water from precipitation and irrigation that reaches the soil surface but does not infiltrate because the infiltration capacity has been reached. At first, small depressions and hollows collect this water. When this storage capacity is exceeded, the excess water starts to move down the slope. The amount of runoff depends on the slope of the surface, soil type, vegetative cover and water holding capacity of the soil.

2.1.5. Leaching or Deep Percolation

Precipitation and irrigation water that does not evaporate becomes either runoff or infiltrates into the ground or both. From the water that infiltrates, a part is used to replenish the soil moisture and any excess is lost as drainage water or deep percolation at the bottom of the soil. In a simple approach, soil moisture is temporarily held at water potential below -10 to -33 J/kg (roughly equal to centibars). This is called field capacity of the soil. When field capacity of the soil is exceeded, water passes through the soil becoming drainage water or deep percolation.

2.2. Soil N Balance and the N Cycle

Applying the law of mass conservation to N in the soil, the following general expression is obtained:

$$N_{in} - N_{out} = \mp\Delta_N$$

In this equation, N_{in} is N input to the system while N_{out} is N output or losses. Δ_N is the change in storage and represents the variation of the N content within the soil for a given time interval.

N inputs may include the following: N applied (inorganic and organic sources); symbiotic and nonsymbiotic N_2 fixation; N mineralization; N in irrigation water and precipitation; N in crop residue and crop seed N input. N outputs or losses may include the following: harvested crop N, ammonia losses from organic and inorganic fertilizers, denitrification, N in water (runoff) and sediments leaving the field, gaseous losses from senescent canopies, and N leaching losses.

In the next paragraphs, a brief description of the N cycle, N forms and processes related to the N fate in the soil are presented. Since a detailed description of this subject may be found in the literature (e.g., Tisdale et al, 1985), only a revision of the most important aspects related to this study is given here.

The N transformations in soils are part of nature but they can be significantly affected by agricultural and industrial activities. These activities usually lead to gains in soil N by fertilization and waste application. Forms of N added to the soil and N already present transform from one form to another depending on environmental conditions. A simple scheme of the N cycle and its simplified relationships is given in Figure 2.1.

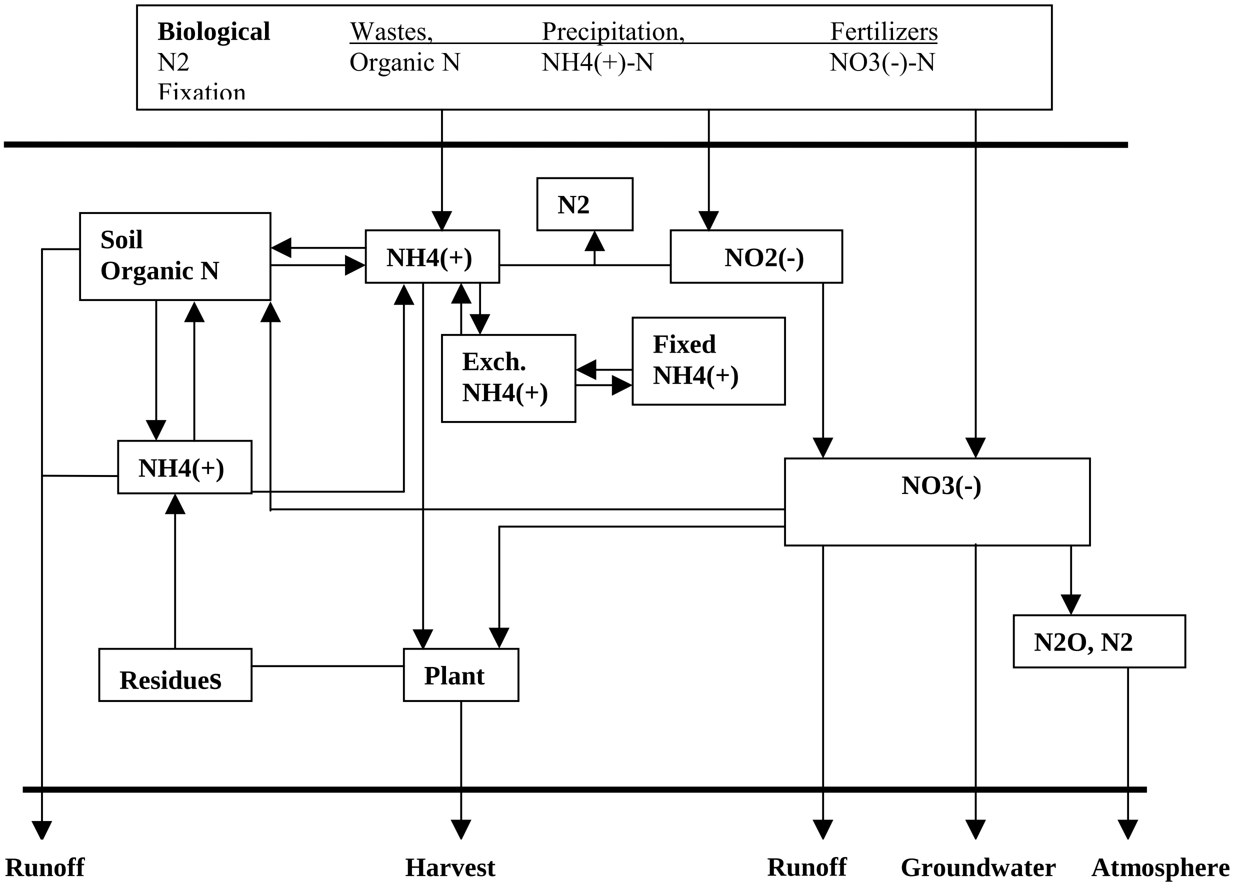
There are three major forms of N commonly found in mineral soils: organic, ammonium and nitrate. Most of the soil N is part of organic compounds and not readily available for transport. This N form is important as a source of slow-release N. Due to the property of most of the soils to have negatively charged particles, ammonium (NH_4^+) is attracted to the soil particles, being partially immobilized. Therefore, this ion does not move readily in the soil. This process is more noticeable in clay soils, depending on the nature and amount of clay in the soil. Nitrate is the preferred form of N ion for plant uptake. Nitrate is an anion, negative charged. It is normally repelled by the soil particles leaving it free to be transported by the water in the soil. This form of N is of special environmental concern and it is generally the form found in groundwater.

Transformation of N among the different forms introduced above plus other gaseous forms is an important aspect of N fate in the soil. Nitrification is a process driven by nitrifying bacteria, and it corresponds to the oxidation of ammonium to nitrate. In the oxidation step, N is first oxidized to nitrite by Nitrosomonas, followed by the oxidation of nitrite to nitrate by Nitrobacter. The two steps require oxygen. The process can be represented by the following simplified expression:

$$NH_4^{+} \quad \overset{\textit{Nitrosomonas}}{\qquad} \quad NO_2^{-} \quad \overset{\textit{Nitrobacter}}{\qquad} \quad NO_3^{-}$$

The chemical requisites for these processes are adequate temperature (25°C to 35°C), neutral to slightly basic pH (7 to 9), and adequate soil aeration.

Figure 2.1. The nitrogen cycle



Denitrification is a process involving the microbial reduction of nitrate to elemental N gas (N_2), which is mainly lost to the atmosphere. During the process, nitrous oxide (N_2O) may also be lost. The N_2O/N_2 ratio is minimum when carbon supply is abundant and not limiting. Denitrification does not require oxygen and is common in poorly drained soils. It also requires carbon as a source of energy. The following steps can represent the process:

Atmospheric losses

$$NO_3^- \qquad NO_2^- \qquad NO \qquad \overset{\uparrow}{N_2O} \qquad \overset{\uparrow}{N_2}$$

Heterotrophic bacteria and anaerobic conditions drive this process and it is of little importance in well-drained soils. Denitrification is of environmental importance because it can release N_2O, a trace gas believed to be involved in the destruction of the ozone layer (Crutzen, 1976; Liu et al, 1976).

Ammonia volatilization corresponds to the losses that occur in the transformation of ammonium into aqueous ammonia. The simplified pathway is the following:

$$NH_4^+ \Leftrightarrow \left(NH_{3\ (aq)}, NH_{3\ (air)}\right) + H^+$$

Volatilization can occur whenever free ammonia is present near the surface of the soil. The ammonia concentrations in the soil solution will increase by applying ammoniacal fertilizers or decomposable organic materials to neutral or alkaline soils. The amounts of ammonia volatilized are small when N materials are incorporated into the soil, and ammonia losses are low (≤15% of applied N) when ammoniacal fertilizers are applied in the surface of acidic or neutral soils. Large amounts of ammonia may be evolved on addition of nitrogen fertilizers or decomposable waste materials (sewage sludge, animal manure) to the surface of alkaline soils. This volatilized N can be a source of N enrichment of surface water (Nelson, 1982).

Net mineralization involves the transformation of organic to inorganic forms of N. It includes mineralization and immobilization. As other N transformations, it is a microbiologically mediated process. Microorganisms use part of the mineralized N as a constituent of their cells, so that a fraction of the N is immobilized in organic form. Net mineralization is the amount of N that is mineralized less the amount that is immobilized. This process is important in some soils and agricultural systems as a source of N for plants.

3. NITROGEN UPTAKE BY CROPS

3.1.1 Overview of the relationships among N uptake efficiencies and crop N requirements

In this section we review the regional, national, and international research that has documented crop N uptake (accumulation) and partitioning, in terms of absolute quantities and relative efficiencies. Nitrogen uptake is influenced by numerous agronomic, environmental and genetic factors, and as a result, there is no single value that will represent the uptake of N by any one crop. Nevertheless, a survey of the literature allows us to summarize a range of N uptake values that are conditioned by these cropping systems variables. The total N accumulation and the seasonal pattern of N uptake can be one of many helpful layers of information in determining a fertilizer, biosolids or processed water recommendation for land application, but it should be emphasized that N accumulation data cannot be used as the sole determinant of a sound N management program (e.g., Lang et al., 1997). In this report, we summarize N uptake by various Washington crops, including N in harvested plant part (e.g., grain, tuber, seed, etc.) as well as non-harvested plant parts where available.

Processed water and manure application to land is conducted to recycle excess nutrients from a production facility and fertilize crops for production purposes. Both goals can be achieved simultaneously with the application of principles of crop response to N applications. By far, the majority of scientific literature addresses N responses in relation to crop production. Much less information has been published about N uptake in systems designed for waste disposal. As a result, the data cited in this chapter reflects this bias in the literature. Nevertheless, the principles of crop response to N application can be applied to the latter goal, keeping in mind that disposal systems will be designed to maximize N removal rather than crop production, which may or may not result in similar application recommendations. However, it should be noted that in many documented cases, soil N buildup occurs in the range of N application rates exceeding that required to achieve maximum economic yield, so the agronomic literature provides a good starting point for defining reasonable N loading rates in crop-soil systems.

In general, the amount of N accumulated by a crop is affected by i) the amount of N supplied by the soil or added as fertilizer; ii) the genetic potential of the species or cultivar to absorb N, which is influenced by genetic factors such as tolerance to biotic and abiotic stresses, rooting pattern and physiological N uptake efficiency; iii) the growth or yield potential under a set of environmental conditions and soil properties; and iv) the ability to retain N in the rooting zone during the period of crop N uptake.

It is common to hear the statement, " the N use efficiency of our cropping systems should be improved to minimize nitrate leaching into groundwater supplies". This is a fair statement of a desirable goal and path toward that goal, but what exactly does this mean? Also, what are reasonable expectations for improving N use efficiency? Unfortunately, even crop and soil scientists are not in agreement when it comes to the terminology such as " N use" and "N uptake". Often the two are used synonymously in the literature, adding to the confusion. Before we can discuss this topic, we need to agree upon some terminology. For the purpose of clarity, we will apply the definitions outlined by Huggins and Pan (1993) and Bock and Hergert (1991), explained here and summarized in glossary format in Table 3-1.

Nitrogen use efficiency (Gw/Ns) is defined as the amount of harvested crop (Gw; e.g. grain, fruit, tubers, cones) that is produced per unit of N supplied (Ns) during the growing season. Thus, to improve N use efficiency means that we would be producing more harvestable biomass per unit of N supplied. This is a useful term because it's inverse, Ns/Gw or the required N supply to produce a unit of harvestable biomass, is the *unit N requirement* (UNR, Fiez et al., 1994; Bock and Hergert, 1991) which is often used to help predict fertilizer N requirements.

Nitrogen use efficiency is related to 1) the unit of crop N uptake (Nt) per unit yield (Gw) which is referred to as the *unit N uptake* (Nt/Gw; UNU) and 2) the proportion of the N supplied that is accumulated by the plant (Nt/Ns; *N uptake efficiency*) by the following relationship:

$$Gw/Ns = (Nt/Ns)/(Nt/Gw)$$

Conversely, the UNR can be calculated by dividing the unit N uptake by the N uptake efficiency:

$$Ns/Gw = (Nt/Gw)/(Nt/Ns)$$

From these relationships, it is easy to see that to improve N use efficiency and lower the unit N requirement, one must either increase N uptake efficiency or decrease the unit N uptake of a crop. However, the potential for changing these components has limitations. It should be recognized that biological efficiencies are always less than 100%. Typical N uptake efficiencies of major agronomic crops range from 30 to 70%, due to several factors. First, it is not possible for a plant to deplete all of the inorganic N from the soil solution. As the nitrate and ammonium concentrations decrease in solution, the rate of N uptake also decreases, in a relationship similar to substrate-enzyme reactions (Jackson et al., 1986). Minimal N concentrations in the soil are required to drive the N influx into crop roots. In addition, some N losses (volatilization or leaching) from the root profile are inevitable during the season. As a result, not all of the N supplied will be available for plant uptake. Finally, and perhaps most importantly that to achieve maximum or near maximum yields, N must be supplied at high levels. According to Mitscherlich's Law, as N supply increases, there is a decrease in the incremental yield increase per unit of N input (Fig. 3-1). As a result, N use efficiency invariably decreases at high levels of N input that are required to achieve maximum yield. On the other hand, if minimal N is supplied so that the soil N is depleted to near zero to minimize nitrate leaching potential, there is an insufficient concentration of soil N to drive maximal rates of N uptake, and crop yield will be limited. For this reason, the presence of residual soil N at the end of a growing season is inevitable in intensively managed cropping systems that are achieving near maximum or maximum economic yields.

In view of the fact that the absolute N uptake is influenced by overall plant vigor, growth and subsequently yield, N uptake will often be expressed as a function of yield and biomass (where data are available). In addition, seasonal patterns of N uptake by specific crops are included in this report where available. The latter information is often useful in identifying timing strategies for N fertilization, and for synchronizing N mineralization from organic N amendments with appropriate crops that will absorb the N as it is mineralized. Since N uptake also depends on root distribution, information on typical rooting depths are also included where possible.

Research values for N uptake efficiency will be summarized when available. It should be recognized that this is a difficult parameter to estimate, since accurate estimates of both the total plant N and the total N supply are not easy to obtain. The accumulation of N by a crop is typically expressed on a per plant or per area (acre or hectare) basis. Experimentally, small areas or numbers of plants are subsampled out of larger plots or fields, and extrapolated to the larger area basis. Often times, only the above-ground crop mass is sampled because the roots are difficult to sample and accurately represent. In these cases where the roots are not measured, the total plant N (shoots + roots) is typically under-represented by 5-15%. Under-representation is even greater percentages in root crops.

Crucial to estimates of N uptake efficiency is the accurate estimation of its denominator, total N supply. Estimates of total N supply must include fertilizer inputs, mineral N in the soil (residual N), soil organic matter mineralization, mineralization of organic amendments, and N inputs from irrigation or precipitation. Some of these processes such as organic matter mineralization are difficult if not impossible to measure directly, and while there are techniques to estimate such parameters, they have inherent difficulties and assumptions. Nevertheless, given these precautions, estimates of N supply, N uptake and N use efficiencies are useful guides for identifying best management practices. For example, a low N uptake efficiency can be an indicator that there is an excessive N supply in relation to crop demand, poor timing of the N supply, or accentuation of N loss pathways (volatile emissions or N leaching losses).

Since total N supply is difficult to estimate, researchers often report *apparent N fertilizer recovery*. It is usually determined as the amount of N per unit of fertilizer N a crop takes up in excess of that taken up by an unfertilized crop. However, this assumes that the same amount of non-fertilizer N is taken up by fertilized and unfertilized plants. Another technique used by numerous researchers is to apply isotopically labeled N fertilizer (^{15}N enriched or depleted) to distinguish fertilizer contributions to plant N from other soil-derived sources. In these studies, direct estimates of *fertilizer N recovery efficiencies* can be obtained, and are summarized in this report when available.

It is also helpful to know how crops vary in partitioning N between vegetative residues (usually returned to the soil after harvest) and the portion that is harvested and exported from the field (e.g., grain, tubers, cones, etc.). The ratio of harvested N divided by total plant N (again, most often represented by total above-ground N) is referred to as the *N harvest index*. Occasionally, a comparison of the quantities of harvested N to the amounts of N inputs over a long-term view of several cycles of a crop rotation, is used as an indicator of overall cropping system N use efficiency. However, this is not as useful an exercise when applied to single growing season and should not be a criteria for making N recommendations, because it does not account for N recycling and turnover between sequential crops in rotation.

The amount of nitrogen uptake can influence the quality of a crop, as well as the quantity produced. In some cases, crop quality is increased, for example when protein production is one of the goals. In some circumstances, however, the additional growth encouraged by a relatively high N supply can be detrimental to the quality of the crop for its intended purpose. For example, increasing N supply has been shown to increase grain N protein concentrations, however high protein concentrations in soft white wheat is undesirable since it is not conducive to quality pastry and noodle production. The types of proteins and amino acids can also be affected by the N supply. Another example is sugarbeets, in which higher N supplies can decrease the sucrose content of the harvested roots, lowering the efficiency of processing. The N supply effects on crop quality are further complicated by interactions with other factors such environmental conditions and genetics. The effect of N supply on crop quality is beyond the scope of this report, but is mentioned since N management recommendations need to consider quality factors as well as quantity.

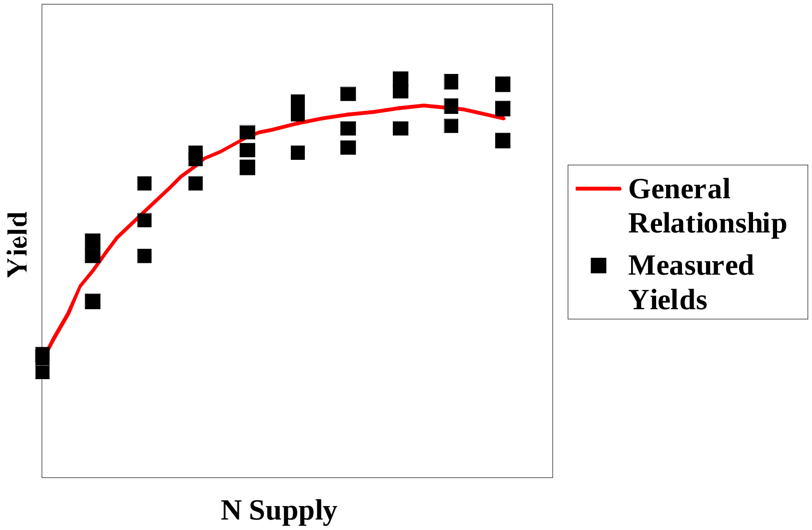


Figure 3-1. Example of a yield response curve developed from measured field data over a variety of site-years. The general relationship shown can be used to estimate the amount of fertilizer needed to meet a particular yield goal for this particular situation.

Table 3-1. Glossary of Nitrogen Accumulation Terminology

Apparent Fertilizer N Recovery (AFNR) = the proportion of applied fertilizer N that is taken up by the plant, when measured by comparing N uptake in fertilized treatment(s) with N uptake in an unfertilized control treatment in the same experiment. This measurement should theoretically estimate fertilizer N recovery (FNR) as measured with isotope-labelled fertilizer (see definition of FNR below), however the two techniques differ in their assumptions. Generally the AFNR approach is considered less accurate the FNR approach. (see Guillard et al. 1995). AFNR is calculated as:

AFNR = (plant N in fertilized treatment – plant N in unfertilized control) / applied N

Fertilizer N Recovery (FNR) = the proportion of applied fertilizer N that is taken up by the plant. This term is used specifically in conjunction with ^{15}N studies that measure the amount of recovered ^{15}N in the plant. (defined by Parr, 1973 as fertilizer N use efficiency.) It is calculated as:

^{15}*N-labelled fertilizer recovered/*^{15}*N-labelled fertilizer applied.*

Ndfa % (% nitrogen derived from atmosphere) = the proportion of plant N derived from the atmosphere through N_2 fixation.

Ndff % (% nitrogen derived from fertilizer) = the proportion of plant N derived from the applied fertilizer

Nitrogen use efficiency (NUE) = yield (grain, seeds, forage, etc.) produced per unit N supply; e.g., bushels per lb N, or kg grain per kg N supplied.

NUE = Gw/Ns = units harvested biomass/units N supply

Unit N Requirement (UNR) = the units of nitrogen needed to produce a unit of yield. Unit N requirement is often useful for predicting fertilizer N requirements. It is equal to the inverse of NUE, and is calculated as:

UNR = Ns/Gw =total N supply / harvested yield

Nitrogen supply (Ns) = total N in form of NO_3 and NH_4 in soil over growing season, including: pre-plant residual inorganic N, net mineralized N, and fertilizer N added.

Nitrogen uptake efficiency (NPE) = the amount of N accumulated in the plant per unit of total N supply. In practice, only above ground N is generally measured and included, due to the difficulty of collecting complete root samples. Roots generally comprise about 10-15% of total plant N.

NPE = Nt/Ns = total plant N/N supply

Unit N uptake (UNU) = the amount of N accumulated in the plant per unit of harvested biomass. Unit N Uptake differs from UNR in that UNU considers the amount of contained in the plant, while UNR considers the total N supply.

UNU = total plant N / harvested yield

Available nitrogen = N supply minus what is lost by leaching, denitrification, etc.

Nitrogen harvest index (NHI) = ratio of grain N to total N in plant.

NHI = grain N / total plant N

3.1.2 Fertilizer Guide Development and Usage

Fertilizer Guides (Nutrient Management Guides) published by WSU-Cooperative Extension form the basis of most fertilizer recommendations made in the State of Washington. The recommendations contained in these publications are based primarily on field trials and years of experience. Generally, they are based on the empirical relationship observed from field soil test calibration and yield response studies for a variety of field situations.

A general procedure in developing a set of recommendations is to evaluate the relationship between yield and N application rate in situations where no other nutrients or pest problems limit yield. Soil testing is used to determine the adequacy of plant nutrients and to determine background levels of N. Once the relationship has been determined for a variety of situations over a number of years, *yield response* curves such as that shown in Fig. 3-1 can be developed. From these curves, the researcher can determine the crop N requirement needed to produce a yield goal. In the past, recommendations were made for yield goals at or near maximum yield. More recently, the idea of targeting the economic optimum yield (which is generally less than the maximum yield) has gained respect. Using the economic maximum yield approach requires including fertilizer costs when making fertilizer recommendations by converting the yield response curve to a set of recommendations.

The Fertilizer Guides generally consist of one or more tables which the grower works through to find his/her specific situation. Items that are considered can include yield goal, residual soil N, soil organic matter content, previous crop, rainfall zone, irrigation, etc. Usually ranges for each item are presented for the grower to choose among. In Washington, many crops have separate Fertilizer Guides for the West, Central, and Eastern parts of the state due to the climatic and soil variation. After determining the appropriate ranges for each of the categories considered (rainfall zone, previous crop, residual soil N, soil organic matter content, etc.), the user of the Fertilizer Guide finds the N fertilizer application rate recommended for his/her yield goal and management capabilities. Because the recommendations in the Fertilizer Guide are designed to meet the needs of a large area with significant variation in production variables and management abilities, the recommendations are fairly broad. Therefore, individual crop consultants and producers have refined these recommendations to better fit their management systems.

During the period when most of the Fertilizer Guides were produced yield and economic return were the driving factors in selection of N rate and management. As increased emphasis has been placed on environmental quality and sustainability of agricultural systems crop consultants and producers have modified N management to increase N utilization. Practices such as tissue testing and split applications of N have become common place, leading to increased N utilization while maintaining yield potential. More recently, people have argued that a better approach than the traditional response curve would be to determine the *N uptake efficiency* and use this in conjunction with the UNU to get a better prediction of fertilizer needed. However, very few measurements of N uptake efficiency exist, due to the difficulty in measuring total N supply (see previous section).

A list of the Extension publications (primarily Fertilizer Guides) relevant to the production of the crops discussed in this report is presented in Table 3-2. Most of WSU’s Fertilizer Guides have not been updated since the 1970's and early 1980's due to lack of funding for this type of work, however, they continue to be relevant and are used as the primary source of information related to fertilizer recommendations in the State. Support by individual commodity groups is allowing updating of guides for major crops.

Table 3-2. Washington State University Cooperative Extension publications related to management of nitrogen in the crops summarized in this report. A complete listing of WSU's Extension publications is available in the publication 'Cooperative Extension: Educational Materials,' as well as all of the following publications are available at: WSU Cooperative Extension, Bulletin Office, Cooper Publications Building, Washington State University, PO Box 645912, Pullman, WA 99164-5912; 509-335-2857

Bulletin #	**Crop**	**Title**	**Year**
CO 506	General	Cooperative Extension: Educational Materials	1997
EB0757	General	Critical Nutrient Ranges in Washington Irrigated Crops	1980
EB1097	General	Agricultural Data: Washington State	1991
PNW0283	General	Fertilizer Band Location for Cereal Root Access	1986
PNW0475	General	Agronomic Zones for the Dryland Pacific Northwest	1990
WREP0043	General	Critical Nutrient Ranges in Northwest Crops	1980
EB1716	Groundwater	Farming Practices for Groundwater Protection	1992
EB1756C	Groundwater	Documented Groundwater Contamination in Washington	1995
EB1756D	Groundwater	Documented Nitrate Contamination in Washington	1995
FG0003	Alfalfa	Fertilizer Guide: Irrigated Alfalfa Central Washington	1980
FG0016	Alfalfa	Fertilizer Guide: Alfalfa-Grass Seedings in Western Washington	1982
FG0030	Alfalfa	Fertilizer Guide: Alfalfa (Non-Irrigated)	1975
EB1260	Barley	Fertilizer Use Field Trials: Spring Barley Fertilization in Non-Irrigated Eastern WA	1982
FG0029	Barley	Fertilizer Guide: Barley for Eastern Washington	1975
FG0005	Bean (field)	Fertilizer Guide: Irrigated Field Beans for Central Washington	1980
FG0006	Corn	Fertilizer Guide: Irrigated Field Corn for Grain or Silage	1970
FG0018	Corn	Fertilizer Guide: Silage Corn	1977
XB0950	Corn-Sweet	Nitrogen and Phosphorus Requirements for Sweet Corn in Western WA	1986
FG0035	Corn-Sweet	Fertilizer Guide: Irrigated Sweet Corn, Central Washington	1977
FG0039	Corn-Sweet	Fertilizer Guide: Sweet Corn for Western Washington	1980
EB1516	Forage	Hay Production Guide for Northeastern Washington	1989
EB1297	Forage	Pasture Management Guide for Northeast Washington	1984
EM3346	Forage	Range and Pasture Fertilization: Eastern Washington	1970
FG0004	Forage	Fertilizer Guide: Irrigated Pasture for Central Washington	1979
FG0037	Forage	Fertilizer Guide: Improved Pasture, Hay, Eastern Washington	1980
EB1569	Grain	Fertilizer Management for Dryland Cereal Production and Groundwater Protection	1990
FG0011	Hops	Fertilizer Guide: Irrigated Hops for Central Washington	1977
PNW433	Onion/Leek seed	Onion and Leek Seed Production	1993
EB1693	Onion	Dry Bulb Onion Production	
FG0025	Pea/Lentil	Fertilizer Guide: Peas and Lentils for Eastern Washington	1980
FG0027	Peas	Fertilizer Guide: Peas	1975
FG0033	Peas(Green)	Fertilizer Guide: Irrigated Peas for Central Washington	1977
FG0007	Potato	Fertilizer Guide: Irrigated Potatoes	1974
FG0046	Ryegrass – perennial	Fertilizer Guide: Perennial Ryegrass Seed--Western Washington	1980
EB1638	Sludge	Recycling Municipal Processed water Sludge in Washington	1992
FG0009	Small Grains	Fertilizer Guide: Irrigated Small Grains, Central Washington	1977

(continued next page)

Table 3-2 (cont.). Washington State University Cooperative Extension publications related to management of nitrogen in the crops summarized in this report. A complete listing of WSU's Extension publications is available in the publication 'Cooperative Extension: Educational Materials,' as well as all of the following publications are available at: WSU Cooperative Extension, Bulletin Office, Cooper Publications Building, Washington State University, PO Box 645912, Pullman, WA 99164-5912; 509-335-2857

Bulletin #	**Crop**	**Title**	**Year**
EB1258	SOILS	Rating Eastern Washington Soils for Potential Nitrogen Losses	1984
EM3076	SOILS	Interpretation of Soil Test Nitrogen: Irrigated Crops in Central Washington	1969
FG0036	Sudangrass	Fertilizer Guide: Irrigated Sudangrass Pasture or Silage	1970
EB1507	Sudangrass/Sorghum	Growing Sudangrass and Sorghum-Sudangrass Crosses in Washington	1988
FG0010	Sugarbeet	Fertilizer Guide: Sugar beets for Central Washington	1970
EB0482	Turf	Home Lawns	1995
EB0924	Turf	Lawn Renovation	1995
EB1153	Turf	Establishing a Lawn in Eastern Washington	1982
EM1627	Turf	Grasses and Legumes	1974
EM3831	Turf	Fertilizers for Play, Athletic Areas: Selection, Purchase, Application	1980
FG0024	Turf	Fertilizer Guide: Lawns, Playfields, and Other Turf, East and Central Washington	1982
FG0038	Turf	Fertilizer Guide: Grass Seed for Eastern Washington	1975
FG0041	Turf	Fertilizer Guide: Home Lawns, Playfields and Other Turf	1982
EM4264	Wheat	Nitrogen Fertilizer Use During Drought in Wheat Area of Eastern Washington	1977
EM4504	Wheat	Holding Back Nitrification in Dryland Wheat Area of Eastern WA	1979
EB1390	Wheat-winter	Fertilizer Guide for Winter Wheat, Eastern Washington Dryland Area	1986
EB1487	Wheat-winter	Fertilizer Guide: Winter Wheat (Soft White), Central Washington, Irrigated	1988
FG0017	Winter Wheat/Barley	Fertilizer Guide: Winter Wheat and Barley for Western Washington	1975
FG0031	Wheat	Fertilizer Guide: Winter Wheat (Irrigated)	1974
FG0034	Wheat	Fertilizer Guide: Dryland Wheat Nitrogen Needs for Eastern Washington	1977
FG0048	Wheat/Barley/Oat	Fertilizer Guide: Spring Wheat, Barley and Oats for Western Washington	1976

3.2 Crop N accumulation

This literature review was compiled by searching the national and international scientific literature for recent articles (last 20 years) that include data relevant to crop uptake of nitrogen. The earlier research (before about 1980) has generally been summarized in review articles, including those of Olson and Kurtz (1982) and Broadbent (1984). The crops reviewed in this report are considered among the most prominent crops grown in Washington State, and are listed in Table 3-3 along with their scientific names and Washington production information. For some crops, such as wheat, a relatively large amount of information has been published relevant to N uptake in Washington specifically. For many of the other crops, including the legumes, there is relatively little published on N uptake from soil and little or no information specific to

Washington. For these crops, almost all available information comes from regions outside the state, making it difficult to draw conclusions for patterns within the state.

Table 3-3. Common and scientific names for the major crops reviewed in this report. Also included are the harvested acreages and dollar values for Washington State in 1995.

Common Name	**Scientific Name**	**WA Production, 1995**	
		Harvested acres	$
Cereal Grain Crops			
Barley	*Hordeum vulgare L.*	290,000	75,150,000
Corn, grain	*Zea mays L.*	102,000	64,923,000
Corn, silage	*Zea mays L.*	48,000	34,344,000
Oat	*Avena sativa L.*	14,000	1,960,000
Wheat, soft white	*Triticum aestivum L.*	2,321,000	total wheat: 733,478,000
Wheat, hard red	*Triticum aestivum L.*	224,000	
Legume Crops			
Alfalfa, hay	*Medicago sativa L.*	500,000	2,550,000
Alfalfa, seed	*Medicago sativa L.*	15,000	10,005,000
Bean, dry	*Phaseolis vulgaris L.*	41,000	20,024,000
Pea, dry / wrinkled seed	*Pisum sativum L.*	95,000 / not avail.	18,573,000 / 7,700,000
Pea, green processing	“ ” “	57,300	30,248
Specialty Crops			
Hops	*Humulus lupulus L.*	30,621	99,290,000
Onion	*Allium cepa L.*	13,500	45,940,000
Potato	*Solanum tuberosum L.*	147,000	553,823,000
Sugarbeet	*Beta vulagris L.*	not available	not available
Forage Crops			
Orchardgrass	*Dactylis glomerata L.*	not available	not available
Perennial Ryegrass	*Lolium perenne L.*	not available	not available
Tall Fescue	*Festuca arundinacea Shreb.*	not available	not available
Cover Crops/Green Manures			
Mustard, white	*Brassica hirtus L.*	not available	not available
Rapeseed, Canola	*Brassica napus L.*	not available	not available
Sudangrass, sorghum sudangrass	*Sorghum bicolor Moench,* *Sorghum sudanese*	not available	not available
Wheat, winter	*Triticum aestivum L.*	not available	not available
Rye, annual	*Secale cereale L.*	not available	not available

3.2.1 GRAIN CROPS

Barley (*Hordeum vulgare* L.)

In 1995, 300,000 ac of barley were planted in Washington for both feed (266,000 ac) and for malting (34,000 ac), with a total harvested yield of about 21 million bushels and worth almost $60 million. Most (97%) is grown under dryland (nonirrigated) conditions (Washington Agricultural Statistics Service, 1996).

Total N accumulation

The unit N uptake range for all treatments in all barley studies surveyed for this report is 0.014 to 0.061 with a mean of 0.025. In addition, total N accumulation averaged 82 kg N/ha, with an average of 61.5 kg N/ha removed with the harvested grain. The range in N uptake was considerable between the various studies, with a range in total plant N uptake of 19 to 260 kg N/ha, and harvested (grain) N uptake of 15-131 kg N/ha (Table 3-4). The nitrogen harvest index averaged at 0.74 (range of 0.50 to 0.91).

The unit N uptake (UNU) for barley following a variety of legume crops or fertilization at 100 kg N/ha was 0.024 (Abernathy and Bohl, 1987). A large range of UNU values (0.025 to 0.061) was observed in barley grown in Alaska (Sharratt and Cochran, 1993).

Fertilizer recovery and N use efficiency

Nitrogen use efficiency (NUE) values for malting barley in the Palouse of eastern Washington ranged from 15.3 to 35.9kg grain dry weight/kg N , depending on the genotype (Nedel et al., 1997). In general, semidwarf genotypes had somewhat lower NUE values than their corresponding standard variety as well as lower yields and malting quality (Nedel et al. 1993). Calculation of NUE included measured values for (NO_3 + NH_4)-N in the surface 90cm of 83 and 22 kg N/ha depending on the year, and estimated mineralized N of 114 and 74 kg N/ha for those same years. In both years, and for both groups of genotypes, increasing fertilizer N rates (from 30 up to 120 kg N/ha) generally resulted in lower NUE (28 or 29 down to 22 or 24 kg/kg N depending on the year). Increasing N fertilizer rate also resulted in higher UNU values (Table 3-4) and increased remobilization of straw N to the grain. In addition, these researchers

Table 3-4. Summary of N accumulation values reported in the literature for barley.

Location	Soil	Cultural Practices	Total N uptake[†]		NHI	UNU[‡]	FNR[§]	Reference
			Mean	Range				
			kg N/ha	kg N/ha		kg N/kg	%	
Riverton, WY	Typic Torrifluvent	Following legume crops	168	180 to 260	0.63	0.028	-	Abernathy and Bohl (1987)
Torrington, WY	Pachic Haplustoll	Following legume crops	87	60 to 120	0.72	0.020	-	Abernathy and Bohl (1987)
Belgium	sandy		101	-	0.65	0.040	57	Khanif et al. (1984)
Corvallis, MT	Typic Argiboroll	1st yr following legumes	107	-	0.89	0.019	-	Westcott et al. (1995)
Kalispell, MT	Pachic Haploxeroll	1st yr following legumes	97	-	0.91	0.018	-	Westcott et al. (1995)
Egypt	sandy loam, pH 4	Avg. 2 yrs; 0 to 167 kg N/ha	41	19 to 73	0.71	0.018	17 (7 to 32)	Abd El-Latif et al. (1984)
Ireland	sandy loam or loam	yrs after pasture, 0-85 kg N/ha	96	61 to 114	0.78	0.020	32 (16 to 47)	Gately and McAlesse (1976)
Canada - Alberta	Dark Brown Chernozemic	Normal weather year	62	33 to 86	0.84	0.027	49 (44 to 54)	Kucey (1986)
Canada - Alberta	" "	dry year	39	26 to 48	0.66	0.034	22 (16 to 28)	Kucey (1986)
Pullman, WA	Ultic Haploxeroll	30 to 120 kg N/ha	-	-	-	0.025	-	Nedel et al. (1993, 1997)
Pullman, WA	Ultic Haploxeroll	11 genotypes, 2 yrs, 45 or 90 kg N/ha	84	59 to 106	0.81	0.021	-	Tillman et al. (1991)
Fairbanks, Alaska	Pergelic Cryaquept	var. row spacing, fertilizer placement, all 100 kg N/ha	133	94 to 205	-	0.037	-	Sharratt et al. (1991)
Montana	Aridic Argiboroll, Typic Argiboroll, or Aridic Haploboroll	5 site-years (3 locations), 0 to 101 kg N/ha	56	19 to 118	-	0.025	-	Jackson et al. (1994)
Canada - Quebec	Typic Hapludalf	200 cultivars, 3 yrs, N source and rate (0 to 200 kg N/ha)	-	-	0.66	-	-	Bulman and Smith (1994)
Canada - Quebec	Typic Hapludalf	3 cultivars, 3 yrs; chemical mgt intensity	0.050g/plant	-	0.63	0.037	-	Bulman and Smith (1993)
Model Value	-	-	-	-	-	0.026	-	Hermanson et al. (1995)

[†] Total N uptake = total plant N (harvested plant part + other above ground plant parts, not including roots).

[‡] NHI = Nitrogen Harvest Index (grain N/total N uptake)

[§] Unit N Uptake = units of N in total plant (except roots) / unit yield. Values shown are the mean of the various treatments of that study.

[¶] FNR = Fertilizer N Recovery = estimated proportion of applied N taken up by the plant. Estimation is based on either FNR or AFNR approach as described in the glossary given in Table 3-1. Values shown for each reference are the mean and range for the various treatments of the study.

present one of the few published sets of estimates for N uptake efficiency (total plant N uptake / total N supply) - with values ranging from 52 to 79% depending on genotype and N application rate.

For the data surveyed in this report, apparent fertilizer N recovery (AFNR) by barley ranges from 7 to 57%, with a mean of 29%. At the highest AFNR (57% of 50 kg fertilizer N/ha), measured in Belgium, the fertilizer contributed 28% of the N contained in the grain, and 26% of the straw N (Khanif et al., 1984). About 32% of the fertilizer N remained in the soil after harvest, and 10% was lost. The loss was attributed to denitrification. Corresponding yields and grain N uptake values in this study were 2450 and 65 kg/ha (dry matter basis).

Early season studies with ^{15}N eight weeks after germination (Dev and Rennie, 1979) found that barley shoots recovered 26.4 to 36.9% of the applied 75 kg N/ha, depending on soil type, and 36.2 to 40.7% of the fertilizer N when the application rate was 150kg 150 kg N/ha for the same two soil types. Ranges for total plant fertilizer recovery were 40.6 to 56.2% and 50.9 to 60.7% for the 75 and 150 kg N/ha rates. Apparent N fertilizer recovery from an irrigated sandy soil in Egypt ranged from 7 to 32%, depending on the study year and N rate applied (Abd El-Latif et al., 1984). In general, greater fertilizer recoveries were obtained a N application rates increased from 0 to 143 kg N/ha. The highest N rate (167 kg N/ha) resulted in decreased yield as well as fertilizer recovery compared to the 143 kg N/ha rate. The yield decrease appeared to be physiological, due to decreased mass of individual grains at the highest rate.

McTaggart and Smith (1995), in studies with spring malting barley in Scotland, found that fertilizer ^{15}N uptake increased almost linearly as N rate increased from 0 to the maximum rate applied (120 or 150 kg N/ha, depending on the site). At the same time they found that uptake of residual soil N was approximately the same across all N Average uptake of non-fertilizer N in their plots was variable, and ranged from 40 to 82 kg N/ha. In a Danish study using ^{15}N, Nielsen and Jensen (1986) estimated 100 kg /ha of non-fertilizer N was taken up by the crop, regardless of the level of N application (30, 90, 120, or 150 kg N/ha).

Seasonal patterns of N accumulation

Bulman and Smith (1994) determined that averaged over 20 cultivars, about 43-72% (depending on growing season and management) of grain N at harvest was due to N accumulation after awn emergence. The corresponding ratio of post-heading N uptake to total plant N ranged from 0.29 to 0.39, depending on growing season and management. Generally less N was retranslocated after heading when higher N rates were applied (Bulman and Smith, 1993, 1994). Working in the Palouse region Eastern Washington, Tillman et al. (1991) found that accumulation of N during grain-filling comprised <17% of total above-ground N accumulation during the entire season. McTaggart and Smith (1995) found that the seasonal distribution of fertilizer and soil N uptake depended on the location as well as form of N fertilizer.

A number of researchers note that a portion of plant N is lost from the crop in later growth stages. Nielsen and Jensen (1986) observed that about 7% of plant-absorbed fertilizer N was lost during the grain-filling period. McTaggart and Smith (1995) observed losses corresponding to about 25 kg N/ha in the period between anthesis and harvest at one site. Tillman et al. (1991) observed losses in many of the genotypes studied, with N losses in these genotypes corresponding to an average 5 to12% (depending on fertilizer application rate) of total plant N at harvest. The most common explanation for these losses is root exudation or volatile losses from the leaves.

Root length.

Sharratt and Cochran (1993) measured root length densities at several intervals in the surface meter of a field soil in Faribanks, AK. The majority of roots were found in the upper 0.4 m with no roots found below 0.8 m. Root length densities measured in July in the surface 0.4 m ranged between 0.22 and 2.64 m/m^3, depending on depth, row spacing, and applied fertilizer location. Highest root length densities were found in the surface 0.10m for all treatments, with a banded skip-row treatment causing the greatest root length densities. Researchers in England measured spring barley root length densities ranging between 88 and 112 cm/cm^2 ground area in a 10 cm soil depth, with somewhat lower root lengths in a relatively wetter year of 74 to 94 cm/cm^2 (Hodgson et al., 1989). Rooting depths of barley grown in the Palouse region of eastern Washington ranged from 90 to 120 cm depending on varying soil resistance with topography and the presence of compacted suboils (Pan and Hopkins, 1991).

Webster et al. (1985) conducted a study with winter barley in England evaluating the relative uptake of $^{15}NH_4NO_3$ injected at four different soil depths. They compared the amount of N uptake from these depths at three times in the growing season (Zadoks stages 23, 31, and 45), and under two different tillage regimes - plowed and direct drilling (no-till). In general, the most N uptake for a given time occurred from the 7.5 cm depth, indicating greater root activity in this zone. The one exception was for the plowed treatment at stage 31, which showed slightly greater ^{15}N uptake from the 15 cm deep sample. Very little ^{15}N was taken up from the 30 and 50 cm depths until the last sampling date, suggesting that roots are not prevalent at this depth until relatively late in the season.

Washington State University recommendations.

Current recommendations for N fertilization on barley in Washington depend on the amount of rainfall, previous crop, whether it is fall or spring planted, and whether it is being grown for feed or malting, and range between 30 and 90 lb N/ac. There are several fertilizer guides for barley production in Washington State (Table 3-2). These guides are for different agronomic situations and give situation-specific recommendations. For example, if peas are grown as the previous crop, then 15 lb N/ac less should be applied. If it is grown under irrigated conditions, a soil test should be used. The possible range of N fertilizer that might be needed is 0 to 180 lb N/ac. University of Idaho N fertilizer recommendations range from 0 to 230 lb N/ac depending on previous crop, preplant soil test N, and yield goal (Tindall et al., 1993). For more specific information see the appropriate Extension publication.

Corn (*Zea mays L.*) Corn is grown in Washington for silage feed for livestock, grain feed (field corn) and sweet corn for human consumption. Most of the information available on soil-corn N relationships focuses on field corn. Information on other types of corn will be distinguished when appropriate.

Total N accumulation and N efficiencies.

A summary of 10 recent N fertility experiments on corn revealed a wide range of total N accumulation across many environments, cultural practices and N fertility management practices (Table 3-5). Interestingly, the average experimental UNU was fairly consistent, ranging from 0.015 to 0.028 kg plant N/kg grain yield.

Maximum dry matter yields of silage corn grown in the Northeastern U. S. exceeded 15 Mg/ha with 112 kg applied N/ha resulting in over 150 kg N/ha total N accumulation (Guillard et al., 1995). Apparent N recovery ranged from 50% at maximum yield to 20 % at 430 kg N/ha applied in excess of that required for maximum yield. Silage corn grown in southern Idaho under irrigation produced 16 to 20 Mg dry matter/ha that accumulated 240 to 260 kg N/ha (Meek et al., 1994). In western Washington, silage corn following various cover crops yielded 7 to 18 Mg/ha while accumulating 60 to 180 kg N/ha (Kuo, 1996). In field corn grown in central Washington, Stevens and Prest (1994) observed that the addition of 112 kg N/ha increased grain yields by 27%, biomass by 26%, and N uptake by 47% in 1993, and by 104%, 54% and 72%, respectively in 1994. Addition of recycled yard debris did not change the fertilizer N requirement. Silage N accumulation was approximately 179 kg N/ha at maximum yield, or 0.0152 kg N/kg grain.

Forage corn grown in eastern Quebec accumulated 130 to 215 kg N/ha and 14 to 18 Mg/ha dry matter (Pare et al., 1992).

Nitrogen uptake by silage corn grown in British Columbia was affected by N source (Paul and Beauchamp, 1993). Corn N accumulation per unit of N applied was ranked: urea > dairy manure slurry > beef cattle solid manure = composted manure, corresponding to 49, 18 and 5% apparent N recoveries in the first year.

In upper state New York, no-till and conventionally-tilled corn yielding 3.2 to 7.2 Mg/ha accumulated 55 to 152 kg N/ha (Sarrantonio and Scott, 1988). Over this wide range of yield and N uptake, the corn exhibited a narrow UNU range of 0.017 to 0.022 kg N/kg grain. Tillage effects on N accumulation were directly related to its effects on yield. In Pennsylvania, total N uptake ranged from 110 to 140 kg N/ha and the UNU averaged 0.017 kg N/kg grain for grain yields ranging from 6.64 to 8.23 Mg/ha (Fox et al., 1986).

The maximum economic optimum rate of N fertilization is dependent on variable yield response over years and locations, and the fertilizer to grain price (F:G) ratio (Cerrato and Blackmer, 1990). The mean predicted economic rates of fertilization over 12 site-years in Iowa, with maximum yields from 8.4 to 13.2 Mg/ha, ranged from 190 kg N ha^{-1} at an F:G price ratio of 2 to 157 kg N ha^{-1} at an F:G price ratio of 10. At an F:G price ratio of 3.36, the economic optimum rates of fertilization ranged from 108 to 302 kg N ha^{-1}, with a mean of 184 kg N ha^{-1} over the 12 site-years.

Crop rotation and tillage can greatly influence N uptake and N fertilizer responses in corn. Residual N availability supplied to two successive corn crops following a previous alfalfa crop was equivalent to about 90-130 kg N ha^{-1} $year^{-1}$ in Pennsylvania, thereby supplying a major portion of the corn N requirement (Levin et al., 1987). In Minnesota, corn following alfalfa required no additional or reduced amounts of fertilizer N to achieve maximum yield compared to continuous corn (Lory et al., 1995). No-till planting increased grain and N uptake of corn in this rotation in one of two years, supporting the concept that initial fertilization requirements may increase with the adoption of no-till systems (Phillips et al., 1980). Nitrogen uptake under no-till ranged from 155 to 192 kg N/ha while conventionally-tilled corn ranged from 138 to 162 kg N/ha, however, the unit nitrogen uptake were similar among N rates and tillage treatments, averaging 0.024 and 0.026 kg N/kg grain in the two years. Similarly, silage corn N uptake at maximum yield was 172 kg N/ha for 14.4 Mg/ha conventionally-tilled corn and 145 kg N/ha for 12.2 Mg/ha no-till corn grown on a Typic Hapludult in Virginia (Menelik et al, 1994). Splitting the N between preplant and at 6-weeks had no effect on yield or N uptake. Applying similar amounts of plant available N as sewage sludge improved plant N recovery by 10%. In eastern Quebec, faba bean grown for seed before forage corn resulted in an N-fertilizer equivalent of

Table 3-5. Summary of N accumulation values for corn reported in selected research reports.

Location	Soil	Cultural Practices	Total N uptake[†]					
			Range	Mean	NHI[‡]	UNU[§]	FNR[¶]	Reference
			kg N/ha	kg N/ha	kg N/kg N	kg N/ kg	%	
Salisbury, MD	Typic Hapludult	Hairy vetch cover; NT	96 to 189	155	---	0.018	38@Ymax AFNR	Clark et al., 1995
Rock Springs, PA	Typic Hapludult	cont. corn; NT	107 to 142	124	---	0.017	----	Fox et al., 1986
Tifton, GA	Kandiudult, Quartzipsamment	Irrigated	199 to 285	221	0.59	0.020	----	Gascho and Hook, 1991
Mead, NE	Typic Argiudoll	Irrigated	90 to 198	131	0.66	0.020	59@Ymax AFNR	Kessavalou and Walters, 1997
Puyallup, WA	Aquic Xerofluvent	Previous vetch, AWP	140 to 180	160	---	0.008 (silage yield)	----	Kuo et al., 1996
Quebec, Canada	Grey Br. Luvisol Humic Gleysol	Cont. corn	97 to 251	174	0.58	0.020	35 to 57 FNR	Liang & MacKenzie, 1994
Lincoln, NE	Pachic Argiustoll AbrupticArgiaquoll	Soybean-corn	53 to 114	84	0.79	0.015	46 FNR	Maskina et al., 1993
VA	Typic Hapludult	CT,NT	80 to 180	164	0.64	0.028	----	Menelik et al., 1994
Guelph, Ontario	Gleyed Melanic Brunisol	Manure or urea	60 to 140	116 for Ntmax	—	0.020 for Ntmax	----	Paul and Beauchamp, 1993
Aurora, NY	Aeric Hapludalf	hairy vetch, NT	44 to 152	94	----	0.020	49@Ymax AFNR	Sarrantonio and Scott, 1988

[†] Total N uptake = total plant N (harvested plant part + other above ground plant parts, not including roots).

[‡] NHI = Nitrogen Harvest Index (grain N/total N uptake)

[§] Unit N Uptake = units of N in total plant (except roots) / unit yield. Values shown are the mean of the various treatments of that study.

[¶] FNR = Fertilizer N Recovery = estimated proportion of applied N taken up by the plant. Estimation is based on either FNR or AFNR approach as described in the glossary given in Table 3-1. Values shown for each reference are the mean and range for the various treatments of the study.

>150 kg N/ha compared with none following soybean (Pare et al., 1992). In contrast, soybean residues in Nebraska increased the uptake of non-fertilizer N in corn, but had minimal effects on fertilizer N recovery (Maskina et al., 1993). Total N accumulation in the corn increased from 53 kg N/ha without fertilizer N or soybean residues returned and no use of hairy vetch cover crop, to 114 kg N/ha with vetch, 150% of the normal soybean residue return rate and 60 kg N/ha applied N.

Rainfed and irrigated corn grown in Wisconsin accumulated 213 to 269 kg N/ha at near maximum grain yields ranging from 8.4 to 11.0 Mg/ha (Oberle and Keeney, 1990). The corresponding apparent fertilizer recoveries in the grain ranged from 30 to 40% for a Plainfield loamy sand to 15 to 30% on Plano and Fayette silt loam soils, or 50 to 67% and 25 to 50% when total above-ground N accumulation was taken into account. Higher apparent fertilizer N recoveries were noted in the irrigated loamy sand, despite the higher amounts of applied N required to achieve near maximum yield. This was explained by the lower contributions from soil N mineralization and possibly more optimum water availability with irrigation. Application of agronomic rates of N to irrigated corn resulted in 50 to 75% apparent fertilizer N recovery, and minimal nitrate percolation below the root zone (Porter, 1995). The amount of residual nitrate to 180 cm was inversely related to the grain yield response to applied N (Olson and Kurtz, 1982). The effectiveness of nitrification inhibitors in improving fertilizer N uptake efficiency by slowing the oxidation of ammonium to nitrate is dependent on the leaching potential of the cropping system (Walters and Malzer, 1990).

In North Carolina, two well drained sandy loam soils yielded 8 and 12 Mg grain/ha corresponding to plant N accumulation of 190 and 130 kg N/ha, with a consistent unit N uptake of 0.016 kg N/kg grain (Overman et al., 1994). In the same year on a poorly drained, high water table soil, the grain yield was 9.5 Mg/ha and total N was 130 kg N/ha or 0.015 kg N/kg grain. Maximum yields were obtained with approximately 15 kg N/ha. In Alabama, corn grain yield ranged from 5 to 8 Mg/ha over 3 years and a range of N rates and timings (Reeves et al., 1993), while total N accumulation ranged from 100 to 210 kg N/ha.

In eastern Quebec, corn yields ranged from 4.7 to 7.5 Mg/ha and total N accumulation ranged from 81 to 155 kg N/ha (Alkanani and MacKenzie, 1996). At maximum yield, the UNU was 0.020 kg N/kg grain. Silage corn grown over 5 years in eastern Quebec produced 3.3 to 18.2 Mg dry matter/ha, while accumulating 48 to 237 kg N/ha (N'Dayegamiye, 1996). Yields were highest when dairy manure and N, P, K mineral fertilizers were supplied. At maximum yields for each year, the UNU for well-fertilized silage corn ranged from 0.012 to 0.015 kg N/kg shoot dry matter. A similar range of UNU was exhibited by unfertilized silage corn.

Crop residues and crop rotations greatly influence soil N availability, N responses to applied N and fertilizer N requirements. While corn residues contribute little additional N to the succeeding corn crop, soybean residues have contributed 60 kg N/ha or 32% of the total corn N accumulation in eastern Nebraska (Power et al., 1986), while alfalfa and soybeans increased corn N uptake 84 to 168 kg N/ha in the first year and 56 kg N/ha in the second year in a Fayette soil in Wisconsin, 67 kg N/ha from soybean residues in a Plano silt loam compared to continuous corn (Oberle and Keeney, 1990). In contrast, no N was apparently carried over from soybeans in a Plainfield loamy sand, where it was speculated that mineralization and leaching occurred prior to corn N uptake. Similarly, fertilizer equivalent values for alfalfa preceding corn were 153 and 36 kg N/ha and 75 kg N/ha for soybeans before corn (Vanotti and Bundy, 1995). Preceding corn with a hairy vetch cover crop can improve corn yield and N uptake, particularly when used as a soil water conserving mulch under dry land conditions (Clark et al., 1995).

An ^{15}N experiment demonstrated that corn fertilized at the V3 stage recovered from 40 to 62% of the applied N by maturity while accumulating 152 to 204 kg N/ha in the above-ground biomass (Francis et al., 1993). Evidence for significant volatile loss of ammonia (perhaps as much as 80 kg N/ha) from the shoots was provided. This suggests that N balance studies that determine N leaching losses by difference could be significantly overestimating the magnitude of this loss. Another ^{15}N experiment conducted in Quebec, Canada demonstrated fertilizer N recoveries of 9 to 58%, with the lower values associated with high rates of fertilization in low yielding environments (Liang and MacKenzie, 1994).

NLEAP, the Evaluation of the Nitrate Leaching and Economic Analysis Package model, uses a default UNU of 0.0214 kg N plant N/kg grain yield (1.2 lbs N/bu), but recognizes that this value is not constant and should be adjusted to fit site specific conditions (Follett et al., 1994).

Seasonal patterns of N accumulation.

Nitrogen uptake by corn over time is typically portrayed as a sigmoidal curve, with little N uptake occurring through stage 2, then rapid acceleration to flowering, followed by slower rates or no net N gain during grain-filling (Olson and Sander, 1988; Stute and Posner, 1995).

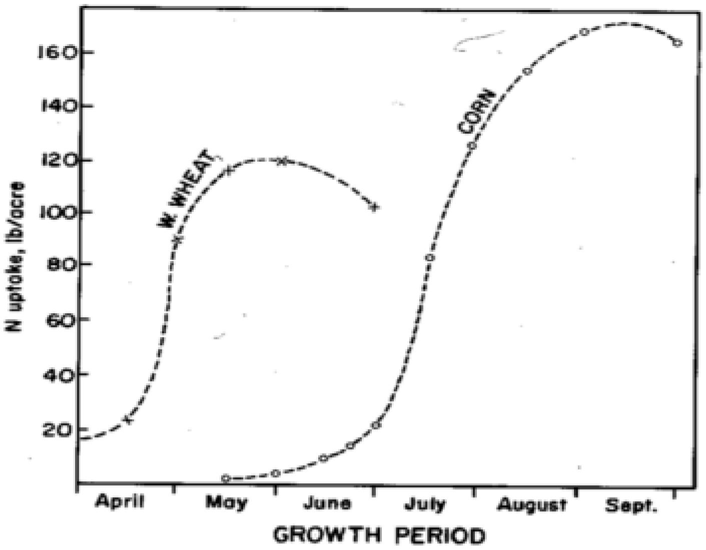


Figure 3-2. Comparative seasonal N uptake patterns for wheat and corn under Nebraska conditions (Bock and Hergert, 1991)

These patterns will vary by year and N timing. Under favorable growing conditions, N accumulation rates were relatively constant from 6 weeks after planting to maturity (15 weeks). In other years, the N accumulation rate declined during grain filling, particularly with lower N rates (Reeves et al., 1993). Senescing leaves become increasingly prone to volatilization of ammonia-N, which may be as significant of a contributor to N losses as nitrate leaching (Francis et al., 1993). In consideration of the time lapsed between planting and significant N uptake, split N applications are typically recommended, particularly for irrigated sandy soils or humid climates. For example, Gascho and Hook (1991) recommends 25% of the fertilizer N applied at planting, and the remaining applied as fertigation by the V6 to V8 stages. The accelerated phase of corn N uptake occurred after that for winter wheat, but preceded bean (Fig. 3-2; Meek et al., 1994).

Nitrogen harvest index

Nitrogen harvest index ranged from 0.79 to 0.85 at maximum yield in three locations North Carolina (Overman et al., 1994) with the lower NHI occurring at the location that was provided with supplemental irrigation. Olson and Sander (1988) reported 68% of the total N in the grain in Nebraska, while Kessavalou and Walters (1997) later reported 63% with 0.0197 kg N accumulation/kg grain and 80% was observed in a soybean rotation (Maskina et al., 1993). Nitrogen harvest indices increased with fertilization and varied among soil types in Wisconsin, ranging from 0.47 to 0.64 (Oberle and Keeney, 1990).

Rooting depth.

Corn root morphology is affected by numerous cultural, environmental and genetic factors (Olson and Sander, 1988). Residual soil nitrate has been used by corn to a depth of 180 cm (Gass et al., 1971), although effective corn rooting depths in irrigated cropping of central Washington is thought to be considerably less, perhaps as shallow as 30 to 60 cm (M.Hammond, personal communication). Corn roots were mainly observed in the surface 20 cm A horizon of a North Carolina soil, with fewer roots measured in the 30 to 60 cm B horizon (Durieux et al., 1994). Increasing N fertilization increased the proportion of roots found in the A horizon. High bulk density and soil compaction can increase the proportion of shallow roots (Vepraskas and Wagger, 1990; Wolfe et al., 1995). Subsoiling allowed roots of dryland corn to extract water from 2.7 m (Eck and Winter, 1992). Corn roots were detected to depths of 75 cm in southeastern Minnesota (Nickel et al., 1995) and in Indiana (Kuchenbuch and Barber, 1987).

Washington State University guidelines

Recommendations for sweet corn management for Central and Western Washington have not been updated since the 1970's. In Western Washington, severe N leaching conditions limits the utility of preplant soil test N assays for providing a basis for making N recommendations. In contrast, N recommendations in the arid Columbia Basin have been based on soil test N levels for over 20 years. Turner et al. (1976) recommended that 75 to 120 lb N/acre be applied to sweet corn in Western Washington. An application of 120 lb N/acre (70 at plowdown and 50 at planting) was recommended when following the incorporation of grass sod, or grain straw or stover; only 90 lb N/acre (40 at plowdown and 50 at planting) was recommended when the straw or stover was removed; 75 lb N/acre (35 at plowdown, 40 at seeding) when following cultivated crops. Dow et al. (1970b; 1979a) recommended rates of 0 to 240 lb N/acre for irrigated sweet corn, silage or grain corn in Central Washington, depending on the spring soil test N level and previous crop. A 40 lb N/acre credit is given to previous legume crops that were harvested, and

80 lb N/acre for legume green manure crops. Soil sampling was recommended to the corn rooting depth, which has not been well defined for this region. Kuo (1985) demonstrated the benefit of sidedressing N in seasons with high leaching potential in Western Washington.

Implications of literature review for N management of corn in Washington.

Although there is only limited data on N uptake and N responses to corn in Washington, the consistent data observed in the literature suggests that a UNU value of 0.020 kg N/kg grain could be initially applied to Washington corn production, and that fertilizer recoveries of approximately 50% could be expected. Total N uptake would be expected to be roughly 200 lb N/A for a 200 bu crop. At 50% N uptake efficiency, an N supply of 400 lb N/A is required from fertilizer, residual soil N, N mineralization, and N in irrigation water, to achieve 200 bu/A grain yield. If N management practices such as split N applications, slow release N fertilizers, and good water management could improve N uptake efficiency to 60%, this reduces the N supply requirement to 333 lb N/A. In view of the relatively consistent N use efficiency values observed in the corn literature, it appears there is good probability that an N budgeting based N recommendation procedure could be developed and verified with field experimentation for corn grown in the Columbia Basin, similar to that available for dryland soft white winter wheat. Field research is needed to define the rooting depths of corn grown in Washington to define the appropriate soil zone of water and N management, and for soil testing purposes to indicate the depth of soil sampling.

A typical UNU can be developed for silage corn by multiplying the average UNU for grain corn (0.020) by the average NHI (0.60), yielding a value of roughly 0.013 kg N/kg silage. Silage corn grown in Western Washington will require multiple N applications to optimize N uptake efficiency due to frequent in-season precipitation. Pre-plant soil testing is less helpful in this environment due to susceptibility of residual nitrate to early season leaching. Crop selection (e.g. cover crops) before and after corn production should emphasized nitrate removal and recycling

Oat (*Avena sativa* L.)

Oat production has been declining somewhat over recent years. In 1995, 32,000 acre of oats were planted, of which 14,000 ac were harvested. This is down from acreages > 60,000 only a few years earlier. The 1995 production value was almost $2 million (Table 3-3).

Adequate N is necessary for crop growth, but an important disadvantage with high N applications on oat grown for grain is an increase in the amount of plant lodging (due to excessive vegetative growth), generally decreasing the grain that can be harvested. In some locations, milling quality has been found to increase with increased N application, though probably not enough to make it a criteria for choice of N rate (Humphreys et al., 1994).

Total N accumulation and N efficiencies.

Two studies that reported both yield and N uptake for oats had UNU average of about 0.24 kg N/kg (Table 3-6). Both studies generally show a slight increase in this value at higher N application rates, though in one treatment of Jackson et al. (1994) the opposite trend was noticed. The range in unit N uptake/unit yield for both experiments was 0.015 to 0.033.

Numerous researchers document the positive correlations that exist between N fertilizer application and oat yield (whether for grain or forage), including Ghosh (1985), Singh and Singh (1979), Chhillar (1980), Stirling et al. (1981), Brinkman and Rho (1984), Marshall et al. (1987), Jackson et al. (1994). However, at the same time, researchers note that an N fertilizer response will only occur where residual soil N is relatively low. For example, Stirling et al. (1981) found that oat forage yields responded to N fertilizer only if residual soil NO_3-N in the surface 20 cm was less than 13 ppm (about 39 kg/ha). Anderson and McLean (1989) found only limited response to applied N (0-120 kg N/ha), and note that seeding rate and sowing date also affected yield. Other researchers also note the role of non-fertilizer agronomic factors in determining oat

Table 3-6. Summary of N accumulation values reported in the literature for oat.

Location	Soil	Cultural Practices	Total N uptake[†] Mean	Range	NHI[‡]	UNU[§]	FNR[¶]	Reference
			kg N/ha	kg N/ha		Kg N/kg	%	
Montana	Aridic Argiboroll, Typic Argiboroll, or Aridic Haploboroll	5 site-years (3 locations)	55	13 to 115	-	0.023	-	Jackson et al. (1994)
Iowa	Typic Haplaquoll	mean of 480 genotypes	-	-	0.63	-	-	Kairudin and Frey (1988)
India, Varanasi	low OM sandy loam	var. N timing; 0 to 90 kg N/ha	62	34 to 85	0.59	0.025	-	Singh and Singh (1979)

[†] Total N uptake = total plant N (harvested plant part + other above ground plant parts, not including roots).
[‡] NHI = Nitrogen Harvest Index (grain N/total N uptake)
[§] UNU=Unit N Uptake = units of N in total plant (except roots) / unit yield. Values shown are the mean of the treatments of that study.
[¶] FNR = Fertilizer N Recovery = estimated proportion of applied N taken up by the plant. Estimation is based on either FNR or AFNR approach as described in the glossary given in Table 3-1. Values shown for each reference are the mean and range for the various treatments of the study.

yield, including seeding rate (Ahmadi et al., 1988), fertilizer timing (Ahmadi et al., 1988; Read and Jones, 1987), extent of lodging - which is often related to increasing fertilizer rates (Brinkman and Rho, 1984), cultivar (Brinkman and Rho, 1984), and planting date (Read and Jones, 1987).

Oat response to residual soil NO_3-N has been documented for a fertilized-corn / unfertilized-oat rotation measured over several years in Wisconsin (Vanotti and Bundy, 1994). These researchers found that oat yield and N uptake was positively related to the amount of residual soil NO_3-N in the surface 90 cm of the soil profile. Residual soil N ranged from about 25 kg N/ha where no fertilizer was applied to corn, up to 475 kg N/ha where the corn had 224 kg N/ha applied the previous April. The leaching environment during and after corn planting also affected residual soil N. They developed the following quadratic plateau regression equations to express the relationship they observed between oat grain yield (kg/ha) and residual soil NO_3-N (kg N/ha, 0-90cm) for each of five years:

1987: $\text{yield} = 611 + 21.6x - 0.0615x^2$, $Y_{max} = 2513$; $R^2=0.88^{**}$
1988: NS (severe drought with very low oat yields)
1989: $\text{yield} = 744 + 28.4x - 0.0828x^2$, $Y_{max} = 3184$; $R^2=0.62^{*}$
1990: $\text{yield} = 1009 + 33.6x - 0.1335x^2$, $Y_{max} = 3127$; $R^2=0.86^{**}$
1991: $\text{yield} = 613 + 29.0x - 0.1228x^2$; $Y_{max} = 2324$; $R^2=0.88^{**}$

where yield = oat yield (kg/ha); x = residual soil N (0-90 cm); Ymax = yield plateau (kg/ha). Y_{max} for these years was reached at residual NO_3-N levels in the surface 90 cm of about 115 kg N/ha. While these equations are of course site specific, they illustrate the type and variety of patterns observed over several years.

Guillard and Allinson (1985) document the effect of various previous legume crops and cutting history on subsequent yield and total N uptake of an unfertilized oat crop. They found that increasing the cutting interval from 30 to 60 days in the legume crop increased oat biomass and N uptake. This increase was due to greater residual soil N.

Nitrogen harvest index.

Nitrogen harvest index in oat generally shows a positive correlation with protein content, i.e., grain with a higher protein content also tends to have a higher proportion of the plant's total N contained in the grain (Fawcett and Frey, 1982; Kairudin and Frey, 1988). Increasing rates of soil N tend to decrease the NHI, though total plant protein accumulation increases (Fawcett and Frey, 1982; Kairudin and Frey, 1988). This decrease in NHI is attributed to a increase in vegetative N without a corresponding increase in grain N, or to depressed N uptake at later growth stages (McNeal et al., 1968). Kairudin and Frey (1988) found that in low N environments, NHI was negatively correlated with total plant protein, indicating that when soil N is limited, the grain had priority on the N present in the plant. However, in high N environments (112 kg N/ha applied N, with little residual soil N) NHI and total plant protein were independent, indicating that when N is not limiting N remobilization and translocation within the plant are independent from N uptake. These results were based on the average of 480 oat lines grown in 0 and 112 kg N/ha environments with corresponding average NHI's of 0.68 and 0.60, and average total plant protein yields of 600 and 700 kg/ha respectively. Singh and Singh (1979) also measured a slight decrease in NHI with increasing fertilizer N, evaluating rates of 0, 30, 60, and 90 k N/ha. The overall average NHI for the four rates was 0.59 with a range of 0.56 to 0.60.

Singh and Singh (1979) found that N applications increased moisture use by the plant, but also increased the efficiency of that use. They found that about 10 mm additional moisture was used for each additional 30 kg N applied (between 0 and 90 kg N/ha), while moisture use efficiency increased by at least 4 kg/mm/ha from 0 to 90 kg N/ha applied. Larsson and Gorny (1988) worked with a variety of new and old cultivars and crosses to assess their relative drought tolerance and the effect of moisture stress on yield. Over all the cultivars tested, yield decreased 35% under their imposed drought conditions during early summer, and harvest index decreased 18%. In the studies summarized, harvest index ranged from 0.25 up to 0.62, indicating a wide variety in the grain to straw ratio depending on the growing environment.

***Root length*.**

Oat root length three weeks after flowering extended to 70 cm where there was a water table at 80 cm depth (Schuurman, 1980). About 50% of total root weight was in the surface 10 cm, with 8-12% present in each subsequent 10 cm increment to a depth of 60 cm. When the water table was increased to 40 cm below the soil surface, rooting depth was only to about 23 cm, with 70% in the 0-10 cm depth.

Some research suggests oat cultivars with greater root length will produce greater yields. Much of this has been conducted by breeders in the context of using seedling root length as an indicator of drought tolerance, invoking the assumption that longer seedling root length would correspond to greater root length in the field (Larsson and Görny, 1994; Barbour and Murphy, 1984). Schwarz et al. (1991), on the other hand, detected no relationship between rooting characteristics of 18 genotypes and yield, though they did find a positive relationship for barley.

Wheat (*Triticum aestivum* L.) - Overview

In Washington State, both soft white and hard red wheats are grown. These two classes are discussed separately in this report since N management differs for the two due to different yield goals and protein production objectives. Both classes can be grown as either winter or spring crops, adding to the complexity of summarizing N uptake patterns.

In 1995, wheat production was the second highest commodity grown in Washington State, second only to apples. Total production for that year was approximately 2.6 million acres worth over $733 million (Table 3-3). Soft white wheat dominated the production, comprising about 2.3 of the 2.5 million acres. About 2.25 million acres were planted to winter wheat varieties, and 0.45 million acres were planted to spring wheat.

Wheat, Soft White (*Triticum aestivum* L.)

Relationship between N recommendations and N use efficiency: an historical perspective.

The basic framework for N recommendations for dryland wheat systems in the Pacific Northwest were also established in the 1950's and 1960's (Jackson et al., 1952; Jacquot, 1953; Leggett, 1959; Reisenauer and Leggett, 1957); Leggett and Nelson, 1960), with subsequent minor updates and adjustments resulting in the current regional recommendations (Engle *et al.*, 1975; Halvorson *et al.*, 1986). The conceptual basis for making N recommendations was founded on experimental determinations of N use efficiencies, which in turn were affected by N uptake efficiencies. In eastern Washington, the rule of thumb is that there are approximately 1.35 lb N accumulated for every bushel of soft white wheat produced, and that with a 50% N uptake efficiency, 2.70 lb N must be supplied to grow a bushel of wheat.

Site selection for the early N trials that established these recommendations varied by researcher. Jacquot (1953) established strip trials transecting typical fields and sampled sites corresponding to different slope positions; however, the data he reported was averaged over the entire field location. Nevertheless, within-field variations in N responses were integrated into the overall N recommendations generated from this research. More typically, researchers selected sites of uniform soil and topography, to represent large areas of land in the immediate vicinity (Leggett and Nelson, 1960; F. E. Koehler, personal communication). These early studies demonstrated that residual nitrate, in-season N mineralization, and N immobilization due to high C:N straw residues altered wheat responses to N fertilization (Leggett and Nelson, 1960). Calculations for predicting N requirements for winter wheat were based on yield potential, the amount of N supply required per unit yield (UNR; unit N requirement), and the soil N supply.

It was recognized in these early studies that yield potential was strongly related to available soil moisture in eastern Washington. Wheat yields were therefore predicted for regional rainfall zones between 10 and 22" annual precipitation. For example Jacquot (1953) established a basic model for predicting yield based on water and N, providing that other growth factors were not limiting:

available soil moisture + nitrogen uptake = wheat yield
(1 acre-inch) (7 lb) (3.5 bu)

It was also observed that the N supply requirement was in excess of the 2.0 lb plant N/bushel, to account for N efficiencies in the system, resulting in recommendations of 2.7 to 3.2 lb fertilizer N/bushel. Jacquot also acknowledged that the N fertilizer requirement was subject to change, based on residual nitrate and soil N mineralization/immobilization rates.

A few years later, this relationship was refined by Leggett (1959), who suggested that 4 inches of available moisture were required to establish the crop, and each additional inch of moisture produced 6 bushels of wheat. By plotting the maximum yield vs. soil nitrate + fertilizer N over several site-years throughout eastern Washington, a general UNR of 2.9 lb N/bu was derived for growing region. Further refinements produced our current recommendations based on 6 bu/inch available water and 2.7 lb N supply/bu wheat (Engle et al., 1975; Halvorson et al., 1986), in which:

Ns = Gw X Ns/Gw
N supply requirement = potential yield x UNR

and N supply is calculated as:

N supply = residual inorganic soil N in root profile + mineralizable N + fertilizer N - N immobilization by high C:N crop residues.

The current recommendations continue to be based on regional variations in yield potential, soil N availability and average UNR. Site-specific variation in UNR, N mineralization, and residual nitrate had not been evaluated in these early studies. As a result, N recommendations were and continue to be location-specific (Halvorson, 1986; Engle et al., 1975), but not site-specific within single fields.

More recently, field experiments have been conducted to examine the potential benefits and constraints of variable N management (Mulla et al., 1992; Fiez et al., 1994a). This approach has the potential for lowering input costs while maintaining yield and improving grain quality, but the yield response to N fertilizer and the N use efficiency components have been shown to widely vary across landscapes (Fiez et al., 1995; 1994b), resulting in quantitative changes in N recommendation factors. The UNR varied by 24 to 70% within four fields in eastern Washington, illustrating the difficulties in applying current N fertilizer recommendation guidelines on a site-specific basis. The current guidelines assume the UNR to be 2.7 lb N/bu. A soil fertility case analysis suggested that site-specific information on yield potential, UNR, residual soil N, and N mineralization are required to accurately predict preplant N fertilizer requirements for winter wheat (Fiez et al., 1994a,b). Variation in UNR across fields results from variation in soil and plant factors affecting N use efficiency (Fiez et al., 1995). Nevertheless in fields with past history of uniform N fertilization where a buildup of residual soil N has occurred on low yielding sites, application of current recommendation guidelines on a site-specific basis can reduce N fertilizer requirements while maintaining grain yield and improving grain quality (Mulla et al., 1992).

Nitrogen accumulation and efficiencies.

Recent research studies in eastern Washington have demonstrated tremendous N accumulation potential of soft white winter wheat. This crop is capable of storing N in the grain as protein, so that N continues to accumulate in the plant as N is supplied above and beyond that required for maximum grain yield production (Fiez et al., 1995; Sowers et al., 1994). Total plant N (above-ground only) ranged from 90 to 250 kg N/ha depending on N fertilizer timing, N rate and landscape position.

The units of plant N accumulation per unit yield varied among landscape position from 0.020 to 0.031, with an average of 0.024 (Fiez et al., 1995). The majority of N uptake occurs between the tillering and boot stages of development, with most of the plant N derived from soil N sources (Fig. 3-3; Sowers et al., 1994). Thus, the accelerated phase of N uptake occurs earlier than that for spring crops such as corn and bean (Meek et al., 1994). A wheat model developed by Rickman et al. (1996) predicts N accumulation to occur between 500 and 1000 growing degree days. Labeled fertilizer studies demonstrated that only 25 to 33% of the total plant N may be derived from fertilizer applied in the current growing season, and that spring N applications can improve fertilizer N recovery and grain productivity in the annual cropping zone of eastern Washington and northern Idaho (Fig. 3-3; Sowers et al., 1994; Mahler et al., 1994). There is little additional N accumulation that occurs after anthesis (Sowers et al., 1994), unless N is applied in suboptimal rates (Koehler, 1960).

Nitrogen uptake efficiency varies by landscape position in the Palouse, presumably because of different magnitudes of N loss that occur across the rolling topography (Fiez et al., 1995). While 2.7 lb N/bu (0.045 kg N supply/kg grain) wheat is a reasonable estimate of N supply (UNR) required for winter wheat across the region, within field variations in this figure have ranged from 1.8 (0.03 kg N/kg grain) to 3.9 (0.065 kg N/kg grain). The UNR can be reduced with split N applications in the annual cropping zone (Sowers et al., 1994). Fertilizer placement can significantly improve N uptake recovery compared to broadcast applications (Janzen et al., 1991).

Table 3-7. Summary of N accumulation values reported in selected research reports.

Location	Soil	Cultural Practices	Total N uptake[†] Range	Mean	NHI[‡]	UNU[§]	FNR[¶]	Reference
			kg N/ha	kg N/ha		kg N/kg	%	
Soft White Winter Wheat								
Moscow, ID	Xeric Argialboll	placement x timing x source	----	----	----	----	(NPE) 44 to 60	Mahler et al., 1994
Pullman & Farmington, WA	Ultic Haploxerolls	placement x timing	125 to 250	190	0.70 to 0.74	----	(FNR) 18 to 33	Sowers et al., 1994
Pullman & Farmington, WA	Ultic Haploxerolls	landscape positions	90 to 240	130 to 250 @ Ymax	----	0.020 to 0.031	(NPE) 38 to 70	Fiez et al., 1995
Hard Red Winter Wheat								
Perkins, OK	Udic Argiustoll	pre or in-season dryland	35 to 98 (all) 56 to 86 (Y_{max})	71 (avg.) 80 (Y_{max})	0.74 (avg.) 0.69 (Y_{max})	0.030 (avg.) 0.032 (Y_{max})	(AFNR) 46 avg 49@Y_{max}	Boman et al., 1995
Lethbridge, Alberta	sandy clay loam	timing x point inj. (pi), broadcast (bc), or band (bd)	-----	----	----	----	FNR: 40 bd; 30 to 35 bc; 20 to 60 (spring pi)	Janzen et al., 1991
Manhattan, KS	Typic Argiudoll	dryland	87 to 129	110	0.66 (fert. NHI)	----	FNR: 44 to 57	
Saxmundham and Woburn, UK	sandy cl loam sandy loam	spring N applications	23 (no N) to 229 (fert N)	NA	----	----	FNR: 46 to 85	
El Reno, OK	Udertic Paleustolls	conv. vs. no-till	91 to 189	151	0.51 to 0.65	0.036 to 0.048	AFNR: 63 to 111	Rao and Dao, 1996
Hard Red Spring Wheat								
Davis, CA	Typic Xerorthent	irrigated	50 to 200	120 avg 200@Y_{max}	-----	0.025@no N to 0.028@Y_{max}	----	Cassman and Plant, 1992
Pullman, WA	Typic Hapluxeroll	dryland, fall or spring N comb.	80 to 105	98	0.77 to 0.84	0.029 to 0.038 0.033@opt N	(NPE) 54 to 68	Huggins et al., 1989a
Davis, CA	Typic Xerorthent	irrigated, preplant + anthesis N	140 to 255	210 avg; 219@Ymax	0.66 to 0.79 0.74 avg	0.024 to 0.036 0.031@Ymax	anthesis N: AFNR: 37 to 116 FNR: 50 to 80	Wuest and Cassman, 1992
Sidney, MT	Typic Argiboroll	dryland, broadcast or band	56 to 69	66	0.75 to 0.77	0.033 to 0.038 0.035 at opt. N	(AFNR) 16 to 29	Jacobsen et al., 1993

[†] Total N uptake = total plant N (harvested plant part + other above ground plant parts, not including roots).

[‡] NHI = Nitrogen Harvest Index (grain N/total N uptake)

[§] UNU=Unit N Uptake = units of N in total plant (except roots) / unit yield. Values shown are the mean of the treatments of that study.

[¶] FNR = Fertilizer N Recovery = estimated proportion of applied N taken up by the plant. Estimation is based on either FNR or AFNR approach as described in Table 3-1 Values shown for each reference are the mean and range for the various treatments of the study. NPE = N uptake efficiency, given where available.

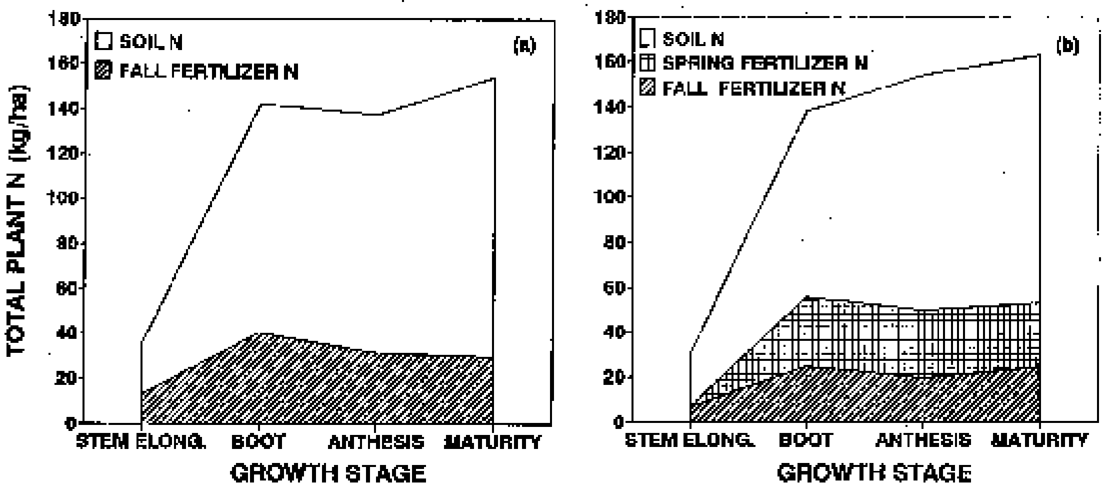
Nitrogen harvest index.

The proportion of above-ground N that is partitioned to the grain has been observed to range from 0.70 to 0.74 in soft white wheat grown in Eastern Washington (Sowers, 1992). Note that this is a slightly lower proportion compared to the hard red wheats, since the hard wheats accumulate more protein in the grain. However, in drier climates of eastern Washington, SWW has been observed to have higher NHI of 0.77 (Rasmussen and Rhodes, 1991).

Rooting depths.

Roots of soft white winter wheat have been detected to a depth of 150 cm in eastern Washington (Sowers, 1992), and plant depletion of soil water and nitrate over the growing season confirmed that roots were active to that depth. Soil water depletion at Lind, WA suggested that soft white winter wheat roots were active to at least 90 cm (Mohammad, 1993). Nitrate removal was noted to a depth of 120 cm under soft white winter wheat (Morton, 1976).

Figure 3-3. Increased fertilizer N recovery with split applications of N on soft white wheat near Pullman, WA (Sowers et al., 1994).



Implications of literature review for N management of soft white wheat in Washington.

Since the PNW specializes in growing and marketing soft white winter wheat, most of the N literature data was generated at WSU. Recent N experiments verified the relevance of historical data and approaches to N budgeting and N management. High yielding soft white winter wheat is capable of accumulating in excess of 200 kg N/ha, much of which is derived from soil N sources, allowing N applications of less than 125 kg N/ha. Average values of UNU of 0.20 to 0.025 result in UNR values from 0.040 to 0.050.

***Washington State University guidelines*.**

The nitrogen budgeting calculation described in section 3.2 provides the basis for N fertilizer recommendations for both hard red and soft white wheats (FG-34, Engle et al., 1975). The UNR value recommended for soft white wheat is 2.7 lb N/bu and 3.0 for the hard wheats. However, Huggins and Pan (1989) suggested that an UNR of 3.5 lb N/bu is required for producing hard red spring wheat with 14% protein. Applications can also be based on soil test nitrate levels (EM4264, Halvorson, 1977; Halvorson et al., 1986; EB1487, Stevens et al., 1988). Banding N fertilizer below or to the side of the seed row is essential for maximizing grain production in no-till systems (PNW283; Veseth et al., 1986).

Wheat, Hard red *(Triticum aestivum L.)*

Total crop N accumulation.

In general, since the grain protein requirement for hard red spring wheat is higher (>14% protein) compared to the soft white wheats (8 to 10% protein), about 30% more N supply is required per bushel to produce good quality grain of hard red spring wheat. Approximately 3.5 lb N supply/bu (0.058 kg N supply/kg grain) should be supplied from soil or fertilizer sources to achieve these protein goals at maximum yield (Huggins, 1991). Due to the lower yield potentials of hard red spring wheat, total N accumulation is generally lower than soft white winter wheat, in the range of 125 to 248 kg N/ha of well fertilized, moderate to high yielding hard red spring wheat (Huggins, 1991; Koenig, 1993; Cassman and Plant, 1992), and 0.031 to 0.071 kg plant N/kg yield. Most rapid plant N accumulation in HRS occurs before anthesis under dryland conditions, although some N accumulation continues during grain filling (Huggins, 1991). Under irrigated conditions with yields >5500 kg/ha, total plant N ranged from 140 to 255 kg N/ha at 0.024 to 0.035 kg N/kg grain (Wuest and Cassman, 1992a and b). Under low yielding conditions (<2000 kg/ha yield), HRS accumulated less than 70 kg N/ha (Jacobsen et al., 1993). Hard red winter wheat has been observed to accumulate 100 to 200 kg N/ha, at 0.038 to 0.048 kg plant N/kg grain (Rao and Dao, 1996). Lower values were observed in Oklahoma when N fertilizer was applied in split applications under dryland conditions: 0.022 to 0.025 (Boman et al., 1995). In the UK, total N accumulation of fertilized HRW ranged from 121 to 229 kg N/ha, and recovery of spring applied, labeled N ranged from 46 to 87 % of the spring application rate (Powlson et al, 1992). Percentage of N lost was correlated to the amount of rainfall. Similar improvements in N response to spring N applications were noted in Colorado (Vaughn et al., 1990).

Late season N accumulation may require good availability of N in the lower root profile, as evidenced by the improved grain protein production when N applications are split between fall and spring (Huggins et al., 1989b). Moderate fall fertilization will improve deep N availability by allowing for nitrate movement into the lower root depths where late season soil moisture is available. In some dryland situations such as in eastern Washington during a winter with mild precipitation, N uptake efficiencies can be improved with fall applications prior to spring planting, due to better positional availability of that N during the growing season.

Nitrogen uptake efficiencies of HRS have been observed to range between 0.54 to 0.84, with the efficiencies tending toward the lower part of that range at maximum yield (Huggins, 1991; Koenig, 1993). Apparent N fertilizer recovery efficiencies ranged from 20 to 34% in irrigated hard red winter wheat in South Carolina (Karlen et al., 1996); however under dryland conditions, it has been demonstrated that hard red winter wheat can serve as an efficient buffer when excess N is applied, whereby fertilizer application of 25 kg N/ha in excess of that required for maximum yield is accumulated in the plant tissue, preventing soil N buildup (Raun and Johnson, 1995; Johnson and Raun, 1995). A greater proportion of fertilizer N was recovered from spring vs. fall N applications, and residual soil N contributed a major portion of the total N accumulated by HRW (Olson et al, 1979).

Nitrogen harvest index.

Nitrogen harvest index of hard red spring wheat has ranged from 0.70 to 0.83 in Eastern Washington (Huggins, 1991; Koenig, 1993), while others report different ranges for different regions, e.g. 0.82 to 0.85 in Montana (McNeal et al., 1971), 0.38 to 0.78 in North Dakota (Bauer, 1980), and 0.32 to 0.65 in Minnesota (Loffler et al., 1985). Under irrigated conditions in California, NHI ranged from 0.62 to 0.80 with preplant N rate and variety (Wuest and Cassman, 1992a). Hard red winter wheat has an NHI of 0.51 to 0.64 in Oklahoma under dryland conditions (Rao and Dao, 1996).

Rooting depth.

Roots of hard red spring wheat have been observed to depths of 90 to 120 cm by the boot stage (Gao, 1995; Pan, unpublished data). In contrast, rooting depth of hard red winter wheat has been observed to 2 m when deep soil profiles are available (Worzella, 1932), or much shallower when roots are restricted by chemical or physical factors (Incerti and Leary, 1990). Rhizotron observations documented HRW roots to 120 cm (Merrill et al., 1994). Hard red winter wheat grown in the UK removed mineral N to a depth of at least 1.5 m (Addiscott and Darby, 1991).

Buildup of residual soil N.

Wheat has some capacity to buffer against excessive N application rates relative to that required for optimum grain yield by accumulating additional N and storing it as protein (Raun and Johnson, 1995). As a result applications of up to 25 kg N/ha in excess of the optimal rate may not result in additional residual soil N. However, several studies have shown that higher, excessive N application rates will increase residual soil N that is susceptible to nitrate leaching (Alessi et al., 1979; Chaney, 1990).

Implications of literature review for N management of hard red wheat in Washington.

Both spring and winter hard red wheats have been shown to have the capacity to accumulate over 200 kg N/ha in grain and straw. The higher protein accumulation in these wheats results in greater N removal (NHI can be expected to range from 0.70 to 0.80), thereby requiring greater N inputs to replenish the cropping system. Unit N uptake values range from 0.028 to 0.036 for well fertilized red wheat crops, and N fertilizer recovery efficiencies can be expected to range from 50% to 70% unless residual soil N is high, which will contribute greatly to the plant N accumulation, but will reduce fertilizer N recoveries. Higher efficiencies may be achieved with small in-season inputs between tillering to anthesis, provided there is ample soil moisture and residual N levels are not excessive. N uptake efficiencies can be maintained with 25 to 40 kg N/ha applied in excess of that required for maximum yield, due to the capacity for protein storage in the red wheats. Rooting depths range from 120 to 180 cm, and optimal protein production requires N distribution throughout the root profile in dryland situations. This may require fall N fertilization in low leaching environments of eastern Washington when residual N is low and deep N is required to sustain grain protein production.

3.2.2 LEGUME CROPS

Legumes have the ability to promote the microbial fixation of N_2 gas into mineral N forms that plants can incorporate into organic N compounds. Legumes form symbiotic relationships with members of either *Rhizobium* or *Bradyrhizobium*. The symbiosis takes place inside nodules that are formed in association with the plant roots, and can only take place if the bacteria are present - either naturally or through inoculation. Legumes are also able to use mineral N found in soil in the same manner as other plant species. A number of studies have shown that the addition of N fertilizers to legume crops can decrease the amount of N_2-fixation, causing the plant to take up more N from soil. However, it has also been noted that a certain level of N_2-fixation continues to occur in the presence of high rates of N fertilization, raising the question of how much excess N is available for leaching in legume systems treated with processed water and manures.

Several studies have been conducted to determine whether the addition of N to legumes can aid in establishment of the crop, ultimately leading toward increased yields. Most studies addressing the N content of legumes have been oriented toward maximizing the amount of N_2 fixation in order to increase yields and/or N content of the harvested beans. This is in contrast to the purpose of this report - namely to address N uptake in the context of an N disposal problem. As responsible manure disposal receives increasing attention, recent and current studies address this issue more directly. However, in general, there are relatively few studies documenting the effect of N addition on the total N balance in a field situation.

The major legume crops grown in Washington State are alfalfa (*Medicago sativa* L.); bean (*Phaseolus vulgaris* L.), especially dry bean; and pea (*Pisum sativum* L.) as dry, seed, and processing pea. Alfalfa is grown primarily as a forage crop (with some acreage planted to harvest alfalfa seed) but is included in this section rather than the forage or seed sections because of its N_2-fixation capability.

Table 3-8. Summary of N accumulation values reported in the literature for legume crops.

Location	Soil	Cultural Practices	Total N uptake† Mean	Range	UNU§	FNR¶	Reference
			kg N/ha	kg N/ha	kg N/kg	%	
			ALFALFA				
Glasshouse	50/50 mix: silt loam & sand	0N, NH4-N, and NO3-N	9.85 mg/plant	4.4 to 17.2mg/plant	0.056	41 (16 to 62)	Barber et al. (1996)
Corvallis, Montana	Typic Argiboroll	field, no added N, 3cuts	178	-	0.028	none applied	Westcott et al. (1995)
Kalispell, Montana	Pachic Haploxerol	field, no added N, 3cuts	216	-	0.032	none applied	Westcott et al. (1995)
Pennsylvania		field, no added N	266	179 to 319	0.032	none applied	Sollenberger et al. (1984)
Minnesota	Typic Hapludoll	field, 0 to 840 kg N/ha	682	617 to 746	0.039	-	Lamb et al. (1995)
Review article approx	-	Field	510	-	0.028	-	Olson and Kurtz (1982)
Standard value for model	-	-	-	-	0.031	-	Hermanson et al. (1995)
			BEAN				
Southern Idaho	Xerollic Calciorthid	field,, 0 to 168 kg N/ha	165	112 to 208	0.058	37 (8 to 53)	Westermann et al. (1981)
Hawaii	Humoxic Tropohumult	field, 9 to 120 kg N/ha	152	142 to 170	-	38 (24 to 51)	George and Singleton (1992)
			DRY PEA				
Australia	red clay loams	Straw, dryland and irrigated trts.	94	70 to 134	-	-	Evans et al. (1997)
Pullman, WA	-	avg. of 3 landscape positions	128	75 to 210	-	-	LaRue and Patternson (1981)
Denmark	perlite	Grown in pots	-	-	-	-	Jensen (1996)
Standard value for model	-	-	-	-	0.022	-	Hermanson et al. (1995)
NE Oregon	Typic Haploxeroll	field, no added N, irr vs. nonirr.	162	97 to 228	0.17 (dry wt)	-	Rasmussen and Pumphrey (1977)

† Total N uptake = total plant N (harvested plant part + other above ground plant parts, not including roots).

§ UNU=Unit N Uptake = units of N in total plant (except roots) / unit yield. Values shown are the mean of the treatments of that study.

¶ FNR = Fertilizer N Recovery = estimated proportion of applied N taken up by the plant. Estimation is based on either FNR or AFNR approach as described in the glossary given in Table 3-1. Values shown for each reference are the mean and range for the various treatments of the study.

Alfalfa (*Medicago sativa* L.)

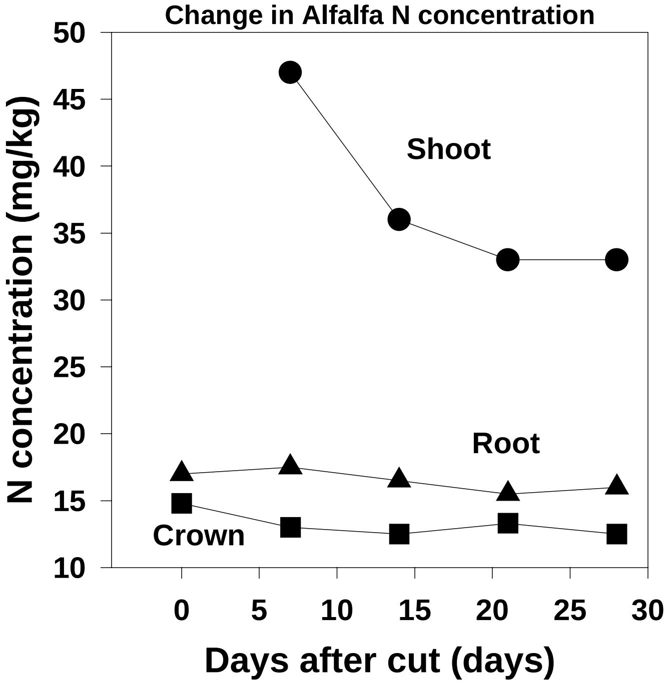
Alfalfa represented 66% of Washington's hay acreage in 1995, with a corresponding production value of $326 million. Total hay production was ranked 7th of Washington's agricultural commodities. Alfalfa seed production is ranked 32 in this list. In 1995, Washington was first in the nation for production of both dry edible peas and wrinkled seed peas, and 8th for production of dry edible beans. Corresponding acreages were 95,000 ac (dry edible pea) and 41,000 ac (dry edible bean), with production values of $18.5 million and $20 million respectively.

Nitrogen accumulation.

Total aboveground N accumulations ranged from 178 to 216 kg N/ha were measured in a conventional three-cut system with annual alfalfa ('Nitro') in western Montana (Westcott et al., 1995). Corresponding dry matter accumulations were 6.4 and 6.8 Mg/ha. Their results found that an average of about 0.03 kg N were required to produce 1 kg yield. In their review article, Olson and Kurtz (1982) cite total N uptake (and removal) of 510 kg N/ha under a 'good yield', which they present as 18,000 kg/ha. The corresponding UNU for this system is 0.028 kg/kg N.

Average UNU for all studies summarized in this report is 0.034 kg/kg N. Reported annual N accumulations range from 178 to 510 kg N/ha.

Figure 3-4. Patterns in N concentrations in the various plant parts of alfalfa following harvest. From Barber et al. (1996).



Seasonal distribution.

Unlike most other crops summarized in this report, alfalfa is a perennial crop that can be cut and harvested several times during the growing season. Nitrogen uptake and concentrations in various plant parts depends on stage of development, as well as nitrogen fertility, cultivar, and environmental conditions. Barber et al. (1996) evaluated patterns of N accumulation in alfalfa following cutting. They found that whether fertilizer N is added or not, the majority of N is contained in the shoots during regrowth, with much lower concentrations in unharvested parts (roots and crowns). Shoot N concentrations decline while root N concentrations tend to increase as growth continues, but shoot N concentration always remains higher than that of the unharvested parts. While the patterns over the season for different N application treatments are somewhat similar, Barber et al. (1996) found that N concentrations were generally higher in all plant parts when N was applied compared to 0 N control plants, and found that NO_3-N was more readily assimilated into plant tissue than NH_4-N. Huang et al. (1996) found that substantially more N was contained in alfalfa at late season harvest dates, with 99, 138 and 161 kg N/ha at sampling dates in June, August, and October, respectively.

A number of studies have shown that the addition of N fertilizers to legume crops can decrease the amount of N_2-fixation, causing the plant to take up more N from soil. However, it has also been noted that a certain level of N_2-fixation continues to occur in the presence of high rates of N fertilization, raising the question of how much excess N is available for leaching in legume systems treated with processed water and manures. Of particular concern is the potential for root turnover and subsequent mineralization after shoot cuttings. These systems should be monitored to ensure that N leaching is minimized.

Role of N_2 fixation.

Nitrogen fixation accounts for varying proportions of total N uptake in alfalfa. Heichel et al. (1981) found that 43% of harvested N in alfalfa came from N_2 fixation. This corresponded to 148 kg N/ha. In other long-term studies, annual average N_2 fixation ranged from 212 to 290 kg N/ha. Several studies have found that N application (300 lb/ac) to this N_2-fixing crop often increased yield and nitrogen concentration, especially at the second cutting. Vandecaveye and Bond (1936) tabulate yields and N concentrations for a variety of soil types and fertilizer treatments in both eastern and western Washington. They found that yields always increased with the addition of inorganic N, while plant N concentration sometimes increased and sometimes decreased. More recently, Teuber et al. (1991) found that applications of N up to 100 kg N/ha resulted in higher dry matter yields - an average (over 4 locations and 2 years) of 115%

higher at the 100 kg N/ha rate compared to no N fertilizer. Plant nitrogen concentration also increased significantly ($p<0.05$) to 36.7 g/kg from 35.8 g/kg. Cherney and Duxbury (1994), working in growth chambers, found that adding increasing amounts of ^{15}N-labeled inorganic N (NH_4NO_3) to alfalfa after the first cutting resulted in linear increases in herbage weight and N concentration, and consistently lower N_2 fixation in all eight alfalfa germplasms evaluated. It appeared that at the higher N rates, the nodules were non-functional. Using non-nodulating strains of alfalfa as non-fixing controls, Lamb et al. (1995) also found significant decreases in N_2 fixation as fertilizer N increased. However they did not find similar yield increases due to increasing fertilizer N, and they observed that some N_2 fixation did occur even at very annual high N application rates - with 20 to 25% of the plant N coming from fixation at the 840 kg N/ha rate. Their study was summarized over two years, and they suggest that the yield benefits from adding N to alfalfa probably do not extend beyond the first or second cutting.

Rooting depth

Alfalfa is generally considered a deep rooting crop, and has a tap root. Huang et al. (1996) found that alfalfa was able to recover 40% of ^{15}N (20 kg N/ha) injected 120 cm below the soil surface, indicating significant root activity at this depth.

Washington State University guidelines

In general, N applications to alfalfa are not needed, except when establishing new seedlings, in which case applying 30 to 40 lb N/ac is suggested under irrigated conditions (Dow et al., 1976). In western Washington, suggested rates for seedling establishment range from 20 to 40 lb N/ac, depending on previous crop (Turner et al., 1975). In some cases/regions N additions may be needed for established stands. For example, Dow et al. (1976) suggest 60 lb N/ac to increase yields under irrigated conditions. However, additions of N to alfalfa do not necessarily result in excess N in the profile, since N the amount of N_2-fixation will decrease and inorganic N uptake will increase when there is sufficient inorganic N in the profile.

Implications of literature review for N management of alfalfa in Washington

Although alfalfa is a legume that would not require high inputs of N fertilizer for production purposes, its deep rooting system and high capacity to accumulate large amounts of N following the multiple cuttings over the course of a growing season make it a good crop for recovering N from processed water.

Bean *(Phaseolus vulgaris L.)*

Dry edible beans were 27th of the top 40 commodities grown in Washington in 1995, with 41,000 acres harvested worth about $20 million in that year. Washington ranks 8th in the nation for dry edible bean production. Adams, Franklin, and Grant counties account for about 70% of the production. The major bean varieties grown in the state are: small red, pinto, small white, pink, garbanzo, great northern, and black turtle soup beans. Snap beans for processing are also grown in the state, though statistics for this crop have been included within the category of 'Other Processing Crops' in recent years.

N accumulation

Common bean relies less on N_2-fixation to meet its N requirement compared to other legumes grown as crops, such as soybean.(e.g., Westermann et al., 1981). Fertilization with < 50 kg N/ha in low-N soils ensured early vigorous plant growth, but did not always increase bean yield. Some cultivars showed a yield increase, others no effect, and others a yield decrease when fertilized. The data suggest that N uptake by fertilized plants was greater than non-fertilized, but no statistical analysis of N uptake was reported. Fertilizer applications of 45 and 134 kg N/ha significantly reduced the number and mass of nodules, but did not affect nodule activity during vegetative and early reproductive stages, suggesting the inhibitory effect of N fertilizer is due to a reduction in nodule formation, and not due to interference of the N_2-fixation process.

Large cultivar differences exist with respect to N_2 fixation. Westermann and Kolar (1978) working in southern Idaho compared N_2 fixation rates in cultivars of pinto, great northern, small white, red Mexican, kidney pink, cranberry, black turtle, brown, and garden white beans. They found five- to six-fold differences in daily N_2 fixation activity among the cultivars. These differences were related to the average nodule weight and to total plant dry weight at maturity. Cultivars with similar plant dry weights had two- to three- fold differences in relative N_2-fixation rates.

Biological N_2 fixation in the bean cultivar 'Great Northern 1140' accounted for 91 kg N/ha, which was between 60 and 90% of the total plant N accumulation (Kucey, 1989a). In a second study with the same bean cultivar, Kucey (1989b) found that N_2 fixation in nonfertilized plants averaged about 75% of total N in the plant. Relatively low amounts of applied N (30 mg N /kg soil) had a stimulatory affect on dry matter production, and subsequently higher N contents and accumulated amounts of N_2 fixed. They note that this stimulatory effect of low amounts of starter N has been observed in other legume crops as well, without inhibiting N_2 fixation. This low rate of fertilizer application did not significantly decrease N_2 fixation compared to unfertilized plants. However higher fertilization rates (60 or 120 mg N/kg), applied before the

6th week significantly decreased the N_2 fixation proportion of harvest plant N content to as little as 10 percent. Greatest N uptake and concentration in the plant occurred when fertilizer was applied at the 6th week after planting - with plant concentrations ranging from 17.3 to 42.1 mg N/kg. They determined that dry matter production of both pods and stover was affected by rate but not timing of fertilizer N additions.

Rennie and Kemp (1983) observed aboveground N uptake ranged from 100 to 184 kg N/ha (depending on cultivar and rate of fertilization (10 or 40 kg N/ha)). At the lower N application rate, an average of 51.8% of plant N was derived from N_2 fixation (range 40 to 125 kg N/ha). At the higher N application rate, an average of 40.7% was derived from N_2 fixation (range 16-112 kg N/ha). In laboratory studies, these researchers found that the 40 kg /ha rate decreased N_2 fixation in most cultivars about 10% compared to conditions with no added fertilizer. One cultivar showed no decrease in fixed N, while another showed a 60% reduction. They also noted that there appeared to be a difference in the time period of N_2 fixation among cultivars.

Smith and Hume (1985) also found that fertilizer N application increased total N uptake by 10 to 20% (despite lowered N_2 fixation, nodulation and nodule activity), but without a corresponding yield increase. In addition they found that water availability also affected N_2 fixation, as N_2 fixation, nodulation and nodule activity were increased by irrigation. Rennie and Kemp (1984) found that climatic conditions affected the proportion of plant N requirements met by N_2-fixation. In the first year, the plants averaged 72% of N form N_2 fixation, while in the second year (which was cooler) only 54% of plant N uptake came from N_2-fixation.

George and Singleton (1992) found that common bean accumulated 142 to 170 kg N/ha depending on elevation and fertilizer rate (9 or 120 kg N/ha). Bean N accumulation was increased to about 190 kg n/ha when excessive fertilizer (900 kg N/ha) was applied. Fertilizer N recoveries (using 15N) for common bean at maturity ranged from 24 to 29% at a relatively low elevation on Hawaii (320 m), and a range of 50 to 51% at higher elevations for 9 and 120 kg N/ha rates. The difference in recovery was attributed to temperature differences at the two elevations. The range of N applications used to generate these efficiencies did not generally affect aboveground biomass, indicating that there were differences in the relative amounts of N_2 fixation among the fertilizer rates.

Westermann et al. (1981) estimated that the (non-fertilized) common bean cultivars they evaluated in southern Idaho absorbed 82% of the soil N present (initial inorganic N plus mineralized N). In studies of fertilizer uptake at application rates of 56 and 168 kg N ha^{-1} using ^{15}N, these researchers found apparent N fertilizer uptake recoveries was cultivar-dependent, with AFNR of 7.5 to 7.9% for one cultivar (UI-1140), while the second cultivar ('Viva') had AFNR values of 28 and 33% for the respective fertilizer rates.

Seasonal distribution.

Typical seasonal patterns in dry matter accumulation, N concentration, and N uptake in field bean can be seen in data from Kucey (1989a, Table 3-9). Vegetative biomass increases rapidly before the onset of pod development, then growth rates slow or cease as the beans come to maturity. Total N uptake increases over the season, however N concentration of both straw and pods decreases over the season as carbon accumulates at a faster rate. Calculations based on the ^{15}N dilution methods indicate that early in the season, N_2 fixation is slow and the plants rely on soil N to get established. Later in the season N_2 fixation becomes more important. Figure 3-5 demonstrates this pattern for Great Northern '1140' in Alberta, Canada. Several authors have found that supplying N fertilizer during early growth stages decreases the contribution of N_2 fixation to total bean N content at maturity (cited by Kucey 1989a). Rennie and Kemp (1984) showed that N_2-fixation generally increases over the course of the season, while N from soil and fertilizer generally decreased after the V3 stage. N derived from fertilizer was always much lower than the other sources of N after V3. Westermann and Kolar (1978) report similar findings, however once podfilling started, the rate of N_2 fixation decreased to zero by physiologic maturity.

Figure 3-5. Source of N in GN 1140 bean over the growing season. From Kucey (1989b)

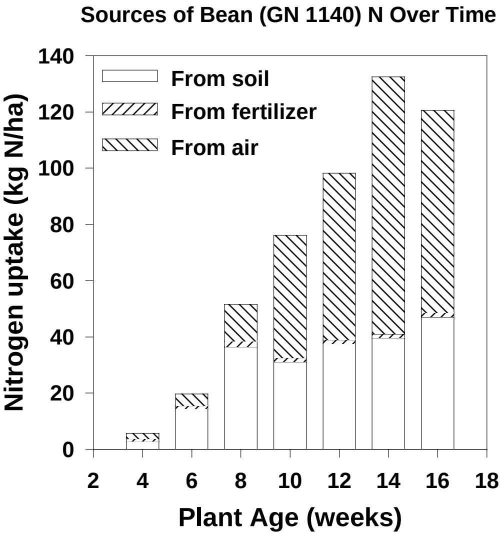


Table 3-9. Patterns in dry matter production, N concentration, and N accumulation for dry edible bean (cv. Great Northern 1140) over the growing season under field conditions in Alberta, Canada

Weeks after emergence	Dry matter (kg/ha)		N concentration (%)		N accumulation (kg/ha)	
	Straw	Pods	Straw	Pods	Straw	Pods
4	121	-	4.09	-	5	-
6	492	-	4.01	-	20	-
8	1805	20	2.82	4.68	50	1
10	2379	517	2.47	3.48	58	18
12	2416	1652	2.14	2.81	52	46
14	2421	3422	1.64	2.71	40	133
16	2269	3339	1.40	2.64	32	121

Kucey's (1989b) study of N_2 fixation patterns found that while N contents continued to increase throughout the growing period, the rate of accumulation of both fixed and total plant N decreased 6-8 weeks after planting. The relative proportion of total N coming from N_2 fixation declined after 6 weeks. Therefore the most important period for N_2 fixation is the first 4-6 weeks after planting. In work with non-fertilized plants, Westermann et al. (1981) found N uptake increased linearly from early pod formation through physiologic maturity.

Washington State University guidelines

Applications of N to irrigated field bean is suggested, with recommended rates depending on the previous crop. Recommended rates range from 40 lb N/ac where the previous crop was corn or potato, up to 120 lb N/ha on newly tilled land. No N is needed if the previous crop was a legume (Dow and Halvorson, 1980).

Pea ***(Pisum sativum L.)***

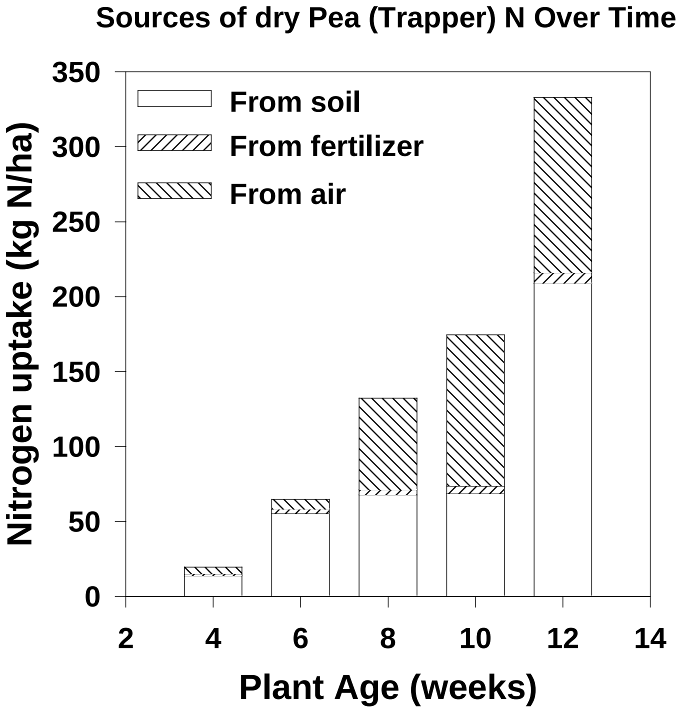
Washington State produces dry edible and dry wrinkled seed pea, as well as green pea for processing. According to Washington Agricultural Statistics Service (1996), Washington was ranked firs in the nation for both types of dry pea production, and green peas for processing is the 26th highest commodity in the state. In 1995, 95,000 ac of dry edible pea were harvested. The combined value of all dry peas in the state was about $26 million in that year. Slightly over 57,000 ac of green processing peas were harvested in 1995, with a production value of about $30 million.

Nitrogen accumulation and efficiencies

Total plant N uptake for pea in Table 3- 8 ranges from 70 up to over 200 kg N/ha. Within these values are three dry pea production sites within a few hundred meters of each other in the Palouse region of Washington, differing primarily in landscape position (Mahler et al., 1979). Much higher N uptake (210 kg N/ha) was found in the bottomland position compared to the relatively less productive side slope and ridge top (99 and 75 kg N/ha respectively). Processing peas (harvested at an earlier stage compared to dry pea) in northeastern Oregon dryland and irrigated production systems were found to take up 97 or 228 kg N/ha at harvest, respectively (Rasmussen and Pumphrey, 1997). Vine residues accounted for about 75% of this N (average NHI = 0.25). The authors point out that since so much N is returned to the field following processing pea harvest, N fertilizer recommendations for subsequent crops need be reduced as suggested in Extension publication FG-34.

In a study of dry bean following wheat with varying levels of wheat straw (Evans et al., 1997), total plant N uptake at one site-year ranged from 63 to 75 kg N/ha, with an NHI of 0.36 to 0.48. Using 15N, the authors estimated 45% of total plant N came from N_2 fixation. At the same site two years later N uptake ranged from 69 to 87 kg N/ha with an average NHI of 0.11 under non-irrigated conditions, while under irrigated conditions N uptake ranged from 87 to 104 kg N/ha with an average NHI of 0.18. Estimates of N_2 fixation averaged 83 and 75% of total plant N under non-irrigated and irrigated conditions respectively. At another location that same year, total N uptake ranged from 114 to 156 kg N/ha with an average NHI of 0.45.

Figure 3-6. Distribution of N sources for trapper pea over the growing season. (From Kucey, 1989b).



A number of researchers have found that N applied to pea at low rates does not significantly affect total N uptake. In pot experiments with non-inoculated pea, McLean et al. (1974) found that increasing fertilizer N application rates increased seed yield and protein. Most of the increase was due to the number of pods per plant (rather than seeds per pod or seed weight). In the study by Evans et al. (1997), there was no difference in total plant N between treatments containing 0 or 50 kg N/ha. Jensen (1996) determined that about 75% of total plant N content at harvest came from N_2 fixation, with the remaining N originating in the soil, seed, or fertilizer (descending order). About 77% total plant N was contained in the harvested pea seed, with the other aboveground biomass containing another 19% of the total N.

In growth chamber experiments, Chalifour and Nelson (1987) found that additions of increasing inorganic N (NH_4NO_3-N or NO_3-N) applied during the vegetative growth stage (6 to 8 nodes; 28 days after planting) significantly increased whole plant biomass and N uptake. This was partitioned such that the shoots had increased dry matter and N uptake, but root dry matter, N uptake, and N concentration were not significantly affected. Biological N_2-fixation was decreased by the higher rates of NO_3-N, with the amount depending on bacterial inoculant. It appeared that NH_4NO_3-N additions inhibited N_2-fixation in pea more than NO_3-N additions. They noted that pea was more affected than faba bean (*Vicia faba* L.), and that other researchers had found no differences between the N sources. Harper and Gibson (1984), in laboratory experiments with a variety of legume species found that nitrogenase activity (a measure of N_2-fixation rate) was decreased 69% by the highest NO_3-N concentrations (4 mM nitrate in solution). This was despite lack of visible changes in nodules, suggesting to the authors that inhibited nodulation is due to nitrate uptake or metabolism within the plant. Kucey (1989b) observed relatively low rates of N_2-fixation early in the season (Fig. 3-6).

Irrigation greatly increased both plant N uptake and grain N, as well as N concentration, yield, and vine dry matter (Rasmussen and Pumphrey, 1977) in a NE Oregon study. These researchers found that plant N concentrations declined steadily over the growing season, with a more rapid decline under dryland compared to irrigated conditions. In late May, plant N concentrations were 3 and 3.5 % for dryland and irrigated conditions respectively, but declined to about 2 and 2.5% by harvest in late June. The final NHI was 0.25, indicating that 75% of the total plant N remained the non-harvested vines. The researchers surmised that if all residues were left on the field and 50% of the N content was available to plants the following year, the residues of the dryland and irrigated peas in this study would contribute about 33 and 75 lb N/acre. Jensen (1996), working with pots in the field, found NHI of 0.77. Studies with ^{15}N showed that N_2 fixation accounted for 75% of the total N acquired by pea.

Washington State University guidelines

Nitrogen additions to field pea in Eastern Washington is generally not recommended as it does not increase profitability. Processing pea production is usually improved with the addition of 20 to 30 lb N/ac in the region (Fanning et al., 1971). Application of N (up to 20 lb N/ac) may be helpful for establishment of a pea crop in Western Washington (Turner et al., 1975).

3.2.3 SPECIALTY CROPS

Several crops are grown in Washington that are considered specialty crops due to limited growing area and or requirements or intensive management requirements. In this section we discuss hops, onion, potato, and sugarbeet into this category. All of these crops are high value crops and generally require careful N management to produce quality products.

Hops (*Humulus lupulus* L.)

Washington is the number one state in the U.S. for hop production. In 1995, 30,000 acres were harvested with a production value of over $99 million. Unlike the majority of crops discussed in this report, hops are a perennial crop, so remobilization of N within the plant from one year to the next is a determinant in growth. Relatively little has been published in the national literature with respect to nitrogen uptake patterns. The majority of the work done has been conducted by researchers in the Pacific Northwest, and is contained in reports for various grants or in the proceedings from professional conferences.

Total N accumulation.

Studies conducted in SE Washington over 1992-95 (Stevens, 1992; Stevens et al., 1993, 1994, 1995) found that on average about 51 kg N/ha is removed from the hop yard in harvested cones. The 51 kg N/ha removal rate is based on the average of several different studies conducted over the 4 year period; including measurements from grower yards as well as measurements from a variety of research experiments consisting of a variety of N application rates, timings, forms, as well as different irrigation practices. The range for these studies was 30 kg N/ha in a drip irrigation study with added N fertilizer at the rate of 115 kg N/ha, to 75 kg N/ha harvested from two grower yard measurements that had added N at the rate of 100 or 150 kg N/ha.

Stevens et al. (1994, 1995) found that yield and plant N content appears to vary between years at a given site. Their range of studies included application rates of 0 lb N/ac to over 200 lb N/ac. Applied N does not appear to be a good indicator of cone N content at harvest, at least partially due to relatively high levels of residual N in the soil profile at the start of some of the seasons evaluated (Stevens, 1992).

Nitrogen harvest index.

The average N harvest index for the SE Washington studies range of treatments was 0.31, meaning that about 32% of all the aboveground N was contained in the cones at harvest. The cones have slightly higher N concentrations than the ‘trash’ (vines plus leaves), as cone dry matter constituted 28% of the total aboveground dry matter.

Table 3-10. Summary of N accumulation values reported in the literature for hops, onion and sugarbeet

Location	Soil	Cultural Practices	Total N uptake[†] Mean	Range	NHI[‡]	UNU[§]	FNR[¶]	Reference
			kg N/ha	kg N/ha		kg N/kg	%	
			HOPS					
Washington, SE	not available	grower yards, 0-112 kg N/ha	203	161 to 261	0.26	0.033	-	Stevens (1992)
Washington, SE	Hezel fine loamy sand	drip irrig; 105 to 151 kg N/ha	212	124 to 162	0.38	0.021	-	Stevens et al. (1993)
Washington, SE		grower yards, 112 -269 kg N/ha	204	157 to 245	0.32	0.030	-	Stevens et al. (1993)
Washington, SE	Hezel fine loamy sand	drip irrig., 115 to 200 kg N/ha	88	74 to 96	0.38	0.022	-	Stevens et al. (1994)
Washington, SE	Hezel fine loamy sand	drip irrig., 122 to 240 kg N/ha	108	97 to 124	0.34	0.023	-	Stevens et al. (1995)
Oregon, Willamette V.	Not Available	on farm plots, 45 - 196 kg N/ha	139	119 to 170	0.42	0.023	-	Christensen et al. (1995)
			ONION					
Idaho, SW	Xerollic Haplargid	2 yrs, 3 mgt, 0 to 224 kg N/ha	86	61 to 83	-	0.002 fresh	-	Brown et al. (1988)
Washington, SE	silt loam (eolian)	grower yards, 97-239 kg N/ha	112	62 to 152	0.83	0.018	-	Stevens (1988, 1997)
			SUGARBEET					
Idaho, southern	Durixerollic Calciorthid	irrigated, 0 to 392 kg N/ha	278	130 to 419	-	-	-	Carter and Traveller (1981)
Idaho, southern	Various	0 N applied	213	82 to 421	-	0.0043 fresh	-	Stanford et al. (1977)
California, Davis	Mollic Xerofluvent & Mollic Haploxeralf	irrigated, 0 to 280 kg N/ha	218	141 to 274	0.52	0.0026 fresh	-	Hills et al. (1978)
California	Various	applying ‘optimal’ N rate	201	155 to 240	0.59	0.0027 fresh	-	Hills & Ullrich(1971)
Sweden	Typic Hapludalf	field, 0 or 138 kg N/ha	174	126 to 222	0.43	0.015	-	Steen and Linden (1987)
England	sandy loam	field, 0 to 125 kg N/ha	215	99 to 324	0.46	0.013	-	Armstrong et al. 1986
not listed	-	field	285	-	0.49	0.027	-	Olson and Kurtz (1982)

[†] Total N uptake = total plant N (harvested plant part + other above ground plant parts, not including roots).

[‡] NHI = Nitrogen Harvest Index (grain N/total N uptake)

[§] UNU = Unit N Uptake = units of N in total plant (except roots) / unit yield. Values shown are the mean of the various treatments of that study.

[¶] FNR = Fertilizer N Recovery = estimated proportion of applied N taken up by the plant. Estimation is based on either FNR or AFNR approach as described in the glossary given in Table 3-1. Values shown for each reference are the mean and range for the various treatments of the study.

Hops grown in the Willamette Valley of western Oregon had similar ratios of cone dry matter to aboveground dry matter (0.31) but an N harvest index of 0.42 (Christensen et al., 1995). In studies using ^{15}N on three grower yards, 30 to 50% of the plant N was derived from fertilizer applied in the same year. On average NO_3-N was more readily taken up than NH_4-N, and more fertilizer N was recovered by plants when N was placed in rings around or bands beside the hills compared to broadcast application. Fertilizer N recovery averaged about 27% across the sites, although the actual recovery varied between sites and with N form (NO_3 or NH_4).

Averaged over all of the seasons and treatments summarized for SE Washington in this report (Stevens 1992, Stevens et al., 1993, 1994, 1995), cone N concentrations were 2.8 % (range 2.0 - 3.8%) and vine + leaf values were 2.4% (range 1.3 - 3.0%). Hop cone NO_3-N concentrations haven't traditionally been used to assess brewing quality, however some brewers are paying attention to this variable out of concern for factors that might increase NO_3-N concentrations in beer (Christensen et al., 1995).

Seasonal distribution

Cone ^{15}N measurements made by Christensen et al. (1995) in the second year indicated 10% of cone N was derived from NH_4NO_3 fertilizer applied the previous year - suggesting to these researchers that N may be stored in the roots between seasons and then redistributed. They also note that hop root N has not traditionally been measured, and including root N content may substantially increase estimates of total N fertilizer recovery by hops. Plant distribution of N was found by Christensen et al. (1995) to be as follows: measured N concentrations at maturity are lowest in the vines (<1%), followed by leaves (about 3% N) and cones (2.2 - 3.1%). Often vine and leaf N are composited for N content measurements.

Washington State University guidelines.

In SE Washington, leaching is not expected to remove residual N from the soil profile between growing seasons due to low rainfall in the region. Stevens and associates are actively working on developing Best Management Practices (BMPs) for hop N fertilization, including a component designed to minimize the amount of residual N left in the soil at the end of the season, and to have growers account for the residual soil N when planning their N applications for the subsequent season. Current Washington State University N fertilizer recommendations for hops production are based on soil test NO_3-N measured in the surface 6 ft of soil depth - ranging from 0 to 140 lb N/ac as soil test N decreases from 60-10 ppm (Dow et al., 1970a).

Petiole NO_3-N concentrations can be used to monitor crop N status through the growing season, allowing the grower to determine whether the plant N supply is adequate, deficient, or excessive (Christensen et al., 1995). In the late spring, petiole N concentrations are relatively high, and decline as the season progresses. Stevens et al. (1995) found that N applications rates of 140-168 kg N/ha applied uniformly from late May to August 1 was sufficient to produce maximum cone yield. In addition, if petiole nitrate-N rates are adequate at the beginning of August only minimal additional N applications (2.2 kg N/ha/week in their study) were needed to maintain petiole N levels. Higher late-season N applications did not appear to affect cone yield. These researchers emphasize that optimum N management is not possible without optimum water management. Other than leaf petiole N concentrations, data for seasonal distribution of N uptake in hops is lacking.

Implications of literature review for N management of hops in Washington

Organic matter additions have historically been a key part of production practices for hop production in central Washington. Use of manure as an organic source led to a large buildup of microbially active organic residues and an accompanying high levels of residual soil nitrate in many old yards. Apparent fertilizer recovery has therefore been low. As management practices are changed to reduce the buildup of residual soil nitrate recovery of fertilizer N will increase. Split applications and N placement will also increase fertilizer recovery.

The hop industry is slowing converting from rill to drip irrigation to reduce soil erosion. This change in irrigation practices significantly impacts N management in the hop yard. As cover crops replace clean tillage in drip yards the vines and leaves are not returned to the yards, placing more reliance on input of fertilizer N. Fertigation with the drip system leads to increased fertilizer recovery by restricting the volume of soil interacting with the fertilizer N and allowing the timing of N application to closely follow plant needs. Petiole analysis will become an even more important tool as residual nitrate in yards is reduced and growers improve their N recovery rates.

Onion (*Allium cepa* L.)

A variety of onion crops are grown in Washington State, including spring-planted dry bulb storage onions, fall-planted Walla Walla sweet onions, and onions grown for seed production. According to Washington Agricultural Statistics Service (1996), Washington was the number 3 producer of dry onions in the U.S. in 1994 and 1995. Onions were ranked number 21 out of Washington's top forty agricultural commodities. In 1995, 13,500 ac were planted to onions, corresponding to a production value of nearly $50 million.

Many studies have been conducted to evaluate the effect of N application on yield and quality, however relatively few of these measured plant or bulb N uptake. None of the studies summarized in this report measured fertilizer N recovery. Onion yield is adversely affected if total N supply (residual soil N plus fertilizer) is deficient, however several authors note that oversupply of N can adversely affect bulb and storage quality in addition to presenting a risk for leaching of nitrates to groundwater (Ells et al, 1993; Batal et al., 1994; Stevens, 1997).

N accumulation and N harvest index.

According to Pelter et al. (1992) approximately 224 kg N/ha are needed to produce acceptable spring (dry) onion yields in the Columbia Basin - including both preplant residual soil N plus fertilizer N. Of this, only 146 kg N/ha are removed by an average crop (yield of 800-cwt). Shallow roots and frequent irrigation are two causes generally cited for the relative inefficiency of onion N use. Because of onion's shallow roots, these authors recommend that onions be rotated with a deep-rooted crop that can scavenge the N that moved below the onion root zone.

Total N uptake by Walla Walla Sweet onions measured in 1988 in six SE Washington grower fields ranged from 121 to 152 kg N/ha (Stevens 1997). Of this, an average of 94% was contained in the harvested bulbs (range was 101 to 112 kg N/ha). Measurements were made in two other fields that later showed signs of disease, and had yields that were only 74% as high as the yields of the fields discussed above, as well as relatively lower bulb N contents. The N harvest index of these fields was only 0.60. Grower-applied fertilizer rates during the study period ranged from 97 to 239 kg N/ha in 1988, with a three year total of 274 to 697 kg N/ha for the three years ending in 1988 (Stevens, 1988). Residual soil N found in the surface two feet was high - about 196-336 kg N/ha for the three highest fields. Other fields containing experimental plots measured in each of 1986 and 1987, showed no effect of N fertilization rate on marketable yield, despite a range in N application rates from 0 to 224 kg N/ha (Stevens 1997). The lack of yield response in these Walla Walla sweet onion fields was attributed to the plants' ability to take up N from below the 30 cm depth during late spring onion growth. These high residual N rates were a big impetus for subsequent N management extension and research efforts conducted with onion growers, financially supported by the onion growers' association.

Onion responses to applied N.

Researchers working with sweet onion in northeast Florida found that increasing N rates from 50 to 151 kg N/ha did not influence growth rates or bulb yields (Hensel and Shumaker, 1992). For comparison, their yields averaged 5376 kg/ha. These researchers were most interested in yield and earliness and did not measure N uptake.

Many other researchers have found that fertilizing with N increased bulb (or seed, in some cases) yield compared to very low or 0 applied N. Researchers in a semiarid region of western Africa found that there was a definite onion seed yield response to N fertilizer

(Nwadukwe and Chude, 1995). In their region, seed yield was optimized with N fertilizer applications of 50-100 kg N/ha. The yield increases were due to both greater numbers of umbels per plant and seed yield per umbel.

Henriksen (1987) found that increasing N applications up to 120 kg N/ha increased yield and bulb N concentration of spring-sown sets and decreased the days to maturity. There was no further yield or N concentration increase, or days to maturity decrease, at an N application rate of 180 kg N/ha. He also saw a trend toward increased yield and bulb N content when starter fertilizer was placed below and adjacent to the seed rather than preplant broadcast and incorporated. Hegde (1986) found that fertilization rate had only a minor affect on patterns of N distribution within the plant, though definite bulb biomass increases were achieved at higher N rates up to 160 (the highest they measured). Slightly more N was partitioned into the bulbs at fertilizer rates of 80 and 160 kg N/ha compared to unfertilized plants. N fertilization also increased other crop growth parameters such as leaf area index, and leaf area duration, crop growth rate. A lack of effect of fertilizer on the net assimilation rate suggests that the beneficial yield affects of N fertilizer are not due to increased photosynthetic efficiency but are probably due to increases in leaf area index instead.

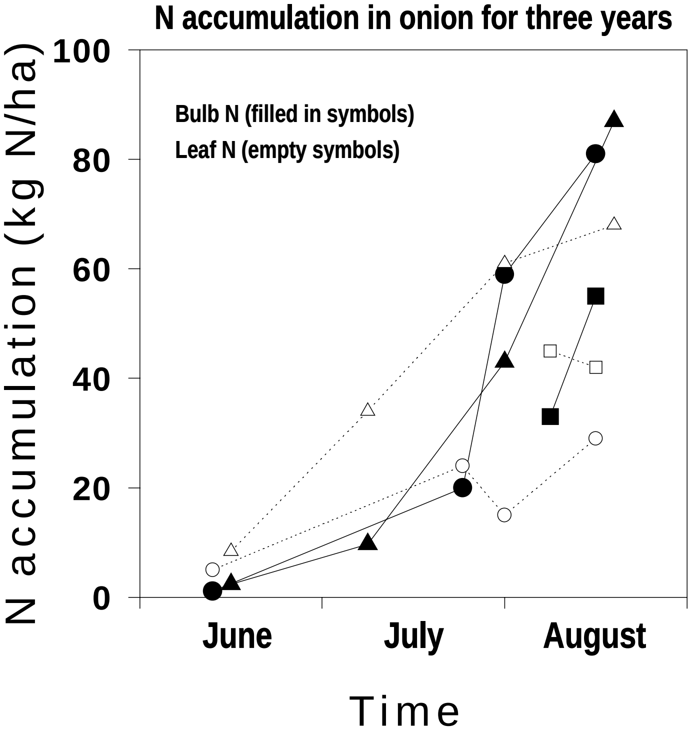
In the studies discussed above, researchers found the highest yields at the highest application rate evaluated, suggesting that perhaps they had not actually found the maximum yield or that other management factors were limiting to N response. Maier et al. (1990) evaluated N rates up to 590 kg N/ha for three site-years in the onion growing region of South Australia. They found that rates of 299 to 358 kg N/ha were required to produce yields 95% of maximum and that these higher rates produced a greater proportion of larger bulbs, fewer culls (unmarketable bulbs), and fewer days until maturity, while only having slight adverse affects on bulb quality factors such as scale thickness, sugar content, and days-to-sprouting while in storage. Residual soil N levels were not reported, but were likely low since the soil was a siliceous sand and therefore excess N could potentially leach from the soil profile. They concluded that application of rates >400 kg N/ha were wasteful, especially under irrigated conditions.

N use efficiency might be expected to be low for onions since they are relatively shallow-rooted. Fenn et al. (1991), recognizing this, set out to determine if additions of Ca^{2+} along with urea fertilizer would increase N uptake by the plants, thereby increasing the apparent fertilizer recovery. They found that additions of $CaCl_2$ increased N uptake and yield over urea applied alone, in both greenhouse and field studies. Most of the increase was centered in the additional biomass in the bulbs, bulb N concentration and biomass of roots and tops were not affected. Interestingly, their results were found using a calcareous soil (already calcium-rich).

Seasonal patterns of N uptake.

Maximum N uptake rates occur during bulb development, although the rate of N accumulation in the leaves decreases. Seasonal distributions of N accumulation in both the leaves and bulbs are shown in Fig. 3-7 for a three year study in Sweden.

Figure 3-7. Seasonal pattern of N accumulation in onion bulbs and leaves for three different years at an applied N rate of 100 kg N/ha. (From Salo, 1996)



Rooting depth.

Generally onions are a relatively shallow-rooted crop with few roots below 45 cm in most soils (Pelter et al., 1992). Measured root length per kg of soil observed in greenhouse pots 84 days after planting (DAP) ranged from 6.1 m/kg for 0 applied N, up to 16.7 and 19.4 m/kg for N rates of 133 and 266 mg N/kg soil respectively (Abbes et al., 1995b). In another study also conducted 84 DAP (Abbes et al., 1995a), the root length corresponding to the N rates that

produced the greatest dry matter ranged between 0.0047 and 0.028 m/cm3 soil (3.6 to 21.5 m/kg soil), depending on fertilizer and soil type. The corresponding mean root radius ranged between 0.23 and 0.29 mm. Assuming an exponential pattern for root growth, they estimated root growth rates during these 84 d of 4×10^{-7} to 8.5×10^{-7} s^{-1} at the N application rates, with the rate depending on N source and soil type.

Washington State University guidelines.

Continued monitoring of grower fields demonstrated that management could successfully limit the buildup of residual soil N levels. Current N fertilizer recommendations in the Walla Walla area emphasize the use of soil testing to determine N fertilization needs. Total N additions are now generally under 120 lb N/ac, substantially lower than five years ago, and many growers no longer apply preplant N (Stevens, 1997). Other researchers in other irrigated regions have reported residual soil N contents under onion fields that are high enough to make the addition of fertilizer unnecessary, for example as much as 1200 to 1800 kg N /ha contained in the surface 2 m (Ells et al., 1993).

Implications of literature review for N management of onions in Washington

The limited number of studies looking at N uptake and partitioning makes it difficult to draw conclusions about N relationships in Washington onions. The low apparent recovery of fertilizer N is related to the shallow rooting habit of onions. Increases in apparent fertilizer N recovery gained by management practices such as placement and split application of N. Major gains in fertilizer recovery related to improvement in irrigation management which reduces in-season movement of N below the root system. As indicated above the use of cover crops following onion production will be an important tool in reducing potential leaching losses following onion production.

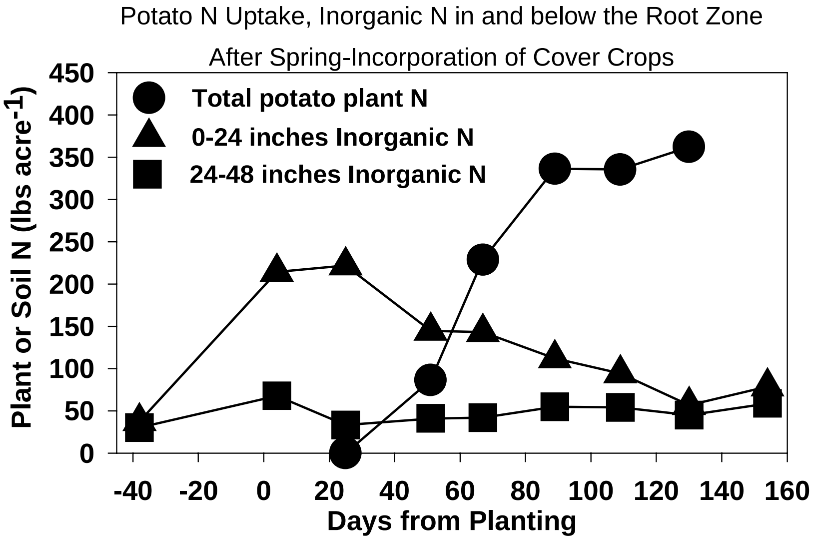
Potato (*Solanum tuberosum* L.)

The Columbia Plateau in central Washington is a highly productive agricultural region where potatoes can be a profitable component in irrigated rotations (Greig and Blakeslee, 1988; Hammond and Neilan, 1992). High fertilizer N and irrigation needs of the potato crop, coupled with a shallow rooting system and coarse textured soils requires careful management to minimize N losses (Lauer, 1986, Ojala et al., 1990; Westermann et al., 1988).

Total crop N accumulation.

Russet Burbank potatoes grown in southern Idaho under furrow irrigation yielded 33 to 48 Mg total fresh tubers/ha while accumulating 139 to 224 kg N/ha (Westermann and Sojka, 1996). Banding N fertilizer beside the seed row promoted more efficient N uptake (216 kg N/ha) than broadcasting (157 kg N/ha). Unit N uptake values were 4.89 kg N/Mg fresh tubers in the banded N treatment and 3.81 kg N/Mg fresh tubers for the broadcast treatment. Heavily fertilized Russet Burbank potatoes grown near Plymouth, WA accumulated in excess of 350 kg N/ha (Weinert et al., 1995). Fertilizer N recovery has been observed to be about 50% in Washington (Roberts and Cheng, 1984) and Michigan (Joern and Vitosh, 1995). However, with good water management, much of the remaining fertilizer N has been retained in the root zone (Joern and Vitosh, 1995).

Figure 3-8. Seasonal N distribution in potato production after cover crop incorporation. (Weinert et al., 1995)



Seeding rate and climatic variation influences N accumulation (Ifenkwe and Allen, 1982). Total plant N across two cultivars increased from 170 to 280 kg N/ha with an increase in seeding rate from 24,960 to 74880 seed tubers/acre. The N uptake of the high populations was far in excess of the 160 kg N/ha applied.

Seasonal N accumulation.

The majority of total plant N accumulation occurs between tuber initiation and mid-tuber development (Rao and Arora, 1979; Pan et al., 1994). Similarly, greenhouse grown seed potatoes accumulated 74 to 95 % of the final plant N from 30 to 80 days after emergence when 65 to 80% of the plant dry matter was in the tubers (Biemond and Vos, 1992). In addition N accumulation leveled off by 80 days after emergence in field-grown potatoes in Scotland (Millard and Marshall, 1986). Ideally, N bioavailability can be optimized in the root zone just prior to and during the accelerated phase of N uptake, as achieved with spring incorporated cover crops at Plymouth, WA (Fig. 3-8; Weinert et al., 1995).

Nitrogen harvest index.

At adequate N fertilization levels, potato (cv. Sebago) partitioned about 60% of the total plant N (excluding root N) into the tubers (Huett and Dettmann, 1992). Greenhouse grown seed potatoes (cv. Bintje) exhibited NHI values of 80-85% (Biemond and Vos, 1992). Increasing the N supply from 0 to 250 kg N/ha increased vine growth, and decreased NHI from 0.69 to 0.57 in Scotland (Millard and Marshall, 1986).

Nitrogen management effects on growth and development.

Potato is a high nitrogen demanding crop. With good growing conditions, 300 to 350 lb N supply/acre is required to produce a 30 to 35 ton/acre crop of Russet Burbank potatoes (Lang et al., 1997; Roberts and Cheng, 1991; Kleinkopf and Westermann, 1986; Roberts and Cheng, 1986; Lauer, 1985; Lauer, 1984). It is recommended that the nitrogen supply be adjusted by ± 10 lb N/acre for each ton/acre deviation from this yield goal (Lang et al., 1997). Nitrogen management influences dry matter partitioning and tuber yield and quality (Ojala et al., 1990; Lauer, 1986). Excessive N applications can stimulate vine growth at the expense of reduced tuber set and root development (Kleinkopf and Ohms, 1977; Kleinfopf and Dwelle, 1978; Lauer, 1984; Lauer, 1985; Ojala et al., 1990; Kleinkopf, 1994). In agroclimatic regions with short growing seasons, a two-week delay of tuberization can result in a 5 ton/acre yield reduction. Split applications are commonly used to supply N during the accelerated N uptake phase during tuber development to avoid overfertilization and reduce N leaching (Roberts et al., 1991; Ojala et al., 1990).

A preplant application of approximately 1/3 of the total seasonal N requirement (60 to 120 lb N/acre) is recommended (Lang et al., 1997). Recent preliminary research has indicated that the use of nitrification inhibitors with the preplant N application may help to minimize N leaching losses (Thornton et al., 1997). A preseason soil test of the upper 30 cm for residual inorganic N and estimate of organic N release should be taken into account in adjusting this preplant N application (Lang et al., 1997). The remainder of the seasonal requirement should be applied in correspondence with the accelerated phase of N uptake, which occurs between tuber initiation and mid-tuber bulking, 40 to 120 days after planting for Russet Burbank (Pan et al., 1994; 1997). Petiole nitrate levels are most commonly used to determine in-season N needs (Lang and Stevens, 1997), however, it should be recognized that factors other than soil N availability may influence petiole nitrate accumulation, and in-season soil testing should also be used to determine N needs (Lang and Stevens, 1997; Westcott et al., 1994).

Rooting depth.

Although potato roots have been observed to depths of 1.5 m (Linford and McDole, 1977; Lesczynski and Tanner, 1976), chemical or physical barriers often restrict potato rooting to shallower depths, and a majority of the potato roots are often observed to be in the top 30 cm (Lesczynski and Tanner, 1976). A calcic layer in a Portneuf silt loam restricts rooting to 0.45 m (Westermann and Sojka, 1996). Deep root development can be improved with improved deep N, P availability and organic matter (Bushnell, 1941).

Root elongation of Russet Burbank grown in the Columbia Basin has been observed with rhizotron computerized imaging (Pan et al., 1997). Root elongation is extensive through tuber initiation and early tuber bulking through 49 DAP, and then declined thereafter. Segmenting the rhizotron profiles into 10 zones provided data to interpret the spatial and temporal distribution of roots. Primary roots extended to 15 to 20 cm under the seed piece prior to shoot emergence, 21 days after planting. Lateral roots began to develop shortly thereafter. Potato roots extended to depths of 60 cm by 4 to 6 weeks after planting, and maximum root density in the hill and furrow was observed by tuber initiation to early tuber bulking. Root development under the furrow maximized by 40 to 49 DAP. Roots shrunk in diameter or disappeared during late tuber bulking (>60 DAP), suggesting that nutrient recovery efficiency of the root system declined during this developmental period, possibly due to root-tuber competition for limited carbon availability. These temporal and spatial trends were similar to previous results using destructive sampling (Nelson, 1990; Pan et al., 1990; Pan and Hiller, 1992; Pan et al., 1994).

Late-season N applications are less efficiently absorbed as the plant roots senesce, and combined with organic matter and plant residue mineralization, results in late-season soil N accumulation (Weinert et al., 1995; Hammond, 1992; Thornton et al., 1996).

Washington State University recommendations.

An extensive review of scientific literature by and subsequent discussions with potato industry representatives have produced a recent update of recommended nutrient management for potato production in Washington (Lang et al., 1997). A companion survey of current potato industry fertilization practices indicated that respondents felt it necessary to recommend higher than average levels of nitrogen to overcome management and environmental problems such as suboptimal irrigation and nitrogen timing, disease pressures, and periods of excess precipitation (Lang and Stevens, 1997). However, the use of higher nitrogen rates to overcome these problems will result in increased potential for nitrate leaching and ground water contamination (Lang et al., 1997). This emphasizes the need for an integrated approach to nutrient, water and pest management to maximize nitrogen use efficiency. We have a thorough understanding of seasonal patterns of N accumulation and partitioning, and root behaviour of Russet Burbank potatoes grown in the Columbia Basin. In addition, the role of cover crops in potato rotations has been emphasized in recent years as an important management tool for improving N cycling. Less is known about other potato cultivars that are gaining in popularity, but some are currently under investigation.

Sugarbeet (*Beta vulgaris* L.)

Sugarbeet yield is evaluated primarily on yield of extractable sucrose. Extractable sucrose is dependent on the combination of harvested root biomass and root sucrose content. Under-fertilization for N results in poor leaf canopies, premature yellowing and decreased yields (Cattanach et al., 1991). Over fertilization with N often leads to increased impurities in the roots and subsequent lowered sucrose extraction (Carter and Traveller, 1981; Cattanach et al., 1991). Washington State has not tabulated records on sugarbeet production because it was not produced on much acreage for many years. However, the crop is now being planted on increasing acres each year. In addition, sugarbeet production was considered to be of interest for this report because of the relatively large amount of processing wastes generated.

Total N accumulation and N uptake efficiency.

Nitrogen fertilizer recovery was 47% in a California study when sugarbeet was fertilized at the optimum N rate for sugar production (112 kg N/ha for this site-year; Hills et al., 1978). These researchers found that the proportion of N derived from fertilizer depended on the N application rate. For roots, the observed relationship was:

$$\text{Root \%N from fertilizer} = 1.31 + 0.26x - 0.00042x^2$$

where x is the applied N rate (kg/ha). Sugarbeet tops showed a similar increase in fertilizer N %:

$$\text{Tops \%N from fertilizer} = -0.76 + 0.23x - 0.00030x^2.$$

The relationship for total plant N uptake (kg/ha) as a function of fertilizer application rate was:

$$\text{total plant N uptake (kg/ha)} = 158.03 + 0.69x - 0.00098x^2.$$

Relying on only soil N, one study in southern Idaho found that sugarbeet yields ranged from 7.8 to24.8 Mg /ha (fresh weight basis) and took up 4.3 kg total plant N uptake per Mg harvested root on a fresh weight basis (Stanford et al., 1977). These researchers estimate that sugarbeets were able to recover 66 and 75% of mineralized and residual NO_3-N from the soil profile in the absence of applied N. Under optimal N fertilization, Cattanach et al. (1991) observed total N accumulation of 4 to 4.5 kg N per Mg (dry weight basis) of harvested root.

Steen and Lindén (1987) found that 75% of fertilizer N was recovered in the harvested root - making sugarbeet one of the more efficient N users among the agronomic crops. In the same experiment, they determined that about 2% of fertilizer remained in the soil - indicating that 23% of applied N was unaccounted for.

Total plant N is equally distributed between the sugarbeet tops and harvestable roots. A survey of fertilizer response and efficiency experiments conducted in California found that when about 130 kg N/ha or less N was needed for maximum sugar yield (that is, in certain soil types), the harvested roots took up as much or more N than was applied. However, for soil types that needed N additions > 130 kg N/ha, less N was removed than was applied (Hills et al., 1978 - citing Hills and Ulrich, 1976). Fibrous roots (rarely measured) in the surface 60 cm contained 3 kg N/ha regardless of fertilizer treatment, comprising about 2% of the total plant N (Steen and Lindén, 1987).

Seasonal pattern of N accumulation.

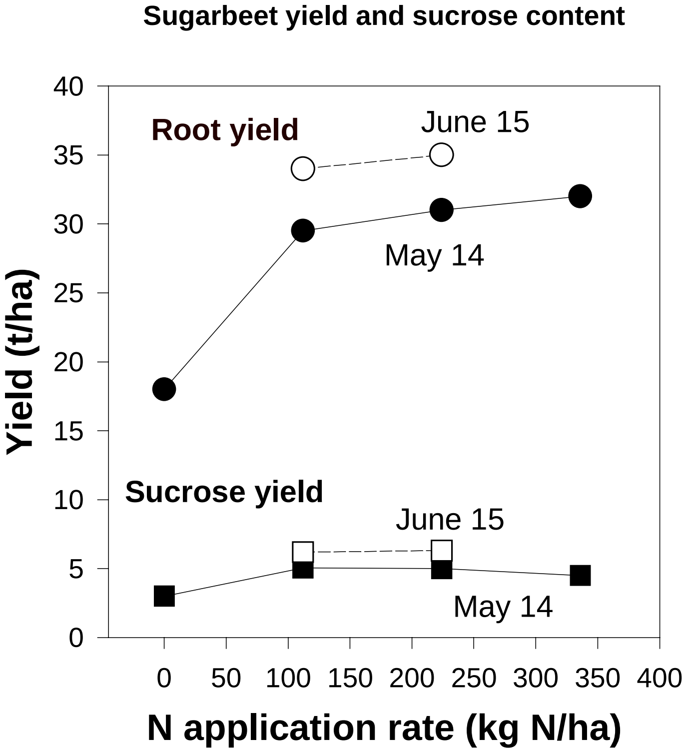
Carter and Traveller (1981) present graphs of seasonal patterns in root and sucrose yield, sucrose %, root N uptake, tops N uptake, total plant N uptake, total plant DM, root DM/total DM from a southern Idaho study. Measured N uptake rates at the start of the season ranged from 2.3 to 5.8 kg/ha per day depending on location and year with 125 kg N/ha applied N, and from 1.6 to 5.1 kg/ha per day in the absence of applied N (Armstrong et al., 1986). Toward the end of the season these rates slowed appreciably to a range of 0.6 to 1.0 kg/ha per day. At this time, a significant amount of remobilization of N from the tops into the root occurs, causing 30-80% of the end-of-season N uptake, depending on the year.

Applying N above that needed for optimum plant growth, or delaying application until midseason, caused a greater proportion of photosynthate to be partitioned to the shoots at the expense of dry matter and sucrose accumulation in the roots (Carter and Traveller, 1981). Late or excessive N applications increased impurities in the beet root, which decreases sucrose extractability and refined sugar production. The researchers concluded that N applications, based on reliable soil tests, should be made before planting or during early plant growth stages, in amounts that will produce optimum plant growth and sucrose production. Deckard et al. (1984) provide an example of the effect of N rate on root and sucrose yield (Fig. 3-9). Hills et al. (1978), on the other hand, working in California found no difference in root, top or sugar yield or N uptake due to time of fertilization (fertilizer rate was 135 kg N/ha).

Root length.

Sugarbeets have a taproot system that utilizes water and nutrients to a depth of 1.5 to 2.4 m (Cattanach et al., 1991). One study that measured sugarbeet root biomass, found an average (30 experiments) of 29.3 g/m^2 in the surface 60 cm. About 20 g/m^2 were in the surface 25 cm (Steen and Linden, 1987).

Figure 3-9. N affects on root and sucrose yield at two times in the season. Adapted from Deckard et al. (1984).



Washington State University recommendations

Recommendations for sugarbeet production in central Washington are contained in Fertilizer Guide FG-10 (Dow et al., 1970c), and are based on soil test N in the root zone and previous crop. The range of recommendations goes from 0 N if there is high residual soil N, or if the previous crop was a legume, up to 200 lb N/ac for low soil test N on new land, or after potato, sugarbeet, silage corn, or wheat with straw removed. N management in sugarbeet is sensitive because the crop does require a relatively high N supply, but excessive rates of N can sharply reduce sugar production.

3.2.4 TURFGRASS AND FORAGE CROPS

3.2.4.1 FORAGE

Overview

The major forage grasses grown in Washington are orchardgrass, perennial ryegrass, and tall fescue. These are the three forage species covered in this report. Forage grasses are often grown in mixture with other species, including legumes. For this report, we have not included legume forages, although including forage legumes in the mix can take the place of applied N for maintaining grass productivity. Even in mixed legume-grass forage mixtures, N additions are often found to be desirable, especially during the establishment phase to help maintain appropriate species ratios (Kanyama-Phiri et al., 1990).

Washington State University recommendations

Since forages are generally grown as mixed stands WSU Fertilizer Guides do not provide species-specific recommendations. Instead there are recommendations for irrigated and non-irrigated pasture (or hay) for different regions of the State (Table 3-2) In general, 80 to 150 lb N/ac annually are recommended for non-irrigated improved pasture production in Eastern Washington. During establishment, about 20 lb N/ac are recommended. (Fanning et al., 1976; Peterson et al., 1984). Irrigated pasture in central Washington can be extremely high yielding, in which case 240 to 300 lb N/ac are recommended for good, long-season stands. If the stand is poor and the season is relatively short then as little as 20 to 60 lb N/ac would be recommended (Dow et al., 1979b). The critical nutrient range (CNR) for orchardgrass is 3.5 to 4.0% N in the tops when the grass is 12" high. If N concentrations are below this level, there is likely an inadequate N supply (Dow, 1980).

Orchardgrass (*Dactylis glomerata* L.)

Fertilizer recovery and N use efficiency

Average apparent fertilizer N recoveries by orchardgrass for all of the studies summarized in this report is 55% (range of 38 to 89%). Researchers in Puyallup, WA recorded apparent N fertilizer recovery rates of 38 to 56% depending on the N rate applied and the year of the study (Turner 1979). Geist (1976) measured fertilizer N recoveries of 57-71% for a variety of N and sulfur fertilization treatments in La Grande, Oregon. Unfortunately this researcher did not specify how N fertilizer recovery was determined. Kunelius and Suzuki (1977), working in the Maritime Provinces of Canada, reported a similar range of fertilizer N recovery (46-70%) at three N application rates between 99 and 297 kg N/ha applied annually. Sollenberger et al. (1984) measured values of 62 to 89% of applied for N rates ranging from 112 to 448 kg N/ha. The highest recovery % occurred at the 224 kg N/ha rate.

Guillard et al. (1995) evaluated the N use efficiency (NUE) and apparent fertilizer recovery over a range of N application rates for three sets of two-year periods. The only N application was at the start of the first year and initial soil N levels were relatively low (<10 mg N/kg soil). They found that both NUE and apparent fertilizer N recovery steadily declined as N application rate increased. For first year harvests, NUE values ranged from about 15 kg DM/kg N at 112 kg N/ha down to 9 kg DM/kg N at 448 kg N/ha application rate. The corresponding values for apparent fertilizer recovery were 50 and 25%. When calculated for the entire two year period, NUE values were slightly higher and ranged from 20 to 10 kg DM/kg N applied for the 112 and 448 kg N/ha fertilizer application rates. Apparent fertilizer N recoveries were about 5 % higher for the two-year period compared to the values given above for the first year only. Note that these researchers calculated NUE somewhat differently than explained in the introduction to this section. Rather than making the difficult measurement of total N supply (fertilizer + non-fertilizer N), these researchers used the yield of the zero N control treatment as a surrogate estimate for non-fertilizer sources of N. The resulting NUE calculation was:

$$\mathbf{NUE = (yield\ at\ Nx - yield\ at\ N_0) / Nx}$$

where Nx is N applied at rate x, and N_0 is the zero N control treatment. Sollenberger et al. (1984) used the same calculation over the same range of applied N rates and found somewhat higher NUE estimates in Pennsylvania - ranging from about 19 to 33 kg DM / kg N applied (per ha basis) depending on the applied N rate. Corresponding apparent fertilizer N recoveries ranged between 62 and 89% in their study.

Table 3-11 . Summary of N accumulation values reported in the literature for forage grasses.

Location	Soil	Cultural Practices	Total N uptake[†]		UNU[‡]	FNR[¶]	Reference
			Mean	Range			
			kg N/ha	kg N/ha	kg N/kg	%	
			ORCHARDGRASS				
Connecticut	Typic Dystrochrept	0 to 448 kg N/ha applied	128	50 to 170	0.024	41 (25 to 50)	Guillard et al., (1995)
Connecticut	Typic Dystrochrept	Total for 2 yrs after applic., 0 to 448 kg N/ha 1st year	162	75 to 220	0.020	43 (30 to 55)	Guillard et al. (1995)
Puyallup, WA	Aquandic Xerochrept	0 to 560 kg N/ha/year	313	112 to 431	0.027	46 (38 to 56)	Turner (1979)
Pennsylvania	Typic Hapludalf	0 to 448 kg N/ha/year	209	79 to 327	0.025	72 (62 to 89)	Sollenberger et al. (1984)
Canada, Pr. Edw. Is.	not available	99 ton 495 kg N/ha/year	195	97 to 255	0.030	46-70	Kunelius and Suzuki (1977)
			PERENNIAL RYEGRASS				
Pennsylvania	Typic Hapludalf	0 to 448 kg N/ha/year	168	57 to 279	0.026	57 (37 to 70)	Sollenberger et al. (1984)
Buckley, WA	Typic Humaquept	Irrigated, 0 to 9 ton biosolids	190	79 to 271	0.021	38 (28 to 71)	Cogger et al. (unpublished data)
			TALL FESCUE				
Puyallup, WA	Vitrandic Haploxeroll	Irrigated, 0 to 9 t biosolids	289	112 to 421	0.025	38 (28 to 63)	Cogger et al. (unpublished data)
Kansas	Mollic Albaqualf	13 to 168 kg N/ha/year, broadcast or knifed	76	56 to 100	0.017	-	Moyer et al. (1995)
Kansas	Mollic Albaqualf	0 to 168 kg N/ha/year, broadcast or knifed	63	25 to 122	0.015	-	Moyer et al. (1990)
Georgia	Typic Hapludult	0 to 896 kg N/ha, various P & K rates, 2 cultivars	191	15 to 444	0.027	62 (40 to 83)	Overman and Wilkinson (1995)
West Virginia	Dystrochrepts & Hapludult	0 to 180 kg N/ha	76	21 to 156	0.016	49 (39 to 64)	Staley et al. (1991)

[†] Total N uptake = total plant N (harvested plant part + other above ground plant parts, not including roots).

[‡] Unit N Uptake = units of N in total plant (except roots) / unit yield. Values shown are the mean of the various treatments of that study.

[¶] FNR = Fertilizer N Recovery = estimated proportion of applied N taken up by the plant. Estimation is based on either FNR or AFNR approach as described in the glossary given in Table 3-1. Values shown for each reference are the mean and range for the various treatments of the study.

N accumulation

The average N accumulation by orchardgrass for all the studies summarized in this report was 244 kg N/ha, with a range of 79 to 439 kg N/ha depending on the study and treatment. The three studies contributing to this average were all conducted in the northern U.S., with N application rates ranging from 0 to 560 kg N/ha. On average, 0.027 kg N were required to produce each kg of forage dry matter (range of 0.019 to 0.136 kg N/kg dry matter).

Orchardgrass dry matter production has been shown to respond to N rates of 448 kg N/ha, and in some cases as high as 717 kg N/ha. Typically the yield response is linear over this range (Guillard et al., 1995), rather than reaching a plateau as shown in Fig. 3-2. These researchers measured linear yield increases up to their highest N rate (448 kg N/ha) in both the first and second growing season after N application. However, N uptake appeared to level off at about 155 kg N/ha at rates higher than 224 kg N/ha in the first season, though it increased slightly over the entire application rate range the second year. When first and second season N uptake are taken together, total N uptake does not begin to level off until the 448 kg N/ha rate. Sollenberger et al. (1984) also observed yield and harvested N response under conditions of annual N fertilization up to application rates of 448 kg N/ha (the highest they measured). Averaged over 3 years with 3-4 cuts per year these researchers measured average harvested N to be 279 kg N/ha at the 448 kg N/ha rate. Kunelius and Suzuki (1977) measured harvested N uptake of 97 to 255 kg N/ha at respective application rates of 98 to 495 kg N/ha.

Research results from Puyallup, WA have found that orchardgrass is capable of taking up large quantities of N that are removed from the site at harvest. Turner (1979) found that N uptake increased as the N application rate increased from 0 lb N/ac up to 560 kg N/ha. At the 560 kg/ha N rates, over 448 kg N/ha was removed by the crop. Residual soil N was not measured. The increased N uptake at the higher rates was not due to increased forage yield, but was due to increased percentage of protein in the more heavily fertilized crops. Turner suggests that application to orchardgrass for waste disposal purposes may have some merit.

Working at lower N application rates (0, 84, and 168 kg N/ha), in four different Pennsylvania soils with low soil N concentrations (<3 mg/kg), Stout and Jung (1992) measured generally increasing accumulation rates for biomass, fertilizer N, and total N uptake as N application rate increased. For example, in the spring growth period on a Berks soil (loamy-skeletal, mixed mesic Typic Dystrochrept) biomass accumulation rates were 51.5, 83.5, and 198.5 kg/ha/day for the 0, 84, and 168 kg N/ha application rates. Corresponding values for total N accumulation during the same period were 0.765, 1.040, and 1.565 kg N/ha/day. The Berks soil had generally intermediate values among the 4 soil types studied. Spring biomass and N accumulation were substantially greater than during the fall growth period.

N concentration

N concentrations over the range of studies summarized in this report average about 2.7%, with a range of 1.9 to 3.6%. N concentration is positively correlated with N application rate - that is, N concentrations are higher at higher N application rates. For example, Turner (1979) measured an average N concentration of 2.5% at zero applied N, and 3.3% at 500 lb N/ac. Kunelius and Suzuki (1977) measured N concentration of 2.5 up to 3.6% at respective N application rates of 98 and 495 kg N/ha. Glenn et al. (1985) measured N concentrations of 2.3 to 2.4 % at 0 applied N, increasing to 3.1 and 3.7% at N application rates of 294 and 882 kg N/ha in Kentucky.

Modeling

In their study of N use efficiency, Guillard et al. (1995), these researchers developed regression equations for yield (dry matter), N uptake, apparent fertilizer recovery, and NUE based on N application rates ranging from 0 to 448 kg N/ha (in intervals of 112 kg N/ha). Their equations for the year of N fertilizer application are as follows:

$$\text{Yield (dry matter, Mg/ha)} = 3.4 + 0.008\,N \qquad (r^2 = 0.868)$$

$$\text{N uptake (kg N/ha)} = 47.9 + 0.664\,N - 8.492\,N^2 \qquad (r^2 = 0.992)$$

$$\text{Apparent N fertilizer recovery (\%)} = 62.2 - 0.074\,N \qquad (r^2 = 0.929)$$

$$\text{Nitrogen use efficiency (kg DM/kg N)} = 17.9 - 0.023\,N \qquad (r^2 = 0.982)$$

where N is the applied N rate (kg N/ha). The developed similar equations for the second growing season (no N applied), and for the two year period (not shown here). While these regression equations are specific to their study conditions in Connecticut, they demonstrate the general trends.

Tall Fescue (*Festuca arundinacea* Shreb.)

N recovery and accumulation

The average N accumulation for all studies summarized in this report is 137 kg N/ha, with a range of 15 to 444 (Table 3-11). Treatments included in these different studies included N application rates ranging from 0 to 933 kg N/ha, including both synthetic N fertilizer as well as biosolids N. In general, 0.0204 kg N were required to produce each kg of forage (range = 0.0113 to 0.0385kg N/kg forage). On average for the studies summarized in this report, 54% of applied N was recovered by harvested forage (range = 28 to 83%). No studies measuring N uptake efficiency or N use efficiency were found in the literature.

Staley et al. (1991) report fertilizer N recoveries ranging between 23 and 31% of applied (^{15}N technique), depending on fertilizer rate (0, 90, 180 kg N/ha) and soil type. In these plots, 23 to 47% of the N in the total plant N uptake was derived from the applied fertilizer. When the difference technique is employed to estimate the apparent N fertilizer recovery, values for this same experiment ranged from 39 to 64%, illustrating the effect of measurement technique on resulting values. The resulting difference between these two techniques is attributed to the 'priming effect' in which added N is thought to stimulate microbial activity so that N mineralization is greater under the N plots compared to the zero N. The difference between techniques was specifically explored by Stout (1995) with respect to forage grasses in the northeastern U.S.. He found that in tall fescue, this priming effect averaged 7.4 and 24.2% of the applied N when the N source was ammonium nitrate and ammonium sulfate respectively. Seasonal differences were also observed, with a greater difference in spring compared to fall growth. For example using the difference technique to calculate recovery, 50.8 and 17.5 kg N/ha were recovered for spring and fall growth respectively, averaged over N rates of 90 and 180 kg N/ha. Calculated recoveries were about one-half as much when calculated by the ^{15}N technique.

Moyer and Sweeney (1990) measured apparent fertilizer N recoveries (difference technique) in SE Kansas ranging between 29 and 54% of applied N, depending on N rate and whether the fertilizer was broadcast or banded. While these researchers do not present values for the individual treatments, they state that higher apparent fertilizer recoveries (> 50%) were obtained when fertilizer was banded 10 cm below the soil surface compared to broadcast or banding at 5 or 15 cm. They cite Raczkowski (1984) as having similar findings of greater recovery with subsurface banding of fertilizer (58% of applied) compared to broadcast (37% of applied). Other researchers have presented much higher apparent fertilizer recoveries. For example, Overman and Wilkinson (1995) measured an average of 62% fertilizer N recovered (difference technique) in Georgia, with a range from 40 to 83% depending on cultivar and application rates of N, P, and K fertilizer.

Raczkowski and Kissel (1989) calculated an N balance resulting from ^{15}N-labeled urea ammonium nitrate (UAN) application to tall fescue in Kansas. A total of 112 kg N/ha were applied, of which 57 kg N/ha was labeled urea. (Determining volatile losses of urea was the main impetus for their experiment.) Of the labeled urea, 23 or 35 % was recovered in harvested dry matter during the year of application, depending on whether it was broadcast or banded 15 cm below the soil surface. Of the remaining, about 40% was immobilized (live roots and soil organic matter), about 2% was left as residual inorganic soil N in the surface 90 cm. Another 2.5% was taken up in the second year (which received no additional N fertilizer). All of the applied ^{15}N was recovered in one of these pools under the banded application treatment. In the broadcast treatment, slightly over 10% was unaccounted for. The authors attributed the loss to volatilization.

Lucero et al. (1995) studied the effect of several rates of poultry litter on the yield, N uptake, and N recovery of a pasture containing a mixture of tall fescue and bluegrass (*Poa pratensis* L.) in the Piedmont region of Virginia. Poultry litter rates ranged from 9.9 to 48.9 metric tons over a two-year period, applied in four applications (two each year). The resulting N additions ranged between 200 and 1000 kg N/ha over the two year period. Both forage yield and N uptake increased over the entire application range, and were well explained by the following regression equations (separate equations were developed for each of the two years):

1991: yield (kg DM/ha) = $4728.7 + 43.9N - 0.066N^2$ $r^2 = 0.992$
N uptake (kg/ha) = $81.8 + 0.7N - 0.00034N^2$ $r^2 = 0.989$
1992: yield (kg DM/ha) = $3261.3 + 108.7N - 0.226N^2$ $r^2 = 0.994$
N uptake (kg/ha) = $59.9 + 1.21N - 0.00074N^2$ $r^2 = 0.993$

where N is the amount of applied N in the poultry litter. Apparent N fertilizer recovery (difference technique) ranged between 55 and 103% depending on the amount of N added and the year. In general, recoveries decreased as the poultry litter application rate increased, and were substantially lower in the first year of the study compared to the second. In this study, the unit N requirement (kg N to produce 1 kg yield) ranged from 0.018 and 0.021 under conditions of zero N application up to the highest measured value of 0.030 at the two highest poultry litter application rate the second year (cumulative N additions of 800 and 1000 kg N/ha over 2 years), indicating higher forage N concentrations when the N supply was greater.

Moyer et al. (1995) determined that tall fescue N uptake was affected by N fertilizer placement as well as N application rate. Increasing the N application rate from 13 to 168 kg N/ha increased yield 69% and N uptake nearly doubled. Applying N in a 10 cm deep band (‘knifing’) at 25 cm spacing increased yield 20% and N uptake 33%. In earlier work, Moyer and

Sweeney (1990) showed that knifing a urea/NH_4NO_3 solution at 10 cm generally resulted in higher yields than banding at 5 or 15 cm deep.

Tester (1989) found that both yield and N uptake were increased when inorganic N fertilizer was added to soil that was also amended with composted sewage sludge. Cumulative tall fescue clippings were 279% greater when a 45 Mg compost/ha treatment (containing 507 kg/ha total N) was also amended with N (200 kg N/ha rate) compared to the same compost rate with no N added. The effect of N fertilizer decreased somewhat as the compost rate increased, so that at the 135 Mg/ha compost rate, the yield increase due to N application was somewhat less at 160%. The respective N uptake for the various treatments also increased as a result of N fertilization (460% at the 45 Mg/ha compost rate, 223% at the 135 Mg/ha compost rate). However, all of the treatments that received fertilizer N had about the same N uptake as each other, indicating that addition of N fertilizer beyond a certain compost rate does not increase N uptake.

N concentration

N concentrations over the range of studies summarized in this report average about 2.0 %, with a range of 1.1 to 3.8%. In all studies, forage N concentration increased as N application rate increased. For example, Glenn et al. (1985) measured N concentrations of 2.3% at 0 applied N, increasing to 2.9 and 3.5% at N application rates of 294 and 882 kg N/ha in Kentucky.

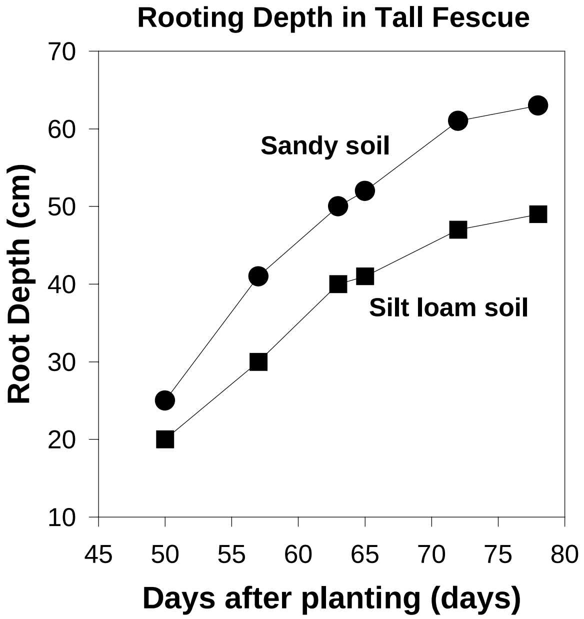
Rooting Depth

Rooting depth in tall fescue increases over the course of the growning season, and generally extends to at least the 0.5 m depth (Brar and Palazzo, 1995). As seen in Fig. 3-10, soil type also plays a role in rooting depth. Irrigation level also influences root development in turf-type tall fescue. Under limited irrigation, tall fescue exploited soil moisture at depths of 31 to 90 cm more efficiently than Kentucky bluegrass (Ervin and Koski, 1998).

Modeling

Overman and Wilkinson (1995) present and evaluate a model for forage grass dry matter yields and N uptake as a function of applied N, P, and K fertilizer. Using two tall fescue cultivars (Kentucky 31 and Kenwell) in the southeastern U.S. these researchers determined that the model predictions were highly correlated with measured values and reflected patterns found in previous work. They demonstrate that their data support a hyperbolic relationship between dry matter yield and plant N uptake. The model is not presented here, but in summary it consists of triple logistic equations with a total of thirteen parameters and requires inputs that include the maximum annual yield and N uptake, plus indices for applied N, P, and K fertilizer. From their field data, they developed maximum annual dry matter yield and N uptake values of 12000 and 440 kg/ha respectively.

Figure 3-10. Seasonal pattern in rooting depth of tall fescue in two soil textures. From Brar and Palazzo (1995).



3.2.4.2 TURFGRASS

Overview

Turfgrass is grown for a great variety of uses, including home lawns, golf courses, athletic fields, corporate lawns, sod farms, orchard and vineyards alleyways, and cemeteries. In addition, bluegrass seed production has been an important crop in the state - ranked approximately 30th out of the top 40 of Washington's agricultural crops (Washington Agricultural Statistics Service, 1996). A number of the above turfgrass uses would lend themselves well to processed water applications. The species and cultivars grown at a given site depend on both use and location. In Washington, some of the major turfgrass species include bluegrass, fine leafed fescue, bentgrass, tall fescue, and perennial ryegrass (W. Johnston, personal communication, 1997). Some studies have been conducted on individual species. However, since most turfgrass is grown as a mixture of species many studies are conducted on mixes. For this reason, we have not separated out the turfgrass section into individual species as we have done for the other crops.

A relatively recent review article summarizes many of the factors related to N fertilization of turfgrass (Turner and Hummel, 1992). They describe how N is a vital constituent of turfgrass plants. An adequate N supply is necessary to have good establishment of new turf, and to maintain turf quality despite frequent mowing and high traffic/compaction. N additions are also beneficial for recovery from drought, herbicide injury, and winter dormancy. Overly high N supplies can have negative impacts on shoot-to-root growth ratio, wear-quality, cold-hardiness, species composition, weed levels, susceptibility to some diseases. Turner and Hummel's review summarize numerous research studies in these areas. N requirements and appropriate timings are influenced by many factors, including species and cultivar, climate, soil physical properties, organic matter, compaction, and N source.

Washington State University recommendations

Fertilizer recommendations for home lawns, play fields, and other established turf in Eastern and Central Washington are to apply 8-10 lb/1000 ft^2 during each growing season (April to September), preferably split in four equal applications (Goss et al., 1982). A more recent publication specifically geared to the home lawn recommends an average of 4 lb N/1000 ft^2 (Stahnke et al., 1997). Establishment of new turf requires about 1 lb N/1000 ft^2. N fertilization of grass cover crops and sods in orchards should be based on the growth of the crop as soil tests for this situation are not well correlated. In general, 50 to 150 lb N/ac are needed annually depending on the specific situation (FG-0028B, 1985).

For irrigated grass seed production, both bluegrass and orchardgrass respond well to N applications and annual fertilizations with 120 to 160 lb N/ac are suggested for high yields. For other species, 100 to 120 lb N/ac is usually adequate (Law et al., 1975). Thirty to 50 lb N/ac is needed for establishment. In dryland situations, recommended N rates vary with average precipitation. In areas receiving <15" rainfall annually, 40 to 60 lb N/ac are recommended. Above 18" the recommended rate is 80 to 120 lb N/ac. Intermediate rainfall requires 60 to 80 lb N/ac. During establishment, 30 to 90 lb N/ac are needed with the low rate suggested for summer fallow areas, and the high rates suggested for seeding into former grass sod (Law et al., 1975).

N accumulation

The average annual N uptake of the turfgrass studies summarized in this report was 212 kg N/ha, with a range from 25 to 494 kg N/ha depending on the study and treatment evaluated (Table 3-12). On average, 0.0243 kg N were required to produce each kg of grass (range of 0.0128 to 0.0364 kg N/kg dry matter).

Huang and Petrovic (1994) measured N uptake in weekly clippings of creeping bentgrass (*Agrostis stolonifera* L.) grown in a greenhouse to be equivalent to anywhere from 60 to 93% of the N applied, depending on composition of the soil (sand or zeolite-amended sand) and N application rate (98, 196, 293 kg N/ha). Only graphical results are presented. In general, higher fertilizer N recoveries were obtained at the lowest N application rate, and zeolite-amended sand had higher recoveries than unamended sand. They report another researcher as finding that about 60% of applied N is recovered in creeping bentgrass clippings at N application rates between 240 and 287 kg N/ha.

Table 3-12. Summary of N accumulation values reported in the literature for turfgrass.

Location	Soil	Cultural Practices	Total N uptake[†]				Reference
			Mean	Range	UNU[‡]	FNR[§]	
			-- kg N/ha –		kg N/kg	%	
Arizona	mortar sand amended with various zeolite %	Creeping bentgrass turf; 25 to 50 kg N/ha/month	138	94 to 178	0.032	-	Ferguson et al. (1986)
Italy	sandy loam 2.28% organic matter	Mixed species athletic field; urea or oxamide N fertilizer (292 kg N/ha)	53	25 to 80	0.015	31 (25 to 36)	De Nobili et al.(1992)

[†] Total N uptake = total plant N (harvested plant part + other above ground plant parts, not including roots).

[‡] Unit N Uptake = units of N in total plant (except roots) / unit yield. Values shown are the mean of the various treatments of that study.

[¶] FNR = Fertilizer N Recovery = estimated proportion of applied N taken up by the plant. Estimation is based on either FNR or AFNR approach as described in the glossary given in Table 3-1. Values shown for each reference are the mean and range for the various treatments of the study.

N accumulation is adversely affected by compaction - with several studies reviewed and summarized by Carrow and Petrovic (1992). They cite studies showing that N use per unit area and N recovery can have respective decreases of 21 to 39% and 10 to 31% due to compaction. Compaction effects were apparently species-dependent. Applying additional N was able to improved N uptake in tall fescue, but not in Kentucky bluegrass. Additional analysis of these studies indicated that addition N application to an adequately fertilized, but compacted trufgrass stand could cause a marked reduction in rooting, therefor Carrow and Petrovic recommend that turf managers not try to use additional N applications to improve growth in poor stands resulting from compaction.

A study of natural organic fertilizer (‘Restore’) effects on turfgrass growth rate and N uptake rate was conducted in a North Carolina greenhouse (Peacock and Daniel, 1992). They compared growth rates of tall fescue and bermudagrass (*Cynodon dactylon* L.) in soil that was amended with the organic fertilizer or with urea at rates of 50 kg N/ha. Because organic fertilizers require microbial activity to eventually release the organic N, they added a second organic fertilizer treatment that included a bacteria/fungi inoculumn. Tall fescue growth rates were substantially higher in the urea treatment compared to either organic fertilizer treatment at 19 days after treatment (1336 compared to 795 or 505 mg/m^2/day) and at 33 days after treatment (690 compared to 296 or 312 mg/m^2/day). The corresponding N uptake rates followed a similar pattern with values of 54.0 (day-19) and 25.8 mg N/m^2/day (day-33) for urea compared to 23.4

and 5.7 mg N/m^2/day for the Restore+inoculumn or 11.7 and 8.8 mg N/m^2/day for the Restore-no inoculumn treatment. A similar patten of slower growth and N uptake rates with the organic fertilizer was observed in bermudagrass as well. Their results highlight that while organic fertilizers do provide N to turfgrass, the effect is much slower than using synthetic N fertilizers. The addition of a microbial inoculumn increased both rates 19 days after treatment, but the effect did not continue through day-33.

Sartain (1992) also evaluated suitability of the natural organic fertilizer 'Restore' as an N source for turfgrass species, including perennial ryegrass, in Florida. He measured ryegrass growth and N uptake rates ranging from 1.0 to 2.6 kg/ha/day and 0.023 to 0.084 kg N/ha/day respectively over a three-year period. N applications during this period were either 50 or 75 kg N/ha every 90 days. Growth and N uptake rates are averaged over the two N application rates, the range in rates is due to the N source used. These N application rates correspond to annual applications of 200 or 300 kg N/ha. The N uptake rates correspond to average annual N uptake rates of 8 to 31 kg N/ha. These researchers found that the N application rate and schedule used was suitable for maintaining ryegrass quality at their Florida location, and that there was variability among the organic fertilizer products evaluated. No measurements of residual soil N were made.

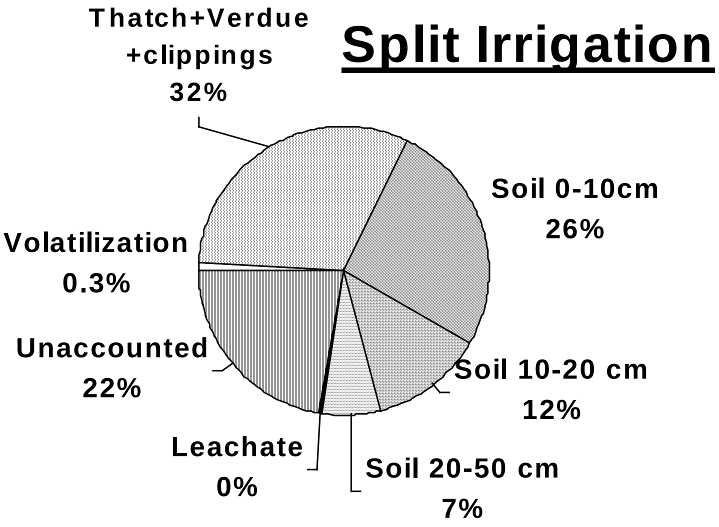
Fertilizer recovery and N use efficiency

In a recent review of the fate of N in turfgrass, Petrovic (1990) summarizes research on N uptake from eight turfgrass studies, primarily in lawn situations. (Four forage studies were also included.). Along with the discussion, he presents a large summary table of turfgrass N uptake expressed as percent of applied N. The summarized studies found that 5 to 74% of applied N is taken up by the plant. Most studies measured the N in clippings, though a few measured N uptake in other plant parts (roots, stems, above ground uncut plant parts) as well. N uptake depended on the N source, N release rate, N application rate, grass species, grass management and use.

Turner and Hummel (1992) also summarize apparent recovery of applied N measured in several studies. They report ranges from 30 to 75%, depending on the study and applied N rate. A portion of applied N (14 to 27%) was retained in the thatch layer through immobilization (Turner and Hummel, 1992). In another study, the thatch of a mixed bluegrass/red fescue (*Festuca rubra* L.) turf was found to have 280 or 510 kg N/ha, depending whether clippings were removed or returned respectively (Starr and DeRoo, 1981). Hummel (1989) reported apparent fertilizer N recoveries (difference method) for a variety of slow-release N sources (and a urea control treatment) at Ithaca, N.Y. Apparent fertilizer N recoveries ranged from 5.6 to 26.4% in a relatively cool year, and 26.7 to57.6% in a year with better growing conditions. All treatments received 196 kg N/ha, and only differed in their slow release characteristics

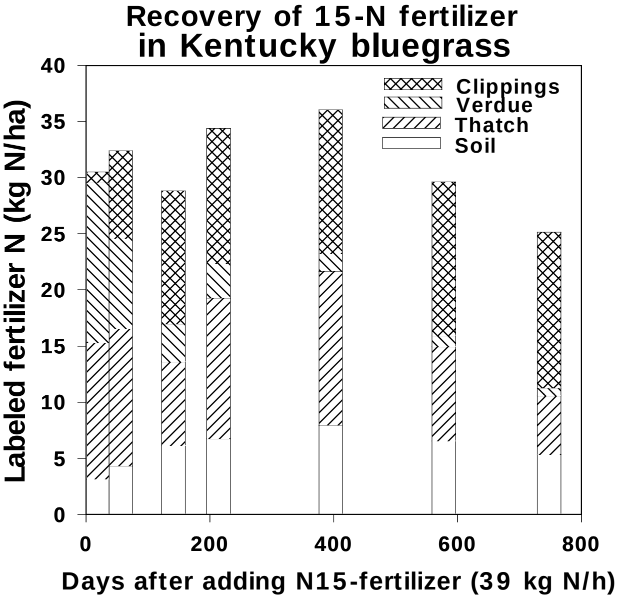
Starrett et al. (1995) determined the fate of ^{15}N-labeled urea fertilizer (49 kg N/ha) seven days after application to irrigated columns of undisturbed soil with an established turf of improved Kentucky bluegrass. Two irrigation schedules were used, both adding 2.54 cm of irrigation. The first schedule added the entire 2.54 cm immediately after fertilizer addition, and the second split the irrigation into four 0.64 cm applications, with the first application immediately after fertilizer addition, and the remaining applications at subsequent 42-h intervals. They were able to account for 74.8 and 77.7% of applied N for the two irrigation schedules respectively (Fig. 3-11). In the single irrigation schedule, 6.5% was found in column leachate plus soil below 30 cm depth, 53.2% of applied N was contained in the thatch plus soil in the 0 to 30 cm depth, and 14.6% of applied N was contained in the clippings plus verdue (uncut, aboveground plant parts). Only a negligible amount was volatilized. Denitrification was not measured, and the authors speculate that this may have been the fate of the missing applied N, since the columns were relatively moist. Clipping plus verdue and volatilization N recoveries were similar in both irrigation schedules. The main difference between the two irrigation schedules was that in the split-irrigation treatment, only 0.9% of applied N was contained in the leachate plus soil below 30 cm depth. The difference was made up in additional N (60.5% of applied) contained in the thatch plus 0-30 cm depth soil.

Figure 3-11. Recovery of applied N in various N pools under split irrigation. (From Starrett et al. 1995)



Miltner et al. (1996) determined the fate of N fertilizer in bluegrass turf by sampling at several intervals after a single ^{15}N-labeled fertilizer addition of 39.2 kg N/ha (Fig. 3-12). Total labeled N recovery in the shoots + thatch + soil was between 64 and 92% for all sampling dates over the subsequent two year period. They found that about half of the applied N was contained in the clippings + verdue (uncut green shoots) within 18 days after N application, and that labeled fertilizer N in this shoot tissue did not change significantly over the time they evaluated (2 years). Thatch N was also quite high initially (31% of applied labeled N), only dropping off in the second year. Soil N did not change appreciably over the 2-y period. Leachate N was only detectible at the end of the second year, and even then, were 0.005 kg N/ha or less (not significantly different from zero). Their results indicate that there is substantial cycling of N between the soil, thatch and shoots.

Figure 3-12. Recovery of applied N fertilizer in soil and various plant parts over time.



Only a few studies that measured NUE in turfgrass species were found in the literature (Sollenberger et al., 1984; Guillard et al., 1995). For all the treatments from these two studies, average NUE is 18 (range 9 to 33) kg dry matter/kg N supply. The average apparent N fertilizer recovery for all the studies summarized in Table 3-12 is 50% of applied N, with a range of 25 to 103% measured.

N distribution in turf plants

In a study with perennial ryegrass (*Lolium perenne* L.) turf over a 48 hour period, Bowman and Paul (1988) measured N partitioning of 40% in roots and 60% in the shoots, and this ratio was unaffected by N form. In a later study, measuring N accumulation by perennial ryegrass over a 48-h period, Bowman and Paul (1992) found an average of 32, 52, and 16% of the N contained in the new leaves, old leaves, and roots respectively. The N taken up during this period represented 35-40% of the N applied. Bowman et al. (1989) estimated N uptake rates under conditions of moderate N-deficiency in four turfgrass species (*Poa pratensis, Lolium perenne, Festuca arundinaceae* and *Agrostis palustris)* by measuring depletion of applied N15 in the thatch and soil. The majority of N recovered by the plants (all species) occurred in the first 24 hours.

3.2.5 COVER CROPS

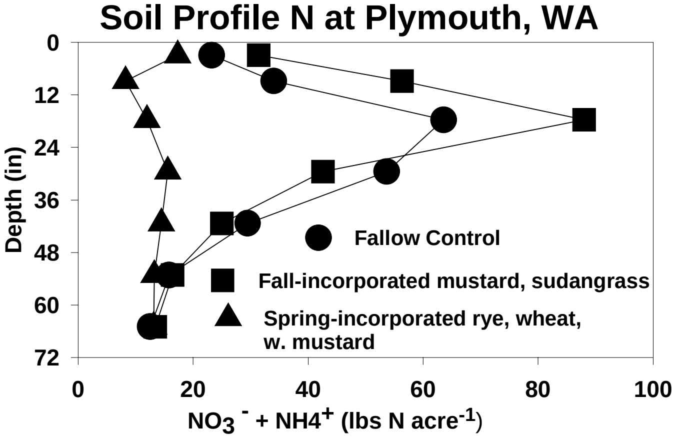
Nitrogen cycling benefits.

Cover crops are non-harvested crops that are inserted into rotations to recycle nutrients, build soil organic matter, protect the soil surface from erosion and provide natural pesticides. When used as green manures, they can serve as trap crops for recovering inorganic N. A primary benefit of cover crops is their ability to recycle nitrogen and reduce leaching losses and groundwater contamination. Fertilizer nitrogen can be conserved through the use of cover cops. For example, cereal rye, annual ryegrass and hairy vetch retained 10 to 45% of the fertilizer N and were more efficient than native weed species (Shipley et al., 1992). Other benefits include prevention of nitrate leaching to groundwater, though the presence of cover crop residues may actually increase N leaching, as a result of biomass decomposition and release of nitrogen, during heavy rainfall events or if overirrigation occurs (Miller et al., 1994). Staver and Brinsfield (1995) determined that overwintering rye cover crops dramatically reduced winter nitrate leaching to groundwater. Weinert et al. (1995) also found significant reductions in deep nitrate movement (below 60 cm) in soil below overwintering/spring plowed cover crops, compared to fallow ground and fall incorporated cover crop treatments.

Fertilizer carryover frequently occurs following crop removal resulting in soil N accumulation below 30 cm (Vanotti and Bundy, 1994). Residual fertilizer nitrogen following corn was conserved using winter cover crops in the Midwest (Shipley et al., 1992). Furthermore, soybeans have recovered up to 50% of soil nitrogen when used in corn rotations (Varvel and Peterson, 1992). Winter and spring beans, winter oats, winter rapeseed and spring peas increased soil nitrogen and subsequent wheat yields (McEwen et al., 1989). Lentil (Bremer and van

Kessel, 1992), soybean (Bergersen et al., 1992) and winter wheat cover crops increased soil N availability to subsequent crops (Hart et al., 1993). Other evidence indicates that crimson clover and hairy vetch cover crops were followed by increased corn yields (Wagger, 1989; McCracken et al., 1989 and Sarrantonio and Scott, 1988), while rye cover crops produced inconsistent effects on corn yields (McCracken et al., 1989). Orchardgrass was also used to recover leachable nitrates from dairy manure in grazing fields (Kanneganti and Klausner, 1994).

Figure 3-13. Reduction of nitrate leaching by overwintering cover crops compared to bare fallow and frost -killed cover crops at Plymouth, WA. (Weinert et al., 1995)



Wagger and Mengel (1988) summarized a number of studies conducted in the eastern U.S., indicating the extent of nitrogen uptake by wheat, rye or barley cover crops. Wheat or rye cover crops following corn generally retained 12 to 91 kg/ha of soil nitrogen that would otherwise be available for leaching. The cover crops also reduced moisture below the root zone, and therefore reduced leaching. Nitrogen uptake by wheat and barley varied depending on mineralization rates and the amount of nitrogen left in the soil following the cropping season. Overall, the experiments summarized by Wagger and Mengel indicate that cover crops may be utilized as nitrogen sinks in the recovery of excess fertilizer applied to corn and sorghum.

Cover crops can increase the amount of soil nitrogen maintained in the rooting zone over the winter compared to fallow fields in Central Washington. Weinert et al. (1995) found significant reductions in soil nitrogen levels below the potato rooting zone at the time of potato planting in fields with overwintering cover crops (Fig. 3-13). Root zone nitrogen is taken up by the cover crop over the winter, stored in the crop biomass and released again in the spring when cover crops are plowed into the soil or killed by herbicides. Ideally, the cover crop residue will act as a slow-release fertilizer. The residual soil nitrogen is otherwise lost to deep leaching in fallow fields.

The ultimate benefits of cover crop adoption include reduced grower cost through reduced fertilizer requirements and reduced nitrate levels in groundwater as leaching decreases.

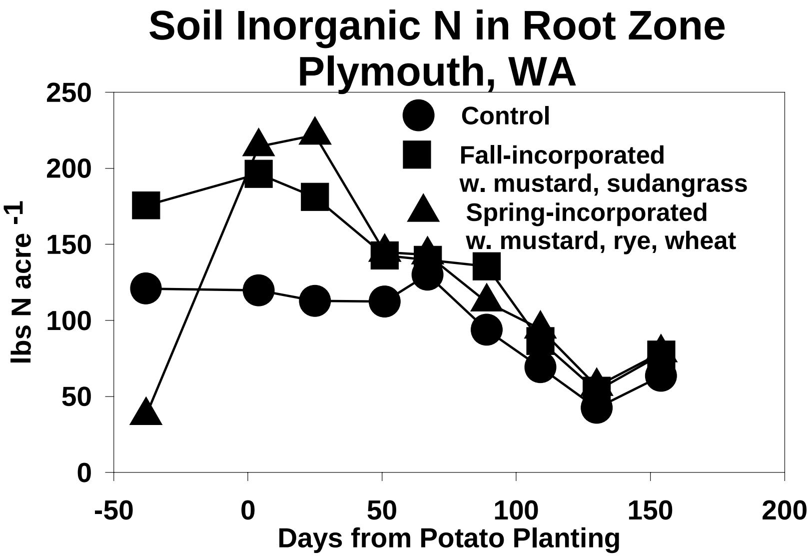
Growers will require a substantial history of success in maintaining yield quantity and quality before they will be willing to reduce fertilizer use; however, little research has been done to develop a nitrogen management program for fertilizer reduction following cover crops. Preliminary studies in cover cropped corn production systems used three different cover treatments (hairy vetch or rye plus corn residue or corn residue alone) and three fertilizer rates (0, 85 and 170 kg/ha). The study found that fertilizer use could not be significantly reduced while maintaining yield quantity and quality, though grain yield increased when vetch residues were present (Utomo et al., 1990). McCracken et al. (1989) also found that corn yield and N uptake were increased more in crops in fields with a history of hairy vetch winter cover crops (28.0 kg N/ha increase) compared to crops in fields with a history of only N fertilization (20.4 kg N/ha increase). Rye cover crops had little or no impact in comparison to no cover crop controls in increasing N uptake in this experiment.

Cover crop N accumulation, rooting depth, and water use.

Non-legume cover crops in the Graminae and Brassicae families serve as excellent cover crops because they can rapidly germinate and establish an extensive root system, many of the crops have good winter-hardiness and exhibit vigorous spring regrowth, and accumulate sizeable amounts of dry matter and N. A survey of the literature suggests these crops can accumulate up to 150 kg N/ha in many environments (Wagger and Mengel, 1988; Bowen et al., 1991; Brinsfield and Staver, 1991; Hoyt and Mikkelsen, 1991; Shennan, 1992; Ditsch et al., 1993; Weinert et al., 1995) and establish effective rooting depths of 80 to 150 cm (Frye et al., 1985; Sarrantonio, 1992; Weinert et al, 1995). In addition, actively growing cover crops transpire soil water, reducing the rate of soil water recharge and the potential for nitrate leaching between summer growing seasons, when precipitation normally precedes evapotranspiration (Wagger and Mengel, 1988). The production of 5 Mg of residue typically requires about 6 cm of water (Power et al., 1961; Hanks, 1983; Meisinger et al., 1991), which constitutes a major portion of the winter precipitation in the Columbia Basin.

Recently, Weinert et al. (1995) observed white mustard, rapeseed, rye and winter wheat cover crops to accumulate between 2.9 and 4.6 Mg/ha dry matter and 112 to 142 kg N/ha when planted on August 25 in Plymouth WA. When incorporated as green manures for the succeeding potato crop, the overwintering wheat, rye and rapeseed residues deplete the inorganic soil N and recycle a major portion of the accumulated N (Fig. 3-14). However, when planted a month later in a cooler season at Quincy, WA, the biomass and N accumulation was less than 50% of the previous year (Weinert et al., 1995). This illustrates that the use of winter cover crops for recycling N is limited to rotations in which there is a reasonable planting window for establishing the cover crops in early fall. For example, sorghum-sudangrass is an increasingly popular cover crop to be seeded after an early harvested crop such as fresh-market potatoes or sweet corn, so that it can be planted by the first week in August. Rapeseed and white mustard grown at Prosser, WA released over 150 kg N/ha to the succeeding potato crop (Brunty, unpublished data).

Figure 3-14. N mineralization from green manured cover crops in synchrony with N demand by the succeeding potato crop at Plymouth, WA. (Weinert et al., 1995)



Factors affecting N mineralization from cover crop residues.

Ladd and Amato (1986) found that total nitrogen recovery by wheat crops was 84% greater when legumes provided crop nitrogen, compared to 80% from fertilizer nitrogen. Mason and Rowland (1992) found that wheat yields increased as the C/N ratio of the incorporated cover crop decreased. Findings in Das et al. (1993) support the importance of a critical C/N ratio. Residues with lower C/N ratios resulted in higher mineralization rates during the first 90 days of decomposition, though by day 120 there was no correlation between mineralization and C/N ratios. The critical C/N ratios (below which mineralization will occur) for 30, 60 and 90 days for field capacity conditions were 46, 55 and 70. C/N ratios for 50% field capacity conditions for 30, 60 and 90 days, respectively, were 39, 50 and 70. An analysis of eight experiments indicated that the critical C/N ratio is 40 and that 75% of differences in N mineralization rates among these studies could be explained by differences in C/N ratios (Vigil and Kissel, 1991). The C/N ratios and residue N concentration were the most significant factors to be considered when predicting mineralization rates of wheat, rye, oat and crimson clover residues (Quemada and Cabrera, 1995). Also, due to concentration of nitrogen and protein in plant grain, incorporation of crop residues following harvest should result in a higher soil C/N ratio, compared to incorporation of whole grain-bearing plants.

Rates of residue decomposition are important to growers because nitrogen must be available to crops at the proper time (as the crops need them). For example, some crops such as peas may have residues that make significant contributions to soil N only in over the course of several years (Jensen, 1994). Similarly, soil-incorporated ground *Medicago littoralis* residue with a C:N ratio of 11.1:1 contributed very little to soil N or crop N uptake (Ladd et al., 1983). In contrast, wheat residue is most available to the first crop following incorporation; 6.6% of N from the winter wheat cover crop remaining in the soil was taken up in the first wheat crop compared to 2.2% in the fourth year after plowdown. Sixteen percent of the cover crop-supplied N was recovered (cumulative), 29% lost to leaching and denitrification and 55% remained in the soil four years after plowdown (Hart et al., 1993). The large proportion of labeled N remaining in the soil may be a result of high C:N ratios found in wheat stubble (41-68 in this experiment). Another experiment determined that the net mineralizable N content of cover cropped soils did not consistently increase until commencement of irrigation, 20 days after plowdown (Wyland et al., 1995).

Several studies indicate that residue placement is a primary concern in future N availability. Post-harvest residue placement effects were most significant in the first 8-10 days of decomposition, with higher rates of mineralization occurring when residues were incorporated (Aulakh et al. 1991); however, incorporation of non-leguminous post-harvest residues may result in initial depression of N mineralization (Smith and Sharpley, 1990). Incorporation of residues also decreased the net immobilization period of high C/N ratio residues (Schomberg et al., 1994). Wagger (1989) found that older residues (by two weeks) decomposed/mineralized more slowly than younger residues and decomposition occurs more slowly in drier years.

Temperature is another important factor in residue decomposition rates (Douglas and Rickman, 1992). Air temperature, expressed in growing degree days, can be related to residue decomposition rates. Furthermore, soil type, soil texture, pH and climate influence the relationship between degree days and rates of residue decomposition, though degree days remain an excellent prediction method for decomposition rates. Honeycutt et al. (1991) developed an equation to relate nitrate production to environmental factors affecting residue decomposition:

$$NO3^{-} = 784.558 - 1.271(MAP) - 93.057(pH) + 0.005(DD*pH) + 0.061(DD*H_20)$$

Where:

$NO3^{-}$ = nitrate-N concentration (mg/kg)
MAP = mean annual precipitation (cm)
pH = soil pH

DD = degree days (^{o}C)

H_20 = soil water content (MPa)

Whitmore (1995) developed a crop growth and nitrogen uptake model in which thermal time is the most significant uptake factor. The model is designed to predict nitrate leaching, mineralization rates and crop nitrogen accumulation, as well as dry matter and grain production.

Growth and N accumulation of individual cover crops

Sorghum and Sorghum-sudangrass

A key factor in effectively using a sorghum-related crop as a cover crop is the requirement for warm temperatures at germination. Although sudangrass has not been well-studied, other sorghum crops have been evaluated for cold tolerance. Six varieties of *Sorghum bicolor* were evaluated for base temperature requirements for germination and root and shoot elongation. Results indicate that minimum temperature requirements range from 3.5-11.4 ^{o}C for germination, 6.8-12.2 ^{o}C for root elongation and 8.4-12.1 ^{o}C for shoot elongation (Lawlor et al., 1990). Other research indicates that sorghum has a base temperature of 10 ^{o}C. Sorghum planted at temperatures below 10 ^{o}C will emerge less quickly and provide less cover (Anda and Pinter, 1994).

Sudangrass nitrogen content increased linearly in response to added fertilizer nitrogen (generally applied as ammonium nitrate) at a rate of increase of 8.5×10^{-4}%/kg N/ha. Maximum forage yields of 16.1 t/ha were reached at 350 kg N/ha applied nitrogen. Sudangrass yielded up to 16.1 t/ha (Muldoon, 1985). Nitrate nitrogen content of sudangrass shoots ranges from 360 ppm to 5500 ppm, increasing with nitrogen availability. A study of seven hybrid sudangrass cultivars suggests that increases in yield in response to increased soil nitrogen are more dramatic after the first month of growth (Harms and Tucker, 1973). Total nitrogen concentration in plant material increased as applied nitrogen increased as fertilizer rates increased from 22 to 176 kg N/ha. However, total nitrogen uptake did not necessarily increase because dry matter actually decreased at higher application rates. Further studies indicate that soil type affects the nitrogen uptake capacity of sudangrass (Bartz and Jones, 1983).

Brassicas

Recent studies indicate that soil water and air temperature have a considerable effect on the low-yielding *Brassica campestris*, though less weather effect was observed in *Brassica* *juncea* and *Brassica napus* (Hellstrom, 1994). *B. napus*, or rapeseed, root extension rates vary with temperature, increasing with temperature between 5 and 23 ^{o}C (Moorby and Nye, 1984). Shoot and root growth rates are also reduced at when the entire plant is exposed to temperatures below 10 ^{o}C (Cumbus and Nye, 1985). A possible explanation for the increased growth rate at higher temperatures is presented in Macduff et al. (1987), wherein nitrate and ammonium ions are taken up four times faster at 17 ^{o}C compared to 3 ^{o}C over 14 days.

Comparisons of canola seedling germination and early seedling development indicate that temperature affects these parameters as well. Poor germination and growth occurred at 2 and 6 ^{o}C, 95% germination was attained between 8-12 days at 10 ^{o}C and germination occurred most rapidly at 22 ^{o}C (Nykiforuk and Johnson-Flanagan, 1994).

Studies of nitrogen uptake in canola and rapeseed have focused almost entirely on increases in seed yield and seed nitrogen content as a function of soil nitrogen for plants intended to grow through the summer, as opposed to winter cover crops. Fertilization requirements for winter rapeseed crops are described in Mahler and Murray (1989). Ramsey and Callinan (1994) found that increasing fertilizer application on canola crops increased seed nitrogen content in the form of protein; however, canola and rapeseed grown as cover crops will generally not be allowed to grow long enough for seeds to develop. No mention was made of nitrogen accumulation in shoots, though nitrogen accumulation did appear to increase as soil moisture increased. Darby and Yeoman (1994) found that nitrogen accumulation in August-sown rapeseed was not affected by increased soil nitrogen, except where straw residue from a previous crop had been burnt. Straw incorporation generally decreased yield. Plant establishment for September-sown crops depends heavily on winter kill damage as well as planting method. Establishment is greater when seeds are drilled, compared to broadcast seeding. Another study indicates that increased soil nitrogen may improve rapeseed growth more significantly following cereal crops compared to rapeseed following pasture (Stoker and Carter, 1984). Seeding rates and nitrogen uptake appeared to interact in another study, at least in a year of abnormally high precipitation (Lewis and Knight, 1987). Increased soil nitrogen levels increased the water use efficiency of canola plants (Taylor et al., 1991). Irrigation increased rapeseed dry matter accumulation response to soil nitrogen compared to rainfed conditions. Higher soil nitrogen levels increased the leaf area index (Wright et al., 1988). Leaf and stem nitrogen concentrations increased as fertilizer applications increased and the timing of applications increased N concentrations when higher levels of fertilizer were applied at the time of sowing, compared to applications delayed until plants reached the rossette stage of development. Also, Nitrogen recovery rates ranged from 18% to 96% in the top 25 cm of soil and from 26% to 98% in the top 50 cm of soil. Recovery rates depend on fertilizer time, the use of split applications and whether or not the crop is irrigated. Irrigated conditions where 100 kg N/ha was applied at sowing (a similar condition to the presence of large amounts of nitrogen from a previous crop at sowing) resulted in the greatest apparent recovery and retention of N (96-98%) in the top half meter of soil (Smith et al., 1988).

Research concerning nitrogen uptake by mustard crops has focused almost entirely on the effect of added fertilizer nitrogen on seed yield. Once again, pre-plant soil nitrogen levels and nitrogen uptake efficiencies are rarely, if ever mentioned. However, an early study on nitrogen relationships in mustard were conducted by Kahn and Agarwal (1983). The study was conducted in soil with initial nitrogen contents of 195, 180, 185 and 183 kg N/ha at depths of 0-30, 30-60, 60-90 and 90-120 cm, respectively. Total plant nitrogen concentration at flowering stage increased from 1.42% with no fertilizer addition to 1.75% when 80 kg N/ha was added (adding another 40 kg/ha did not significantly increase nitrogen concentration). Dry matter totals, rooting depths and nitrogen uptake efficiencies were not reported. No significant differences in nitrogen concentration were observed under different soil moisture regimes (Khan and Agarwal, 1983). Narang and Singh (1985) found that nitrogen uptake by Indian mustard crops increased the most dramatically between 78 and 11 days of growth in the first year of the study, with only slow increases in nitrogen content between 40 and 78 days after planting and slow increases or even decreases in N content between 78 and 111 days after planting. However, results from year 2 indicated that the greatest increase in nitrogen content occurred between days 40 and 74. The percent nitrogen recovered was greater in the second year compared to year one and percent recovery was greater at the lowest fertilizer rates in both cases. In year 1, the crop recovered 25.0, 20.1 and 16.1 of added fertilizer nitrogen for application rates of 50, 100 and 150 kg N/ha, respectively. Year 2 results, for the same respective fertilizer application rates, had recovery percentages of 52.6, 50.6 and 44.2%. The differences in total recovery were attributed to the high rate of nitrogen accumulation in the early vegetative stage in year 2, compared to the later stages of vegetative growth in year 1, though the underlying reason was not determined.

Wheat, Triticale and Rye

Rye and triticale have been shown to accumulate dry matter faster than wheat when grown at temperatures of 10 and 20 ^{o}C. The tolerance of rye for lower temperatures may arise from several factors. First, winter rye cultivars appear to have adaptations in the photosynthetic apparatus that increases resistance to freezing (Oquist et al., 1993). Second, leaves of cold-adapted rye varieties endogenously produce an antifreeze protein that inhibits ice formation on leaves (Griffith et al., 1992). Finally, increased daylength (16 vs. 24 hours) and irradiance positively affect both growth and frost tolerance of cold-grown rye (5/3^{o}C day/night) (Griffith and McIntyre, 1993).

Klepper et al. (1982) developed methods to quantify and model developmental stages of small cereal grains, specifically relating leaf and tiller development to environmental conditions for model development. Klepper et al. (1984) characterized root and shoot development over time, as well as root classifications and order of development. Klepper and Rickman (1990) used root development and classification information to model root growth and function. Growth of two wheat cultivars, Sunset and Rosella, increases linearly with temperature (10-25^{o}C) while growth of Condor and Cappelle Desprez showed rapid growth increases only between 10 and 19 ^{o}C. Base temperatures for growth to anthesis of the four varieties ranged from 2.5-5.5 ^{o}C, with an average of 4 ^{o}C; base and optimum temperatures increased with each group as growth stage of the plant increased.

One study suggests that root cooling reduces leaf growth by reducing hydraulic conductivity of stems, thereby causing water stress in the plant (Malone, 1993). Inhibition of wheat growth appears to continue in cold-treated plants even after the cold conditions are removed. Seedling hydration decreases as plants grow at 2 ^{o}C compared to plants grown at 20 ^{o}C and hydration remained lower in 2 ^{o}C plants transferred to 20 ^{o}C as compared to control plants (Dubert et al., 1994). Comparisons of winter rye, barley, oats and ryegrass were compared as potential cover crops to follow late potatoes. Rye biomass was 38% greater than barley, 80% greater than oats and 130% greater than ryegrass. In an additional field study, rye root biomass was twice that of winter rapeseed. Seed mass may account for a considerable portion of these differences (Edwards and Sadler, 1992).

Undersander and Christiansen (1986) found that water availability has a significant impact on wheat growth and inclusion of water variables in GDD equations provide more accurate results. In addition, a base temperature of 4^{o}C provided greater accuracy than a base temperature of 0^{o}C. Baker et al. (1986) found that leaf emergence rates were affected by irrigation and cultivar. Another study indicated that low moisture reduced percent tiller formation, though only in the coleoptile tiller, final mainstem leaf appearance (decreased with decreasing moisture) and increased the number of GDD before tiller appearance (Krenzer et al., 1991).

Planting date has been shown to determine rate of leaf growth. Equations 11 through 16 indicate main stem leaf numbers (LN) for wheat as a function of degree days (DD), according to the corresponding planting date (Cao and Moss, 1991):

22 September: $LN = 0.52 + 0.0114*DD$
13 October: $LN = 0.97 + 0.0103*DD$
3 November: $LN = 0.18 + 0.0123*DD$
24 November: $LN = 0.22 + 0.0.122*DD$
15 December: $LN = 0.44 + 0.0137*DD$
5 January: $LN = 0.57 + 0.0142*DD$

Planting date may affect phyllochron values for two primary reasons. First, plants transferred from low to high temperatures showed accelerated growth while plants transferred from high to low temperatures showed varied responses, depending on stage of development. Older plants are less affected by a temperature drop. Second, plants transferred from short to long days showed accelerated growth and emergence while plants transferred from long to short days were again affected according to stage of development. Older plants were *more* affected in this case (Cao and Moss, 1994). Finally, a recent evaluation of nine equations developed to estimate wheat phyllochron indicated that none of the equations, including some of those listed above, are valid across a wide variety of cultivar types. Correlation coefficients ranged from 0 to 0.119 for winter varieties and 0.008 to 0.486 among spring cultivars. Therefore, these equations may not accurately predict wheat growth rates when used as general estimates for growers (McMaster and Wilhelm, 1995).

4. LAND APPLICATION METHODS AND CRITERIA FOR ORGANIC WASTE AND PROCESSED WATER RECOMMENDED TO PREVENT N LEACHING

Organic waste is defined here to include animal manure, crop residue, food processing and other industrial waste, treated municipal wastewater, and biosolids (sludge from treated wastewater). Organic wastes are potential resources that can serve as fertilizer and as beneficial soil amendments. Hazardous heavy metals may be present in these organic wastes and must be dealt with according to State regulations. Manure is a good source of plant nutrients, including nitrogen, phosphorus and potassium. Furthermore, land application of organic waste improves the physical and microbiological properties of the soil, which are beneficial for good crop growth and production. However, it is essential to know the optimum amounts of organic waste to apply because excessive applications potentially contribute to environmental pollution through leaching and runoff of the surplus nutrients. Computing organic waste application rates to balance nutrients with crop needs while protecting the quality of surface water and groundwater is necessary to meet public environmental concerns.

Processed water applied to a land treatment system, LTS, is usually applied by sprinkle (spray) irrigation. LTS are used frequently in some parts of Washington. Sixty-five facilities in Washington have LTS permits (Carey et al., 1994). Fifteen are allowed to discharge up to 3,785,000 liters per day to their LTS. The ultimate concern of the state of Washington (Department of Ecology) is whether the LTS are designed, operated, and maintained so the nitrogen loads to the LTS do not exceed their capacity and contaminate groundwater with nitrate-nitrogen.

Some agricultural activities produce significant amounts of waste containing nitrogen, including manure[*] and food processing waste. Municipal and industrial processed water effluents and their biosolids[**] may also contribute important amounts of nitrogen. Processed

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[*] As excreted, manure is called fresh, or raw, manure consisting of feces and urine. In practice, manure is usually a composite of feces, urine, spilled feed and drinking water, bedding, and process water (flush cleaning, wash water, etc.).

[**] Biosolids means municipal sewage sludge that is a primarily organic semisolid product resulting from the wastewater treatment process, that can be beneficially recycled and meets all applicable requirements under Chapter 173-308 Washington Administrative Code. All applicable requirements include those of the U.S. Environmental Protection Agency.

water must be treated before disposal, and manure is stored with variable treatment before land application.

4.1. Organic waste and processed water treatment

Organic wastes have similar characteristics (properties) that influence their biochemical degradation to their end products. Whether biosolids or wastes/processed waters from food processing, livestock production, and municipal wastewater treatment, all have common characteristics but they differ in magnitude. Regardless, the reactions during storage, land application, and in the soil-plant-water system follow the same physical and biochemical laws.

Municipal and industrial processed water treatment is regulated by a permit from the Washington Department of Ecology that specifies the total maximum daily load (TMDL) that can be discharged in the treatment plant effluent. The TMDL includes some or all of the contaminants biochemical oxygen demand, suspended solids, nitrogen forms, phosphorus, and heavy metals. In brief overview, processed water is commonly treated in a plant by three processes: primary, secondary, and tertiary treatment. Primary treatment settles the solids. Secondary treatment to degrade the waste employs one of several aerobic processes that include disinfection. Tertiary treatment removes nutrients, nitrogen and phosphorus, and also can disinfect the wastewater so the treated effluent can be discharged to a stream. Primary settling and secondary settling of bacterial solids from secondary treatment produces sludge commonly stabilized by treatment in an anaerobic digester. When treated sufficiently to meet USEPA criteria sludge is called biosolids and is suitable for land application (footnote page 4.1). They are further treated by various dewatering methods to facilitate handling and storage. Processed water treatment plant effluent can frequently be applied to crop or forest land. Wastewater treatment plants are not economically feasible for small towns so they use oxidation ponds (aerobic lagoons) and generally need land disposal of effluent to acceptable crops unless evaporation is sufficient to remove the stored water.

Treated wastewater, biosolids, manure, and food processing waste are handled similarly in that they are kept in short-term to long-term storage, which results from detention time of a flow or fill and draw methods. Handling is by gravity, pumps or mechanical means. Section 4.2 describes animal manure handling systems. Organic wastes and processed waters are handled similarly by collection, transport, storage and/or treatment, transport and application to land. Municipal and industrial processed waters are treated by sophisticated processes to allow discharge to streams or water bodies. Wastes used on agricultural cropland need little stabilization. The organic matter and plant nutrients (N, P, K) have soil and crop production value. The composition varies with the kind of waste/processed water and how it is treated. Nitrogen is the characteristic of concern here. Table 4.1 gives total nitrogen examples for selected waste/processed water relative comparisons.

Table 4.1. Total Nitrogen in Selected Waste and Processed water

	Biosolids	Dairy Manure		Fruit and Vegetable Processing	Potato Processing	Municipal Wastewater	
		Solid	Lagoon			Primary Influent	Secondary Effluent
	% db	% wb	mg/L	mg/L	mg/L	mg/L	mg/L
Total N	3.3	0.44	560	17	130-175	40	27

Source: Ardern, 1976; Hermanson, 1996; Adriano and Erickson, 1974; Smith et al., 1976; Liu et al., 1997; Palazzo 1976; USEPA, 1983; MWPS, 1985; Bezdicek, 1977; Smith and McWhorter, 1976; MWPS, 1985; and Don Nichols, ERO Dept. of Ecology, Spokane, WA. Communication to Diane Dent-White, DOE Headquarter, Lacey, WA. October 29, 1998.

The best waste/processed water handling system will make the best overall use of available land, labor, and capital. The system must avoid pollution and nuisance problems and ideally will fully use the waste's fertilizer and soil conditioning characteristics. Most waste/processed water management systems ultimately return the organic waste to the land. There must be a storage or detention period between collecting and removing waste from the facilities and application to cropland. Care must always be taken to prevent any waste or processed water from reaching the surface and groundwater of the state and violating the water quality standards.

Livestock manure is used as the primary example of waste/processed water historically applied to the land as a LTS to treat by the crop-soil-water-nutrient-climate system. The purpose goes beyond producing an economic crop because protecting the quality of surface water and groundwater is required by state and federal law. More than four decades of research has produced coefficients needed for the methodology used to calculate application rates with worksheet methods that were developed first, and with computer software used today. Before presenting the methods used in determining manure application rates, it is appropriate to note that the methods were designed as a framework with procedures that can be adapted for other organic waste/processed water. The procedure requires certain coefficients specific to the kind of waste/processed water:

1. Default values were designed to be easily changed to waste/processed water specific coefficients.
    a) Application losses of ammonia-nitrogen.
    b) Mineralization rates.
2. Denitrification and nitrogen uptake are independent of the kind of waste/processed water.
3. Nutrient analysis of the specific waste/processed water to be applied.
4. Soil test.

4.2 Land application systems

Systems used for applying organic wastes to cropland differ for wastes in solid (semi-solid usually) or liquid form, however, the functions are similar. Successful application begins with scientifically based calculations of the application rate for the crop. Timeliness of the application with respect to the stage of crop growth, the season, and whether the soil is too wet, frozen, or snow covered to apply waste/processed water to land is imperative. The management plan must consider these factors to produce crops successfully and to protect the quality of surface water and groundwater. The Natural Resource Conservation Service (NRCS), formerly the Soil Conservation Service (SCS), specifies in a nutrient standard: "Organic nutrient liquids shall not be applied to frozen, saturated, or snow-covered soils. However, the plan should designate the best application sites for use in the event of emergency weather conditions or flooding," (Soil Conservation Service, 1993). The standard is designed to protect surface water from contamination, not to protect groundwater. However, applying the amount of manure nitrogen correctly calculated for the crop minimizes the chance of nitrate-nitrogen leaching to groundwater. Irrigation of crops based on crop water requirements determined by a scheduling program will minimize percolation and thus leaching of nitrate-nitrogen. All application systems cited will protect groundwater quality provided they are properly managed. Management is the key to achieving the goals of the producer and the demand of the public for clean water.

Storing and Spreading As a Solid

This system usually has short-term storage between the time of collection and land spreading. Long-term storage works well in high-rise layer houses. For other livestock manure, a roofed facility may be needed in high-rainfall areas with drains to convey liquid to separate storage.

System components:

c) Scraper.
c) Storage unit.
c) Ramp or front-end loader.
c) Spreader.

Storing and Spreading As a Liquid

Some producers believe that a liquid system is best. Land spreading of liquid waste, however, is not as simple as many thought. Two major disadvantages are the cost of the system and the odors associated with agitating and field spreading partially decomposed manure. In addition, a greater volume of manure is handled in a liquid system than a solid system because of dilution water. Advantages are minimal labor cost because the manure is usually flushed from the system with recycled water and transported by pumps. Systems can be operated with microprocessor timers and electrically activated valves and pumps, further reducing labor costs. Because a reinforced concrete tank for long-term storage is too costly, most producers use an anaerobic storage lagoon. Manure is scraped or flushed into the lagoon. Alternative injection equipment places the liquid slurry 10 to 15 cm below the ground surface and covers it immediately. Tillage offers the same opportunity to incorporate the slurry soon after application. Injection and tillage significantly reduce the ammoniacal-N loss over the loss if slurry/wastewater were to remain on the land surface. Soil incorporation (injection/tillage) also protects air quality by placing the slurry/wastewater in the soil to prevent release of anaerobic odors. However, quick incorporation of ammonia-N after application reduces N removal by volatilization and increases the amount of nitrate-N in the soil (via transformation of ammonia to nitrate) potentially available for leaching.

Big gun sprinklers that are moved between sets are common, but are rapidly being replaced with traveling sprinklers. Center pivot systems can be used for very dilute manure water. A tank wagon equipped with a vacuum pump may be used with small lagoons, but a separate pump for mixing and loading works better. A rear-loading tank wagon can be backed down a ramp into the lagoon. The use of tank wagons is limited to small lagoons (earth storage basins), because tank wagon capacity is too low to be practical for large lagoons. The greatest problems with lagoons are odors and the difficulty in removing solids. The lagoon effluent should not be spread on a hot, humid day because odors resulting from the spreading operation may create a nuisance. Correct lagoon design and management can minimize odors. Solids removal is aided by mixing with a propeller provided the lagoon is not too large. Due to the difficulty of solids removal, the separation of solids is recommended to yield solids and manure water that is stored in the lagoon. A special sieve (screen) or a concrete solids-settling basin can accomplish this to improve materials handling. Separated solids can be composted and used as bedding, applied to the land, or sold if a market exists.

System components:
c) Scraper.
c) Flush system.
c) Optional solids separator.
c) Anaerobic lagoon.
c) Pump or propeller agitator.
c) Irrigation or spreader.

Loss of Nitrogen Due to Application Method

Nitrogen losses for the common application methods are given in Table 4.2 (Hermanson, et al., 1995):

Table 4.2. Manure Ammonia Nitrogen Loss Due to Application Method: Percent of Total Kjeldahl Nitrogen

Application Method	Loss, %
Broadcast Spreader	20
Broadcast Spreader, immediate tillage	5
Grazing	17
Sprinkling	25
Sprinkling, very dilute, solids separated	7
Sprinkling, immediate tillage	7
Tankwagon	20
Tankwagon, inject or immediate tillage	5

Nitrogen loss due to ammonia volatilization differs somewhat from manure to biosolids as shown in Tables 4.2 and 4.3. However, this is not a drawback to the use of Manure Nutrient Balancer (MNB) because the user can easily change default values to those appropriate to the waste/processed water being studied. (Hermanson et al., 1995).

4.2.1 Municipal wastewater effluent

Treated municipal wastewater is applied to cropland in many rural locations in eastern Washington. Ecology conducted a study reported by Carey (1995) of the Deer Park land application site. Wastewater was treated in an aerated lagoon and two storage lagoons. The LTS consisted of a 64.8-ha alfalfa spray field divided into 9, 6.88-ha fields. Three of the five objectives were to 1) characterize the soil pore-water under the fields before mixing with groundwater; 2) estimate effluent nitrogen treatment in the unsaturated zone; and 3) evaluate effectiveness of unsaturated zone monitoring.

Table 4.3 Estimates of Ammonia Plus Ammonium-N Loss Due to Biosolids Application Method.

	Tillage within	
	0-2 days	>6 days
	Loss, % of applied	
Liquid, pH>7	20	40
Dewatered, pH>7	40	60
Liqiud or Dewatered, pH<7	10	10
Lime stabilized	90	90
Composed or drying bed and injection	No loss	

Soil sampled to 28.4 cm deep located coarse sand that is typically very permeable. Thin layers of loam resulted in greater water holding capacity than normal. The discharge permit allowed effluent application April through September. Precipitation plus effluent was limited to 3.2 cm/month or 2.3 million liters/day. Treatment of total nitrogen in the unsaturated zone was low. Ninety-one to 183 cm from the surface the treatment ranged from 26 to 35% from a low application of total nitrogen of 112 kg/ha. Suction and wick lysimeters provided more representative samples than the barrel lysimeters. Mean total nitrogen concentrations in the wick and suction lysimeters were 17 and 6.8 mg/L, respectively. The effluent loading appeared to affect downgradient monitoring wells because nitrate+nitrite-nitrogen increased during the study.

General recommendations included that future permits for LTS should monitor the unsaturated zone. Such monitoring can help evaluate LTS practices at specific sites and enable prompt adjustments to improve treatment and protect water quality.

4.2.2 Food processing waste

Waste and processed water from food processing plants in the nation are applied to agricultural land for treatment and disposal as a preferred practice. Food processing wastes derive from fruit, vegetables, dairy products, seafood, meat, poultry, etc. Agricultural land treats the organic constituents by soil microbial decomposition to avoid serious environmental pollution (Smith, 1986). A well-designed and managed system does not endanger groundwater quality nor surface water quality. Microbial degradation of the organic constituents in waste and processed water releases nutrients to be used by the crops growing as part of the treatment system. Most food processing waste effluents can be applied to agricultural land to supply water and crop nutrients. Thus, the land treatment system (LTS) provides beneficial use of the waste resource. There are several land treatment methods that can be used by food processors. These are slow rate, rapid infiltration, and overland flow (Ritter, 1987). Slow rate land treatment is most common and is used by Pacific Northwest food processors. Slow rate treatment includes application by spraying (sprinkling), ridge and furrow, or flooding.

Clearly, nitrogen loading must be designed correctly for food processing wastewater LTS. Organic loading must also be considered. Limiting nitrogen application to the amount crops can use normally keeps the organic load to the amount that will decompose between applications. Field and laboratory experiments by Jewell (1976) and Jewell and Loehr (1975) showed that soils conditioned to receive processed water carrying organic matter can handle high loading rates under favorable conditions. Two LTS fields received vegetable processing plant processed water loads of 9,000 kg chemical oxygen demand per ha-day with >99% removal efficiency. Food processing wastes were considered treatable by LTS and the soil was determined to have great capacity to assimilate these organic wastes. The nitrogen concentration in organic processed waters is usually low, nevertheless the application rate is not controlled as easily as for commercial fertilizer. The timing of processed water irrigation and the amount are important because the demand of a crop for water is not necessarily at the same time as the demand for nutrients (Krauss and Page, 1997). Application of processed water when the crop need for nitrogen is low can cause leaching of nitrate-nitrogen. Both nitrate nitrogen and processed water rates must be monitored and controlled to reduce the potential for groundwater contamination.

4.2.2.1 Potato waste

Large amounts of nitrogen can be supplied to the land in food processing wastewater (Smith et al., 1975, 1978). Smith (1976) studied LTS of potato processors in Idaho and determined that 160 to 490 cm of processed water was applied annually. Nitrogen supplied to the land was 1,080 to 2,200 kg N/ha. Potatoes were processed most of the year, producing large discharges of processed water ranging from 1.9 to 19 million liters per day. The long processing season discharged so much processed water that excessive nitrogen was applied to the land treatment system. Smith et al., (1975) determined nitrogen application rates for five potato-processing wastewater irrigation systems in Idaho. Annual nitrogen applications ranged from 800 to 2,200 kg/ha, however, grass grown on the application fields could not use that much nitrogen. The researchers concluded that soil nitrate-N increased and likely leached to groundwater.

The US Environmental Protection Agency raised concerns in 1994 about the efficacy of state issued permits to protect groundwater quality at six potato processing plants in the mid-Columbia Basin, Washington. Reports by the US Geological Survey (Jones et al., 1995) indicated increased nitrate-nitrogen concentrations in groundwater in local areas in the mid-Columbia Basin. Ecology responded with a study reported by Cook (1996) to assess the ability of each permit to protect groundwater quality and to determine the effect on groundwater quality near each plant. The plants studied were one each at Connell, Pasco, Richland, Moses Lake and two at Othello, all in Washington.

Methods for conducting adequate hydrogeologic assessments of the effects on groundwater quality were not used when potato processors in Washington began land application of processed water (Cook, 1996). The Department of Ecology (Ecology) developed land application guidelines in 1993 that provided consistent evaluations of land application. Statewide groundwater quality standards provide Ecology with regulatory means for establishing permitting requirements for LTS.

The improvements made at the six plants that were under permit were documented by Cook (1996). The resultant changes are abbreviated here:

1. Connell - Cropland for land application was increased by 243 ha in 1993. A lined lagoon for 90 days of winter storage was constructed and aerated for odor control. The nitrogen overload was reduced by treatment in constructed wetlands. Wetland treatment and lagoon storage was predicted to reduce the nitrogen load 70 percent from the current value. During 1993-1994 groundwater nitrate-nitrogen concentrations in three of five downgradient monitoring wells statistically significantly exceeded background concentrations. Concentrations in three of the monitoring wells exceeded the MCL of 10 mg/L. Movement of nitrate-contaminated water beyond the facility could not be determined due to lack of downgradient wells.

2. Pasco - A flow-equalizing storage pond provided winter storage. Additional land for processed water application increased the land application area by 208 ha to total 380 ha. Using additional land will reduce the hydraulic loading during the winter period of application which has been a 25-percent over-irrigation. During 1992-1994 groundwater was monitored for nitrate-nitrogen concentrations. Water from three of the ten downgradient monitoring wells exceeded background on a statistically significant basis at the 90% confidence level. Background nitrate-nitrogen concentrations in groundwater were quite high, so a causal relationships could not be made between the LTS spray field and surrounding water supply wells.
3. Richland - Reported to be modifying pretreatment and land application. Land for application was nearly doubled (73 to 134 ha). An advanced processed water treatment plant began operation in the fall of 1994 and began discharge to the Yakima River in the fall of 1995. The result will be substantially reduced hydraulic and nitrogen loads on the land application site in the winter and throughout the year. During 1993-1994 analysis of water from the five downgradient monitoring wells indicated statistically significant increases above background nitrate-nitrogen and routinely exceeded 10 mg/L.
4. Moses Lake - A processed water storage pond was constructed in 1994 and by 1995 winter application to land ended. The land for application was increased by 1,538 ha in 1993-1994. In 1996 the plan called for increasing the land area to total 2,915 ha. During 1993-1994 groundwater monitoring results were analyzed statistically, finding that nitrate-nitrogen increased above background concentrations at the 90% confidence level in two of the four downgradient wells. Groundwater in twenty-four of the forty surrounding water supply wells within a 0.62 Km radius of the permitted application field was analyzed for movement of nitrate-nitrogen beyond the LTS spray field. Three wells had elevated nitrate-nitrogen. Data for the remaining wells did not indicate increases under the current management practices.
5. Othello 1 - A storage pond constructed in 1989 enabled regulation of winter application from none to the maximum, depending upon low crop water need or frozen soil. Applying processed water to frozen soil is risky due to the potential for runoff. Soil monitoring is conducted annually to assess the potential for nitrate-nitrogen leaching to the aquifer. Soil monitoring was accepted as an alternative to monitoring wells. Fourteen water supply wells (agricultural irrigation) were located within 0.62 km of the LTS spray field. Nitrate-nitrogen concentrations from six wells near the LTS spray field (Cook, 1996) did not indicate a causal relationship between the spray field management and the nitrate-nitrogen concentrations.
6. Othello 2 - The irrigation system has been improved and the land application area increased from 202 to 1,498 ha. The storage lagoon was slated for replacement in 1996. Leakage from the existing unlined storage lagoon was being studied to determine the effect on

groundwater quality. Annual soil monitoring was required to determine the leaching potential of nitrate-nitrogen to groundwater. Groundwater monitoring was not required because of local hydrogeology. During 1994 sixteen surrounding irrigation and domestic wells were monitored for nitrate-nitrogen. Fourteen wells had no evidence of groundwater contamination due to the LTS spray field. Two wells had previous nitrate-nitrogen concentrations significantly greater than in the surrounding wells. This appeared to be a local effect.

According to Ecology's report (Cook, 1996) from 1990 to present (1996) the potato processing facilities operating within the Columbia Basin have adopted measures to reduce groundwater contamination by nitrate-nitrogen, both currently and in the future. These measures reduced the nitrogen applied to spray fields on average 48 percent thereby significantly decreasing the potential contamination of local and regional groundwater. The following practices were implemented by one or more of the facilities:

- Acquired additional land to apply processed water.
- Installed lined impoundment's for winter storage.
- Limited processed water application to agronomic rates during the growing season and either reduced or halted application during winter months.
- Employed additional pretreatment to the processed water to reduce the concentration of nitrogen compounds in applied process processed water.
- Installed comprehensive groundwater and soil monitoring networks to assess spray field (land application) management techniques.

Whereas there was local nitrate-nitrogen contamination, Cook (1996) did not find current evidence that spray field operation, past of present, caused contamination of offsite domestic wells or community water supply wells.

4.2.2.2 Fruit waste

The Tree Top LTS near Selah, Washington on the west bank of the Yakima River was selected by Ecology (Carey et al., 1994) for a study that was conducted June 26-December 7, 1992. The objectives were to determine 1) the effectiveness of the LTS in treating processed water in a typical setting for treating organic wastewater, 2) the effectiveness of lysimeters vs. wells for monitoring LTS, 3) the rate that liquid moves through the unsaturated zone, and 4) recommendations for improving the efficacy of the Tree Top LTS.

Wash water from fruit processing is a major kind of organic waste in central Washington. Such processed water from the Tree Top plant was applied to 146 ha of nearby cattle pasture to treat the processed water and irrigate the pasture. The pasture soil was determined to be alluvium with a shallow water table. Nearly 3,785,000 liters/day of processed water were applied during the study period. Processed water was mixed with irrigation water and applied with small sprinklers at intervals of 18-20 days. The average annual application was 170 cm. Twenty-seven percent of this was processed water. The total nitrogen application was estimated to be 10-34 kg/ha-day before sampling in July, August, and October. Total nitrogen concentrations in the wells often exceeded the barrel lysimeter values. Mean well values were quite stable for the four sampling dates at about 2-2.5 mg/L. Mean barrel lysimeter values were about 1-2.5 mg/L.

A general finding of the study was that monitoring the unsaturated zone was a more sensitive measure of nutrient loading to groundwater, based on comparing lysimeters and nearby shallow wells. Specifically for the Tree Top LTS, the study found that total N was treated in the top 46 cm of soil. Total nitrogen was treated 95% with a standard deviation of 6.8%. (This reviewer assumes 95% treatment is a 95% reduction of total nitrogen.) Nitrogen application rates were found to exceed monthly Ecology permit limits by 2-5 times. Managers must be aware that nitrogen can be over-applied if processed water and commercial fertilizer nitrogen rates are not planned jointly. Monitoring the unsaturated zone was recommended for the Tree Top LTS to help predict potential problems before groundwater is affected. These data can be used to assess LTS performance and modify management to improve treatment efficacy.

Most food processing wastes can be used on the land as a source of plant nutrients (especially nitrogen) and irrigation for crops (Smith and Peterson, 1982). The organic mater decomposes in the soil making nitrogen available. Nitrogen is seldom deficient to limit decomposition.

4.3 Criteria for determining land application rates

To avoid contaminating groundwater the manager/operator must follow the basic rule: Apply manure/waste/processed water at the rate calculated to meet the crop need for the grower's yield goal, while minimizing leaching of nitrate-nitrogen to the watertable. The crop production system affects the potential for groundwater contamination. Crop, rainfall, temperature, processed water, soil, and nutrient management are pertinent variables. The nutrient management plan consists of three functions that can be varied: application rate, application method, and timing of application.

The application rate is crucial to crop and water quality. It depends greatly on crop nutrient requirement (nitrogen here), soil nutrient content, and processed water nitrogen concentration.

The application method depends upon timing and processed water storage capacity (impoundment). Large scale application is feasible by irrigation equipment: center pivots and traveling big gun sprinklers, for example. Tankwagons (with or without injectors) and pumped injection with a large tractor pulling the injectors and supply hose are suitable for farm-scale operations, as are traveling big gun sprinklers.

Timing of application plays a key role in determining the application method. Timing is a function of waste storage capacity, labor, equipment, cropping schedule, and whether the soil is too wet, frozen, or snow covered.

The elements of the procedure for calculating the waste application rate to provide the design total nitrogen is outlined as follows:

1) Test soil and organic waste for N. Testing for P and K also will enable a more complete waste nutrient recommendation.
2) Account for nitrogen transformations and losses after waste is removed from storage and applied to cropland.

    Inorganic nitrogen gain

    a) Mineralization of organic nitrogen to ammoniacal-N.
    b) Nitrification of ammoniacal-N.

    Inorganic nitrogen loss

    a) Application loss by volatilization of ammoniacal-N.
    b) Immobilization due to crop residue.
    c) Denitrification of nitrate-N.

3) Determine waste application rate by dividing the nitrogen requirement of the crop for the specified yield goal by the nitrogen recovery efficiency (NRE)[1], or use recommendations based on fertilizer guides.

Regardless of the kind of organic waste, the procedure for calculating the N requirement and the waste application rate is the same whether the waste is liquid, semi-solid, or solid. The calculations can be made using a worksheet method or appropriate software. The procedure and detail are illustrated by reviewing and discussing software development and detailing a WSU program designed for manure that will work for most situations in Washington.

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[1] The nitrogen recovery efficiency (NRE) estimates the fraction of available nitrogen that is taken up by a crop for a given soil condition (Table 4.2). This is used to compute the nitrogen supply requred for the selected yield goal. NRE is equivalent to plant N uptake efficiency.

Land application software review

During the 1970's, Oregon State and Washington State Universities organized a working group to develop a manure nutrient management planning tool for the Pacific Northwestern States. Agronomists, Agricultural Engineers and Soil Scientists from both Universities met several times to develop a worksheet method for calculating manure application rates. The tables of coefficients and the calculation procedures were made into a worksheet method and published as a cooperative extension bulletin for the Pacific Northwestern States (Hermanson et al., 1983).

In the early 1980's the Soil Conservation Service (SCS) in Washington and the SCS National Technical Center in Portland, Oregon joined with WSU as a team to develop and program a manure nutrient management model to run on Nebraska's AGNET[2] system which operated in all Washington Cooperative Extension Offices. The program, WASTEAPP, was quite thorough and state-of-the-art. Extension agents and SCS personnel however, did not adapt quickly to the WASTEAPP and computer technology. Soon Washington State University Cooperative Extension (WSU-CE) developed its PC capability linked to the WSU mainframe computer, AGNET was replaced, and WASTEAPP ended.

Moore and Gamroth (1989) prepared a worksheet following the method and tables previously described (Hermanson et al., 1983). The model NCALC (Gamroth, 1991) was based on the Oregon State University bulletin (Moore and Gamroth, 1989). NCALC was designed for balancing the use of the manure resource. Many good models have been developed across the US and in other countries. However, a study of selected models found that significant features were not included to varying degrees. Inasmuch as the models did not have the desired utility, a team was formed at WSU to design and program a versatile, modern model. Manure Nutrient Balancer, MNB (Hermanson et al., (1995). Thompson et al., (1997) evaluated computer programs for calculating manure application rates to cropland. Twenty programs were obtained in 1995 and twelve were selected for rigorous evaluation. These used a diverse range of conventional programming languages and commercial developmental languages. The WSU program, MNB, compared favorably to the 12 models evaluated. MNB was designed for the Pacific Northwest, yet was rated as being widely useful. The evaluation was summarized in four tables (Tables 4.7 to 4.10) presented at the end of this section as useful model comparisons.

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[2] AGNET is an agricultural computer network at the University of Nebraska.

MNB can be used for many organic wastes and processed waters by testing them for N, P, and K, and by soil testing. These values and the volume or weight to be applied to land enable MNB to calculate the application rate for the desired crops. MNB is versatile and is designed so the user can change tabulated coefficients if necessary. Default values for application loss of ammonia and mineralization rate for the specific waste/processed water must be entered for best results. MNB includes nine kinds of livestock and poultry, twelve crops, three soil-climate zones, and ten fields. The user is guided to input relevant farm details such as livestock information, manure system components, manure and soil test data, crop yield goals, and previous three years of field history. From this information and stored tables of data, MNB recommends manure application rates.

Decisions on the land application of organic amendments such as animal manure, crop residue, treated municipal wastewater, biosolids, compost, food processing and other industrial waste as sources of crop nutrients are typically based on i) the crop demand for those nutrients, ii) the efficiency of crop nutrient recovery, iii) the inherent soil supply of the nutrients, iv) the predicted amount of nutrients supplied by the amendment, and v) the extent of nutrient loss, (Fig. 4.2 (Hermanson et al., 1995). Since the primary plant nutrients N, P, and K are often the most limiting nutrients in a crop production, the land application rate and timing are usually calculated to optimize one of these nutrients, however, the accompanying additions of the other nutrients should be considered to ensure proper rates of application of all elements contained in the processed water. For example, a rate of application based on N may cause excessive application of P which could potentially limit crop production or impose an environmental risk. The approach used in MNB for calculating nitrogen loading rates onto crop land integrates the five factors that were previously mentioned. This model can provide a framework for illustrating how a fundamental understanding of the N behavior in systems described in this review can be used as a theoretical foundation for making sound N-based recommendations.

MNB as a framework for calculating organic waste application rates

Manure Nutrients:

Some producers prefer a method that begins by estimating manure excreted daily and its properties. It then calculates collection and storage losses of nutrients to approximate the nutrients in storage available for land application. Three accepted sources of data on manure production and the percentage N, P, and K excreted are (ASAE Standards, 1993; Midwest Plan Service, 1985; and Soil Conservation Service, 1992). The latter two references also include their best estimates of losses from collection and storage; land application losses; and mineralization and denitrification rates.

However, it is strongly recommended that the user have a laboratory analysis, or at least a field test, conducted on the manure source to provide data that will allow calculation of nutrient content in useable units such as nitrogen in kg/1,000 liter and kg/Mg (or lb/1,000 gal and lb/ton) adapted from (Hermanson, 1996). Manure analysis is a key step in determining more accurate agronomic rates of application. MNB uses laboratory and field analyses of manure. The soil must also be tested for nutrients and organic matter. Two variables define the amount of nutrients N, P, and K in storage available for application to cropland. These are analyses of 1) manure nutrients and 2) the amount of stored manure (volume or mass) to be used.

Step 1: Analyze the manure source.

Laboratory measurement of N, P, and K in the manure, in combination with estimates of the amount of stored manure, will provide the best predictions of the quantity of nutrients available for application to fields. Several methods are available, ranging from complete laboratory analysis to quick field measurements. The use of these analytical tools is highly recommended over nutrient estimates from manure excreted and losses in storage. Information on laboratories that conduct manure analyses can be obtained from the local cooperative extension, conservation district, and NRCS representatives.

Standard manure tests are conducted by commercial or state laboratories for determination of nutrient concentrations. Total N, P and K concentrations can be determined, as well as ammonical-N (NH_4-N). Whereas these analyses are the most accurate, more time is required to obtain the results because of total turn-around time. The Nitrogenmeter or Agros meter (Agri-Waste Technology, Inc.) is a proprietary device that can be easily used onsite to measure the readily available ammoniacal-N. Another onsite method developed at North Carolina State University (Chescheir and Westerman, 1984) is the slurry meter, which was devised by Tunney (1979) and is a calibrated hydrometer that reflects the solids content of liquid manure. Nutrient concentrations can be predicted because they are related to the solids concentration. For this work, predictive equations were developed for dairy cattle manure using laboratory data from samples in Stevens and Spokane Counties in northeastern Washington. The predictive equations for nutrients in liquid swine manure were developed by Tunney (1979) and verified by Chescheir and Westerman (1984). The slurry meter is used only for liquid dairy cattle and swine manure.

Step 2: Estimate supply of manure nutrients.

The volume and weight of manure accumulated during the storage period can be determined from the dimensions of the storage. The NRCS or the local conservation district likely designed the storage/treatment facilities. If so, they can prepare a table or graph that will give the amount of manure as a function of storage depth. If they were not the designers, they or cooperative extension can develop the information needed. Nitrogen, phosphorus and potassium are usually reported by laboratories as percent or parts per million (ppm) for liquid manure and as percent for solid manure. Slurry meter results are in pounds/1,000 gallons which can be converted to kg/1,000 liter. Laboratories can also be asked to report kg/1,000 liter (pounds/1,000 gallons) or, for solid manure, kg/Mg (pounds/ton). These units of measure express concentration. Nutrient concentrations multiplied by the volume of liquid manure or the weight of solid manure estimate the total nutrients in the storage facility. These amounts of N, P, and K are available to be removed from storage and applied to fields.

Manure Application Rates:

The steps used by MNB to calculate agronomic rates of manure application for crop production are outlined in Figure 4.1. The MNB model bases recommendations on N, P, or K at the user's discretion. The approach differs for each nutrient chosen by the user.

Nitrogen Basis for Determining Manure Application Rates:

The nitrogen recommendations are computed based upon the crop requirements for nitrogen and the deficit in the soil N supply. Figure 4.1 outlines the different sources of N supply that are considered by MNB and the steps involved for computing the manure rates.

Step 3: Estimate crop N requirement.

MNB estimates crop N accumulation based on yield goal, the N accumulation per unit of crop, and nitrogen recovery efficiency (NRE) provided in Table 4.4. Recovery depends on crop and soil characteristics (Bock and Hergert, 1991). While MNB provides default values for N accumulation per unit of crop, regional data can be substituted if they are available from other sources such as NRCS or Cooperative Extension. Crop species differ in N uptake efficiency, due to differences in rooting characteristics and N demand. For example, perennial grasses exhibit high NRE potential while shallow rooted crops such as onions have lower NRE potential. Soil conditions also influence NRE. For example, NRE values are predicted to be low in poorly drained soils to account for denitrification losses which are higher than in well drained soil. NRE and denitrification are a function of soil aeration which is represented here by drainage class: well drained, moderately well drained, and poorly drained.

There are various soil sources of N that should be taken into account in formulating an N fertilizer recommendation. MNB computes contributions from these sources, based on soil test and cropping history information. Sources include organic matter, residual N, previous crop residue, and previous manure application. The net difference between the N supply and crop demand is the estimate of N to be supplied as manure or inorganic fertilizer.

Step 4: Estimate soil N sources (CREDITS) and N sinks (DEBITS).

There are several soil sources of N to account for in formulating an N fertilizer recommendation. MNB computes contributions from these sources, based on soil test and cropping history information.

Nitrogen CREDITS or DEBITS toward the total N supply are based on the following factors.

a) Inorganic N. (NO_3-N and NH_4-N) in the soil profile to the depth of rooting, which varies by crop. Consult your soil test laboratory, NRCS or WSU CE representatives for assistance in calculating total inorganic N that is available to the depth of rooting.
b) N mineralized from the soil organic matter. Organic matter mineralization is based on the percent organic matter of the soil and the soil moisture condition. Since organic matter decomposition varies considerably under aerobic and anaerobic conditions, MNB uses different mineralization coefficients for the three kinds of soils i.e. well drained, moderately well drained, and poorly drained.

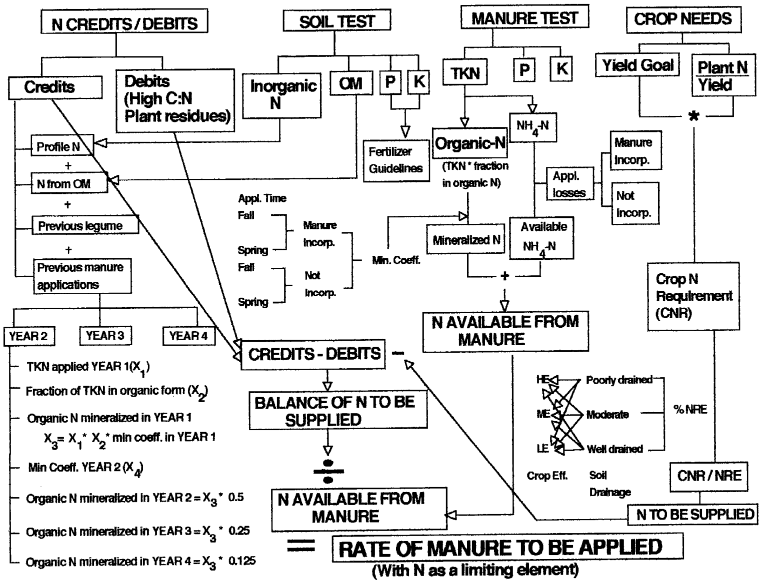

Figure 4.1. Steps for calculating agronomic rate of manure application.

c) Previous legume contribution. The N credits for a previous legume crop in the rotation vary with crop and region. For example, it varies from 20 lb N/ac for peas yielding >2000 lb/ac in Eastern Washington to 50 lb N/ac for alfalfa stubble/beans/peas in Central Washington.

Calculate nitrogen debits that decrease total N supply.

d) Nitrogen immobilization. Incorporation of previous crop's residue will tie up a fraction of the inorganic N into organic N forms, due to enhanced microbial activity. The amount of N that is likely to be tied up in this process varies with the quantity and composition of crop residue. Hence, some of the applied N is held by the previous crop's residue. MNB varies N immobilization estimates from 20 lb N/ac for wheat/barley residues in Eastern Washington to 60 lb N/ac for corn/small grain residue incorporated in Central Washington.

Table 4.4 Nitrogen Recovery Efficiency[3] For Different Groups of Crops and Soil Conditions (Modified from Bock and Hergert 1991).

	Nitrogen Recovery Efficiency		
Soil	High	Moderate %	Low
Aerated/well drained	75	55	45
Moderately well drained	70	50	40
Poorly drained	65	45	35
		Crop Groups	
	High	Moderate	Low
	Orchard grass	Barley	Asparagus
	Alfalfa grass mixture	Wheat	
	White clover grass mixture	Canola	
	Red clover grass mixture	Potato	
	Alfalfa	Corn grain	
	Corn silage	Hops	

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[3] The nitrogen recovery efficiency (NRE) estimates the fraction of available nitrogen that is taken up by a crop for a given soil condition (Table 4.2). This is used to compute the nitrogen supply requred for the selected yield goal. NRE is equivalent to plant N uptake efficiency.

Step 5: Estimate N fertilizer recommendation.

The net balance of N gains and losses (CREDITS and DEBITS) is subtracted from the crop N to be supplied as manure or inorganic fertilizer. The program determines manure application rates and allocations for each field, then rates of additional nutrients (N, P,K) required as mineral fertilizer and of excess nutrients are given.

Step 6: Estimate N release from manure.

Manure-N has two components: the ammoniacal-N (NH_4-N) and the organic-N. Laboratory analyses are recommended for both total Kjeldahl nitrogen (TKN) and ammoniacal-N. Subtract ammoniacal-N from TKN to get organic-N. If ammonical-N is not determined, MNB estimates it. Ammonical-N is readily lost by volatilization, so the loss is accounted for. MNB credits the ammoniacal-N remaining after application losses as plant-available N during the cropping year after application. The application losses vary depending upon whether the manure is incorporated. Only a fraction of the organic-N is available to the crop during the cropping year after application. This is predicted using N mineralization coefficients (Midwest Plan Service, 1985; Soil Conservation Service, 1992). During the years following the manure application, decreasingly smaller fractions of organic N are available to the crop. These residual contributions last for about 3 years with heavy rates of manure application. The mineralization coefficients vary with livestock species, whether manure is liquid or solid, whether it is soil incorporated, and the season of application (Midwest Plan Service, 1985). Table 4.5 was developed by the Midwest Plan Service (1985), an organization of 13 Midwestern Land Grant Universities, as representative organic nitrogen mineralization factors (coefficients). It summarizes the dimensionless fraction of organic N mineralized (released) during the first cropping season after manure application. Applications 1, 2, and 3 years before the current year of application are mineralized about 50%, 25%, and 12.5%, respectively, of the mineralization factor for the first cropping season. The fraction of ammoniacal-N that remains after application losses and the fraction of organic N that mineralizes during the application year constitute the total available N from the manure.

Cogger et al., (1987) in a worksheet method of calculating sludge application rates estimated first-year mineralization fractions as 0.20 for anaerobic digestion, 0.30 for aerobic digestion, and 0.08 for composting treatments. For all sludges, 1, 2, and 3 years after the year of application, use 0.03. Washington State biosolids guidelines (Sullivan, 1993) estimate 0.08, 0.03, and 0.01 of the organic N originally applied mineralizes 1,2 and 3 years after the year of biosolids application. The 1993 recommendations reflect additional research since the 1987 recommendation by WSU-CE. Dimensionless first-year mineralization factors from the

Washington State biosolids guidelines are given in Table 4.6. Although the biosolids factors are similar to manure factors, the best results will be obtained by changing the MNB default mineralization factors.

Organic nitrogen mineralization rates were available for biosolids and manure. These are given in Tables 4.5 and 4.6. Values were not found, however, for other waste and processed water. Although the rates tabulated can be used to approximate rates for other waste/processed water, accurate application rate predictions require mineralization rates developed by research. If application rates of organic nitrogen are the same year-after-year, the mineralization rate approaches 1.0 (100%). This continuum eliminates the need to apply mineralization rates for each previous year. Rather, the factor 1.0 (100%) is appropriate. It means the current year application of organic nitrogen will all be mineralized on the average. The mineralization factor 1.0 for approximately constant annual organic nitrogen application rates over several years (10 years) allows use of the factor 1.0 without need to conduct research for the annual factor and the cumulative mineralization of preceding years. With a mineralization factor of 1.0 and an application loss based on Tables 4.2 and 4.3, a good prediction of the nitrogen application rate to use can be made with MNB.

Table 4.5. Manure Organic Nitrogen Mineralization Factor: Dimensionless First-Year Values

	Manure	Incorporated		Not Incorporated	
Livestock	Type	Fall	Spring	Fall	Spring
Beef	Liquid	0.30	0.25	0.25	0.20
	Solid	0.25	0.20	0.20	0.15
Dairy	Liquid	0.30	0.25	0.25	0.20
	Solid	0.25	0.20	0.20	0.15
Fryer/Broiler	Litter	0.25	0.20	0.20	0.15
Horses	Solid	0.20	0.15	0.15	0.10
Layers	Solid	0.30	0.25	0.25	0.20
Sheep	Solid	0.25	0.20	0.20	0.15
Swine	Liquid	0.30	0.25	0.25	0.20
	Solid	0.50	0.45	0.45	0.40
Veal	Liquid	0.30	0.25	0.25	0.20

Step 7: Compute the manure application rate.

MNB calculates the recommended manure application rate as the N recommendation divided by the amount of N released per unit of manure applied (Fig. 4.1).

Step 8: Compute excess P or K applications.

When manure rates are computed with N as the limiting nutrient element, it is possible to under- or over-apply P and/or K. MNB computes the imbalance of P and K that results from the manure application. In regions where P pollution of the environment is a problem, manure rates should be computed with P as the limiting element. MNB computes P and K fertilizer recommendations based on soil test results and WSU fertilizer guide recommendations. Recommended P and K fertilizer rates are compared to P and K released from manure which is calculated from the quantity of manure recommended based on N and multiplied by the P and K concentrations in the manure then by the P mineralization coefficient derived from the literature (Midwest Plan Service, 1985; Soil Conservation Service, 1992). K is not mineralized because it is not in the organic form.

Table 4.6 Biosolids Organic Nitrogen Mineralization Factor: Dimensionless First-Year Values.

Processing Method	Mineralization Factor
Anaerobic digestion	20-40
Aerobic digestion	30-45
Aerobic/Anaerobic digestion and >6 months lagooning	15-30
Anaerobic digestion and dewatering	20-40
Drying bed	15-30
Heat drying	20-40
Composting	0-20

Step 9: Phosphorus or potassium basis for determining manure application rates.

MNB requires P and K soil test information to calculate manure application rates based on these essential nutrients. WSU recommendations of P and K rates for different soil test levels are summarized in MNB Tables 5-8 (Hermanson et al., 1995). Next determine the P and K available from the manure. MNB calculates the recommended manure application rate as the recommended P or K fertilizer recommendation divided by the amount of P or K released per unit of manure applied. Supplemental N fertilizer may be required when manure application rates are based on P as the limiting element. MNB calculates needed N supplements or excess quantities applied by comparing the N released from the manure to the N recommendation.

Timing and Storage

Timing of application of organic waste/processed water to land:

- Consider organic nitrogen mineralization rates and apply as close as possible to time of crop nitrogen need. Use crop growth curves.
- Generally, organic nitrogen applied in the fall, especially in early fall, can mineralize and nitrify so nitrate-nitrogen may be available to leach to the watertable. A cover crop to scavenge nitrogen in the rootzone is important, especially in western Washington where mineralization and nitrification are quite complete due to warm soil. Regardless, in Western Washington any residual nitrate-nitrogen in the soil profile will be flushed by winter rains to contaminate groundwater.
- Organic wastes shall not be applied to frozen, snow covered, or saturated soil to prevent runoff and surface water contamination.
- Storage of waste (processed water) is usually necessary during the winter when the soil is frozen, snow covered, or saturated (Soil Conservation Service, 1993). Wastewater storage is usually in anaerobic or aerated storage lagoons, but, depending upon the volume it can be in other structures. Waste in a solid form is stored on a relatively impervious surface with a roof if needed because of precipitation.

Timing is not the same for all LTS. It is specific to:

- Climate
- Soil
- Crop
- Wastewater

The need for storage impoundments (variety of storages) or storage of nitrogen in the soil during the likely non-application season (fall-winter) can be determined by a mass balance analysis of nitrogen and water year-after-year (weekly, or as appropriate) as a predictive tool and for a permanent record. Monitoring wells are not good indicators because groundwater is massive and moving making accurate interpretation of data difficult or impossible. Monitoring wells are useful, however, to measure long-term effects on groundwater. The better method is by analysis of soil to track nitrate-nitrogen in the soil profile, and by collecting soil water in lysimeters in the soil profile.

Recommendations for Land Application of Organic Wastes

1) Use a science-based method to calculate an N balance that provides for crop requirements and accounts for N losses and gains before determining the waste application rate. This N balance minimizes the leaching of nitrate to groundwater. The procedure can be a worksheet or software such as MNB. Follow Washington State Guidelines that regulate the use of biosolids (Sullivan et al., 1993).
2) Irrigation must be scheduled scientifically to maintain the correct water balance and provide only enough deep percolation for leaching salts from the soil profile. Include irrigation water as a source of N if significant.
3) Timeliness of application with respect to stage of crop growth, season and whether soil is too wet, frozen, or snow covered to apply waste/processed water to land is a good practice that reduces and prevents water contamination to benefit society.
4) Keep records of waste and processed water applications (nitrogen and water application rates), crop harvested, nitrate-nitrogen in soil profile and water analyses. Ideally, the records would enable a nitrogen balance: inflow = outflow + storage in the soil. Software can be made to keep all records and calculate results.
5) Design a waste and nutrient management plan. The key to success is following the plan.

Table 4.7. Programs examined that determine dairy manure application rates - authors, source, cost, year of release, and hardware and software requirements

Program	*Institution of primary author/s*	*Authors*	*Institution selling the program -Name and address*	*Institution selling the program - Tel. and FAX No's*	*Cost (US$)*	*Year of release of current version*	*Hardware requirements (IBM compatible PC's)*	*Software requirements*
AMANURE (v2.02)	Purdue Univ., West Lafeyette, IN, USA	A. Sutton, D. Jones, B. Joern	Farm Bldg Plan Serv, Purdue Univ., 1146 Ag.Engr, W. Lafeyette IN 47907	Tel: 317-494-1173	15	1994	IBM compatible PC RAM: ≥512Kb	MS-DOS
Cornell nutrient management planning system	Cornell Univ., New York, NY, USA	S. Klausner, T. Tylutki, D. Fox, M. Barry	S. Klausner, Dept Soils, Crops and Atmos Sci, Cornell Univ, Ithica, NY 14853	contact S. Klausner Tel: Fax 301-314-9041	not defined	expected release: Summer 1996	Recommend 486DX or Pentium; 8 Mb of HD; 8 Mb RAM, 4 OK with virt. mem.	Windows 3.1, or Windows 95
Fertrec Plus v2.1	Univ. of Maryland, MD, USA	Steffi Li , Paul Shipley, F. Coale, P. Steinhilber, Alen Bandel,	Dept. of Agron, Univ of Maryland, 1103 H.J.Patterson Hall, College Park MD 20742	Paul Shipley, Tel: 301-405-2563 Fax: 301-314-9041	15	1996	286 or greater; HD: 3.5—5.0 Mb; Requires printer with capacity for landscape	MS-DOS?
Manure Application Planner v3.0; (MAP v3.0)	Univ. of Miinnesota, St.Paul, MN, USA USA	M. Schmitt, R. Levins, D.W. Richardson	Ctr for Farm Financial Management, Univ of Miinnesota, 1994 Buford Ave, St. Paul, MN 55108	Tel: 612-625-1964, or 1-800-234-1111	?	1995	386 or greater; RAM: 2 Mb , preferably 4 Mb; HD: 2Mb of space	MS-DOS 3.2 or higher, preferably 6.0 or higher
Manure Nutrient Balancer; (MNB)	Coop. Ext., WSU Pullman, WA, USA	R. Hermanson, A. Rao, W. Pan, K. Duncan, M. Wright	Bull Office, Coop Ext, Cooper Publ Bldg., WSU, Pullman, WA 99164—5912	Ron Hermanson, Tel: 509-335-2914, FAX: 509-335-2722	25	1995	IBM compatible PC; RAM: =512Kb; HD: 482 Kb	MS-DOS 3.3 or higher
Michigan State University Nutrient Management v1.1; (MSUNM v1.1)	Michigan State Univ., East Lansing, MI, USA	B. MacKellar, L. Jacobs, S. Bohm	MSU Bull Office, 10-B Ag Hall, Michigan State Univ, East Lansing, MI 48824-1039	FAX: 517-353-7168	75	1995	286 or greater; RAM : =512Kb; HD: 10Mb recommended	MS-DOS 3.3 or higher, 5.0 recommended
OMAF Nutrient Management Computer Program; (NMANPC)	Ontario Min. of Ag. Food and Rural Affairs, Woodstock, Ontario, Canada	D. Hilborn, C. Brown	Ontario Min of Ag Food and Rural Affairs, P.O. Box 666, Woodstock, Ontario N4S 7Z5, Canada	Don Hilborn Tel: 519-537-6621 1-800-265-7896 FAX: 519-539-5351	30	1995, updated release in 1996	IBM compatible PC	MS-DOS
Program	*Institution of primary author/s*	*Authors*	*Institution selling the program -Name and address*	*Institution selling the program - Tel. and FAX No's*	*Cost (US$)*	*Year of release of current version*	*Hardware requirements (IBM compatible PC's)*	*Software requirements*

Penn. State University — Nutrient Management Plan; (PSU-NMP v1.1)	Pennsylvania State University, Pennsylvania, USA	D. Beegle, P. Bohn	Dept. of Agron, Penn. State Univ, 116 ASI Bldg, University Park, PA 16802	P. Bohn, Tel: 814-865-3774 FAX: 814-863-7043	50	1995	386 or greater; HD: 4 Mb ; RAM: 640 Kb (485 free)	MS-DOS 3.3 or higher
UGFERTEX v1.0	Cooperative Extension, University of Georgia, Athens, Georgia 30602, USA	C. O. Plank, S.C. Hodges	Coop Ext, The Univ of Georgia, Ag.Bus Office Conner Hall, Athens, Georgia 30602	Tel.: 706-542-8999 FAX : 706-542-2378	$10	1990, updated Windows version in '96	IBM compatible PC; RAM: 256Kb	
Vermont Manure Nutrient Manager; (VMNM)	UVM Extension, University of Vermont, Burilington, Vermont, USA	W. Jokela, J. Rankin, S. Hawkins	UVM Ext, Plant and Soil Sci Dept, Univ of Vermont, Burlington, VT 05405.	W. Jokela; Tel: 802-656-2630	No Cost	1993	IBM compatible PC	
WEES?	Silsoe Research Institute, Wrest Park, Silsoe, Bedford MK45 4HS, England, United Kingdom	T. Cumby in England; US contact: F. Wolak[1]	F. Wolak. Dept. of Ag. and Biol. Engr, Clemson Univ, Clemson, SC 29634, USA	F. Wolak			IBM compatible PC?	MS-DOS?
WISPER[1] v 2.12	Soil & Plant Analysis Lab. Uni.versity of Wisconsin - Madision, Wisconsin, USA	S. Combs, S. Bullington	WISPLAN, Comp Serv, 1575 Obs. Dr, Madison, WI 53705	Tel: 608-262-4552	75	199?	IBM compatible PC; RAM: 460Kb; HD: 760 Kb	

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[1] Wisconsin Interactive Soils Program for Economic Recommendations

Table 4.8 What the programs do - general

Program	***Type of program; underlying software***	***Max. no. of fields per farm***	***Program generates nutrient requirements of crops?***	***Program estimates amount of stored manure available for land application[1]?***	***Manure nutrient composition: program estimates, default used or user inputs.***	***Economic analysis of manure application***	***Automatic allocation of a known quantity of manure to multiple fields. What options for prioritizing fields?***
AMANURE	menu-driven; Compliled spreadsheet (Lotus 2..01 or similar)	1, can be a group of fields	For N, P_2O_5 and K_2O; P_2O_5 and K_2O are determined from soil test	From animal no.'s and standard excretion values and the collection period	User accepts default values or enters results from laboratory analysis.	No economic analysis done	Not applicable, only considers one field or one group of fields.
Cornell	dialog box driven Windows? program; MS FoxPro database v2.6	No defined limit	For N, P, K, Zn, B and lime requirements.	From dimensions, no. of loads, or standard excretion values. The latter considers animal no.'s, collection periods, washwater, run-off and bedding	User enters results from laboratory analysis.	No economic analysis done	Based on N, P or K. Considers hydrological sensitivity ratings entered by user.
Fertrec Plus v2.1	menu-driven; Database (FoxPro)	No defined limit	For N, P, K, & Mg; can also do lime, Mn, Zn, S and B.	Program does not consider the amount of stored manure	User enters results from laboratory analysis.	Determines reduced fertilizer cost achieved by using manure nutrients	Not applicable, considers multiple fields but does not consider the amount of stored manure.
MAP v3.0	menu-driven; Pascal	50	User encouraged to enter; can estimate nutrients removed by crop	Recommends user determines from dimensions; can determine from animal no's and std. excretion values but no provision for washwater, rainfall, bedding etc.	Recommends user enters results from lab. analysis; can estimate from std. excretion values with storage N loss factor but no dilution considered.	Considers hauling & application costs of manure app. *c.f.* mineral fertilzer costs application app	Most economic use of manure nutrients, considers cost of hauling and spreading manure and cost of purchase and applying mineral fertilizer
MNB	menu-driven; Vermont views, MSC programed????	10	For N, P_2O_5 and K_2O; all from soil test	Recommends user determines from dimensions; can estimate "as excreted" amount from animal no's and std. excretion value.	Recommends user enters from lab. analysis; can estimate "as excreted" content from std. excretion values applying collection & storage N losses. factor.	No economic analysis done	User manually prioritizes fields; program allocates manure on basis of selected nutrient. For each field user enters % need for selected nutrient to be met by manure.
MSU v1.1	menu-driven; Clipper 5.0	No defined limit	For N, P_2O_5 and K_2O; P_2O_5 and K_2O are determined from soil test	From No. of loads in previous year	User enters results from laboratory analysis, or can use averaged from previous years' manure analyses	Determines reduced fertilizer cost achieved by using manure nutrients	Allocates manure on N, P or K basis, or max. rate/min. area (meeting N, P or K needs), or on most economical use of manure nutrients re. reduced fertilizer costs.

OMAF Nutrient Management Computer Program; (NMANPC)	menu-driven; turbo BASIC	10	For N, P_2O_5 and K_2O; all determined from soil tests. Default values for crop types available	Uses MSTORPC (Table 1c); from dimensions, and from animal no's, std. excretion values, washwater and rainfall. Determines required size of storage.	User enters results from laboratory analysis or from a quick test based on electrical conductivity, or selects from 400 manure analyses in databank.	Determines reduced fertilizer cost achieved by using manure nutrients	User manually prioritizes fields. Program allocates manure to fields in selected order until all manure has been applied.
PSU-NMP	menu-driven ; MS FoxPro 2.6 Database	No limit	Yes	User can input; or program estimates from animal no.'s, std. excretion values, washwater, run-off, rainfall, evaporatiion using county climate data.	Accept default or enter lab. results, or program estimates from animal no.'s, std. excretion values, washwater & run-off, using county climate data.	No economic analysis done	Automatic - for selected fields, ranked by highest requirement for selected nutrient. Manual - user accepts/rejects sequential suggestions for individual fields.
UGFERTEX	menu-driven; Expert system written in Prolog	1, can be a group of fields	For N, P_2O_5, K_2O, Ca, Mg, Zn, Mn; can for B and S; all but N and S from soil test	Not applicable. The amount of manure is not considered.	User can accept default, or enter results from laboratory analysis.	No economic analysis done	Not applicable, does not consider amount of manure nor more than one field or group of fields
VERMONT	spreadsheet; Lotus 2.2	30	User enters crop nutrient requirements for N, P_2O_5 and K_2O.	Uses Dairy Man. Pr. Estimator (Table 1c); from animal no.'s, std. excretion values, milk prod. levels, confinement period, washwater, run-off, ave. rainfall & evapor.	User can accept default, or enter results from laboratory analysis.	Determines reduced fertilizer cost achieved by using manure nutrients	Does not allocate manure, but does monitor the quantity of stored manure available. The amount is reduced as a rate is determined for each field.
WISPER	menu-driven, text-based ; written in FORTRAN & Microsoft C	15	For N, P_2O_5, K_2O; can also do pH, Ca, Mg, B, Zn, S; all but N from soil test	solid - animal numbers, std. excretion values; liquid - storage volume, % filled, times emptied	User can accept default, or enter results from laboratory analysis.	Per field and farm saving of fertilizer costs by using manure	Determines rates for multiple fields on basis of crop N, P or K requirement, but does not consider amount, and does not prioritize fields.
WEES	menu-driven; Crystal expert sytem shell						NO

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[1] User can replace with own values.

Table 4.9. Input data for determining crop nutrient requirements and describing manure composition; application methods and availability factors

Program	***Crop nutrient requirements - field, cropping and soil data used***	***Dairy manure types or storage systems***	***Manure nutrient composition: input data required***	***Manure nutrient composition: units***	***Methods of manure application***	***Potential nutrient availability (%) in year of application;***	***NH_3 loss from surface application: no incorporation***	***NH_3 loss from surface applic.: incorporated in < 1 day***
AMANURE	Crop type, yield goal, soil tests for P and K ?	solid (pack), liquid-tank, liquid-lagoon, daily scrape & haul	total N, NH_4^+-N, P_2O_5, K_2O,	liquid: lbs/1000gallons solid: bs/wet ton	surface - no inc.; surface - inc. <1 d; injection; sprinkler irrigation	Org. N: 30%; P: 100% K: 100%	of total N: solid - 25% liquid - 20% sprinkler - 40%	of total N: 3% 3% 3%
Cornell	Crop type and expected yield in context of the crop rotation; soil type; soil tests for P, K, Zn and B.	Any	total N, NH_4^+-N, P, K, dry matter	liquid: lbs/1000gallons solid: lbs/wet ton	not defined	Org. N: 35% P: 100% depends on soil test P value; K: 100%	of NH_4^+-N: half-life of 3.5 days, 75% in 7 days.	of NH_4^+-N: Spring 35%; Fall & Winter: 100% (other N losses)
Fertrec Plus v2.1	Crop type, yield goal, tillage methods, manure applications in previous 3 years, legume in previous year; soil tests for P, K, Ca, pH, organic matter, texture	liquid, solid	total N, NH_4^+-N, P_2O_5, K_2O, Ca, Mg, S, Mn, Zn, Cu, dry matter	% wet weight	Surface — user enters no. of days to incorporation; injection.	Org. N: 35%; P: 100%; K: 100%	of NH_4^+-N: 100%	of NH_4^+-N: 20%
MNB	Crop type, yield goal, soil drainage class, previous crop. Soil tests for inorganic N (pre-plant), soil organic matter, P and K. Can also do Zn, Mn, Fe and Cu from soil test, which next version will not	liquid, solid, liquid and solid after mechanical separation	total N, NH_4^+-N, P_2O_5 or P; K_2O or K;	liquid: ppm, %, lb/1000 gallon; solid: lb/ton, ppm, % (wet/dry)	surface/sprinkler: no inc.; surface/sprinkler immediate inc.; injection; sprinkler: dilute liquid	Org N: 15-30% — solid/liquid, season, incorp. or not; P: 70%; K: 70%	of total N: 20%	of total N: 5%
MSU v1.1	Crop; expected yield; Soil tests: pH, lime index, Bray P, K, Ca, Mg	solid with bedding, solid without bedding, liquid (anerobic), liquid (flushed)	total N, NH_4^+-N, P_2O_5, K_2O, dry matter;	liquid—lbs/1000gallons solid—lbs/wet ton	surface no inc.; surface inc 0-1, 2-3, 4-7, >7 days; injection	Org N 25-35% — solid/liquid, bedding; P: same as fertilizer; K: same as fertilizer	of NH_4^+-N: 90%	of NH_4^+-N: 30%

Ontario	Either (i) crop type and yield and soil tests for N, P and K; or (ii) crop removal data based on crop type and yield	liquid, solid, liquid and solid after mechanical separation	total N, NH_4^+-N, P, K dry matter; electrical conductivity is optional as quick test	liquid—lbs/1000gallons solid—lbs/wet ton	surface no inc - Spring or Fall; surface inc. in 1,2,3,4 or 5 days; injection; irrigation (spri)	Org. N: 5 -30% — solid or liquid, DM P: 40%; K: 90%	of NH_4^+-N: 40%	of NH_4^+-N: 20%
PSU-NMP	Crop; expected yield, soil test data (optional???);	solid; liquid; irrigation water (sprinkler)	total N, P, and K.	solid: lbs per ton liquid : lbs per 100 gallons; irrigation: ppm	customizable; default options are: surface - no inc. inc in <1, 2-4, 5-6 d; irrigation; Fall -diff	Total N availabilty: customizable for application method; P: 100%; K: 100%	Total N availabilty customizable, default total N availabilty — 20%	Total N availabilty customizable, default total N availabilty - 40%
UGFERTEX	Crop type; expected yield; Soil management group; Soil tests for P and K;	slurry, FYM	total N, NH_4^+-N, P_2O_5, K_2O, dry matter	liquid: lbs/1000gallons FYM: lbs/wet ton	surface - no inc.; surface - immediate inc.; surface - inc. <2, <4 days; injection;	Org. N: 50% P: 100%; K: 100%	of NH_4^+-N: 80%	of NH_4^+-N: 30% within 2 days
VERMONT	User enters crop nutrient requirements.	liquid, solid	total N, NH_4^+-N, P_2O_5, K_2O, Mg, dry matter	liquid: lbs/1000gallons solid: lbs/wet ton	Spring: surface - no inc & inc. 1-7 days; Autumn: surface - inc. <2, >2 d; injection	Org. N 18-40% - soil drainage & manure DM; P 80%; K 100%	of NH_4^+-N: 100%	of NH_4^+-N: 20%
WEES								
WISPER	Crop type, expected yield, soil texture; soil series; Soil tests for P, K, pH, soil org. matter, sample density, SMP buffer pH; can do Ca, Mg, B, Zn, S	liquid, solid	available N, available P_2O_5, available K_2O, available S	liquid: lbs/1000gallons solid: lbs/wet ton	surface - no inc.; surface - immediate inc.; injection	Total N 35% P: 55% K: 75%	of total N: 5%	of total N: 0

Table 4.10 Additional features - rate of manure estimation, data handling characteristics, options for altering assumed values, provision of a manual and distinguishing features

Program	*Approaches for determining manure application rate*[a]	*Limits or warnings for excessive applications of manure nutrients*	*Determines no. of loads to individual fields*	*Enables examination of what-if scenarios for factors affecting manure applic. rates*	*Provision for saving input and output data*	*Can alter factors used in calculations e.g. N availability*	*Is a detailed manual provided with the software?*	*General nature of program and distinguishing features or characteristics*
AMANURE	Crop requirements for N, P or K, Minimum area (based on N, P or K) max fert. value (based on N, P or K); user can enter rate	Warning when >150 lb N/acre, Dept. Environ., Indiana	determines distance spreader travels	Yes, but requires re-entering all data that is input subsequently to the altered data	NO	NO	2 pages of instructions. Note, is a simple program.	Practical program for determining manure application rates to a single field
Cornell	Crop requirements for N, P or K	Limits that vary with crop type.	Yes	Yes, done rapidly	Both input and output data can be saved.	NO, these values are fixed.	Currently resource manuals only.	Very comprehensive. Based on crop & soil nutrient management, and animal nutrient management.
Fertrec Plus v2.1	Crop requirements for N, P or K	No specific warnings or limitations; max. rate set by which nutrient selected for crop requirements	NO	Yes, can alter values and very quickly run the changed scenario	All input and output data is saved in one database	Enter % of manure org. N miner/ed in current year; can alter %'s of NH_4^+-N volatilized as NH_3.	67 page indexed manual.	Comprehensive program for strict nutrient management in an environmentally sensitive area.
MAP v3.0	minimal cost for hauling & spreading manure and purchase & application of fertiliser; or user enters rate	user specifies max. rate P_2O_5; this limits manure application rate	NO	Yes, can be done rapidly	Yes, separate files for each farm	Nutrient availabilities, prices, can add application methods specifying N losses	88 page manual, screen by screen approach	Very easy to use, generates manure application rates rapidly. Economic analysis includes application costs. Adaptable to other regions.

Table 4.10 Additional features - rate of manure estimation, data handling characteristics, options for altering assumed values, provision of a manual and distinguishing features

Program	*Approaches for determining manure application rate*^{a}	*Limits or warnings for excessive applications of manure nutrients*	*Determines no. of loads to individual fields*	*Enables examination of what-if scenarios for factors affecting manure applic. rates*	*Provision for saving input and output data*	*Can alter factors used in calculations e.g. N availability*	*Is a detailed manual provided with the software?*	*General nature of program and distinguishing features or characteristics*
MNB	Crop requirements for N, P or K	Calculates rates of N, P and K in excess of crop requirements, issues N and P warnings restrictions or;.	NO	Yes, can be done rapidly	Input and output data saved in a separate file for each farm	N loss following applic; storage losses; mineralization of N in application year; crop requirements	42 page manual, screen by screen approach	Easy to use, practical program for determining crop nutrient requirements and manure application rates for a whole farm
MSU v1.1	Crop requirements for N, P or K, Minimum area (based on N, P or K) Max. fert. saving (based on N, P or K)	restrictions based on Bray P1 soil test result (lbs/ac);	Yes, and for previous manure app's, user can enter No. of loads	Yes, may involve working through the tiered structure of the program	Yes, separate files for each farm	NO	220 page detailed manual, screen by screen approach	Comprehensive nutrient management program for a whole farm. Has extensive record-keeping facilities.
Ontario	Lowest application rate of 75 or 100% of crop N requirements or crop P requirements. User can enter.	several levels of warning for excess nutrient rates. liquid applications >20,000 gal/acre not permitted.	NO	Yes, can be done rapidly	Saves output files.	User cannot alter. Author will change on request.	2 pages of instructions. 40+ HELP screens, demo. program	Easy to use yet comprehensive program. Addresses a variety of information requirements. Can handle sludges (heavy metals).

Table 4.10 Additional features - rate of manure estimation, data handling characteristics, options for altering assumed values, provision of a manual and distinguishing features

Program	***Approaches for determining manure application rate***[a]	***Limits or warnings for excessive applications of manure nutrients***	***Determines no. of loads to individual fields***	***Enables examination of what-if scenarios for factors affecting manure applic. rates***	***Provision for saving input and output data***	***Can alter factors used in calculations e.g. N availability***	***Is a detailed manual provided with the software?***	***General nature of program and distinguishing features or characteristics***
PSU-NMP	Crop requirements for N, P or K ; considers spreader capabilities for practical application rates.	customizable; default excess rates per acre: 25 lbs N, 100 P_2O_5 and 125 lbs K_2O.	Yes; can estimate spreader capacity; considers max., min. rates of spreader	Yes, can be done rapidly	Yes, all input data and output can be saved	N availabilities for applic. method; allowed excess; add application methods specifying N availabilities	Manual; extensive context sensitive HELP within program.	Comprehensive nutrient planner; many customizable lookup values; adaptable to other regions; many additional functions; very versatile
WEES								
UGFERTEX	Crop requirements for N only	None, cannot exceed crop N requirements. No restrictions on P	NO	Yes, can be done rapidly	NO	Cannot alter assumed values. However, many default and calculated values can be altered.	23 page manual	Simple and easy to use program for crop nutrient recommendations and manure application rates for a single field.
VERMONT	Crop requirements for N, P or K	Informs of rates of nutrients in excess of crop requirements	Yes	Yes, changing an input in the spreadsheet alters all subsequent values	Yes, input and output for 30 fields saved in worksheet	NO	4 pages of instructions; this is a relatively simple program	Practical program for determining manure application rates; considers previous manure and fertiliser applications in same cropping year.

Table 4.10 Additional features - rate of manure estimation, data handling characteristics, options for altering assumed values, provision of a manual and distinguishing features

Program	***Approaches for determining manure application rate***[a]	***Limits or warnings for excessive applications of manure nutrients***	***Determines no. of loads to individual fields***	***Enables examination of what-if scenarios for factors affecting manure applic. rates***	***Provision for saving input and output data***	***Can alter factors used in calculations e.g. N availability***	***Is a detailed manual provided with the software?***	***General nature of program and distinguishing features or characteristics***
WISPER	Crop requirements for N, P or K	Cannot exceed crop N requirements, or apply >75 lbs P per acre on slopes >9% nserv. tillage	Yes, user can input manure rate as no. loads. Calibrates solid spreader	Yes, may involve moving through a series of screens.	Yes, input data for each field saved in separate files.	NO	151 page indexed manual, screen by screen approach	Comprehensive nutrient management program for a whole farm over several years

5. FATE OF N WHEN APPLIED AT RECOMMENDED AGRONOMIC RATES OR WHEN APPLIED DURING THE NON-GROWING SEASON

Summary

The soil N content is the result of a dynamic equilibrium among several components. Land application of N should not exceed the crop uptake capacity after subtracting any unused soil N left by the previous crop (residual soil N) and supply from other sources such as N mineralized from soil organic matter and crop residues. Management designed to enhance gaseous losses may provide an additional avenue to balance land application of N.

Matching N applications to crop N requirements is not easy. Management, environmental conditions, and crop uptake limitations may preclude a good match and result in residual nitrate after crop harvest. Excess infiltration of water will move nitrates down the soil profile, sometimes beyond the reach of roots and in its way to groundwater. Fall or winter N applications, particularly of inorganic forms, may further aggravate the problem.

Volatilization and denitrification are possible pathways for applied N. Volatilization occurs rapidly after application. Denitrification is usually small during much of the year with periodic major events occurring when rainfall or irrigation rewet the soil. Denitrification can be significant when a shallow or a perched water table are present. Gaseous losses can be minimized or enhanced depending on management objectives.

N mineralization from organic residues, applied waste, or from stable soil organic matter occurs throughout the year, with peak amounts when temperature and moisture conditions are suitable for the microbial activity that is responsible for the process. Mineralized nitrogen may lead to excess soil N and leaching if not accounted for when N application decisions are made. Significant mineralization may also occur when plants are not actively absorbing nitrogen. Low soil temperatures during the winter in Central and Eastern Washington will tend to inhibit mineralization during this period.

Water drainage (percolation) takes place when rainfall or irrigation exceeds water loss by evapotranspiration. Since nitrates are soluble in water, the amount of nitrogen that may be lost with percolating water depends on the nitrate concentration in the soil profile. The type of soil has an influence on the N leaching potential. Due to their lower water holding capacity and greater saturated hydraulic conductivity (greater transport velocity), all other factors constant, N leaching will be apparent first in sandy soils. The type of crop also has an effect. Corn is an annual crop with a limited root system, especially in the early growing season, and is planted in widely spaced rows. Therefore, corn does not intercept all the NO_3*-N in the soil solution. This effect is more pronounced with a shallow-rooted crop such as potatoes. Alfalfa is a perennial with a longer growing season and has closely spaced plants. The root system for alfalfa is more*

extensive and deeper than that for corn and does not allow as much percolation. Although alfalfa is a legume crop, it utilizes soil N if available. However, caution must be taken to consider in the N balance the amount released from alfalfa roots after the crop is terminated.

Nitrogen losses may occur even when N is applied to crops at recommended agronomic rates. Reports indicate NO_3*-N losses from crops amounting to 24 to 55% of the N applied at recommended rates. The apparent crop recovery (crop uptake) of applied N is in the order of 40 to 80%, depending on the timing of fertilizer applications, crop type, irrigation management, and other factors. Unused nitrogen will accumulate in the soil, which may lead to subsequent leaching losses if careful management is not applied.*

Literature comparing organic and inorganic sources of nitrogen in typical production agricultural operations often shows a higher risk of nitrate leaching associated with organic N sources. This is due to greater uncertainties in the quantity of organic N applied, the amount of ammonia N volatilized, the fraction of applied organic N that will be mineralized in each growing season after the application, and the amount that will be denitrified. Managing organic wastes to supply crops at recommended agronomic rates is challenging because organic wastes are a slow-release source of N, often with effects beyond the growing season of the application. These facts indicate the need for careful budgeting and monitoring in the management of organic waste application to land.

Regardless of the management objective (production agriculture or processed water recycling), the amount of soil nitrate during the off-season period should be minimized. Rainfall typically exceeds evapotranspiration (greater percolation) and N leaching losses are typically observed to be more predominant during this period. Cover crops grown during the off-season period may help to immobilize soil nitrate otherwise available for leaching. The build up of nitrate by mineralization during and after the growing season, once significant crop uptake has ceased, is a challenge for N management. Subsequent excess percolation during fall, winter, and early spring will increase the risk of leaching. The use of cover crops may be a necessary element to minimize this risk.

As shown by the introductory concepts on nitrogen and water balance, the soil N content at any point in time results from a dynamic equilibrium among several components. When N is applied at recommended agronomic rates (see the definition given in the first item of the General Principles and Recommendations section of the Executive Summary), crop N uptake should be the most significant component balancing N inputs. N applications should be scheduled to meet crop demand after N supplied by other sources such as net mineralization and residual soil N (N left in the soil from the previous season) are accounted for. Although N requirements of most crops are known, the management of N applications to match these requirements has often some constraints.

In addition to the total amount, another consideration is the temporal distribution of crop N uptake, which should be closely met to maximize uptake efficiency. Management and/or environmental limitations may preclude a good matching, with the end result that some nitrate may be left unused in the soil profile. Excess infiltration of water will move nitrates down the soil profile, sometimes beyond the reach of roots. Fall or winter N applications, particularly of inorganic sources, may further aggravate the problem.

When applying organic wastes, it is important to know their N content and mineralization rate to properly evaluate their impact on the overall mineral N budget of the soil. In vegetable-processing wastewater, for example, NO_3-N concentrations are generally low (< 3 mg/L). However, the organic material contained in the processed water from vegetable and fruit processing are mostly water soluble and readily decomposable (Smith and Peterson, 1982). As these organic materials rapidly decompose, the organic N is also rapidly converted to ammonium and then to nitrate (Jewell, 1976).

The mineralization of organic N contained in organic waste, crop residues, and stable organic matter occurs throughout the growing season, with varying rates according to temperature and moisture conditions, and not in response to crop requirements. Depending on climatic conditions, substantial amounts of mineralization may occur after crop uptake has ceased (or become small) and after harvest. In Central and Eastern Washington, low soil temperatures during the winter largely inhibit mineralization during this period. Mineralized N is normally transformed rapidly to nitrate. Excess nitrate not used by the crop will be available for leaching during the fall and winter.

An important aspect of the fate of nitrogen in agricultural systems is that N leaching may occur even under well-managed conditions. Notwithstanding, the amount of leaching can be minimized if good land N application and irrigation practices are followed.

5.1. N losses during the growing season

During the growing season, organic and inorganic N applied to the soil may undergo transformations. As a result, a fraction of the applied N may leave the soil in gaseous form (volatilization or denitrification). Soil NO_3-N, otherwise available for crop uptake, may also be subject to leaching beyond the root zone, depending on the transport capacity of irrigation and precipitation water infiltrating the soil during the cropping season.

5.1.1. Gaseous emissions.

Gaseous emissions reduce the amount of N available for plant uptake, but they also limit that available for leaching if conditions change to favor the latter. This may be an important consideration for land application of organic waste where maximization of N removal is sought. However, denitrification and ammonia volatilization may also constitute an environmental hazard (Pain et al., 1989). Nitrous oxide is classified as a “greenhouse gas”, a category of gases that may be involved in global warming. However, the contribution of this gas to the greenhouse effect appears insignificant compared to CO_2 emissions (Philip Mote, University of Washington, personal communication). Interest in ammonia emissions from livestock wastes has been stimulated by the recognition of the importance of this gas in atmospheric chemistry and its role in acid deposition. In the form of ammonium aerosols, ammonia can be transported over long distances (Apsimon and Kruse-Plass, 1991).

Ammonia volatilization is a complex process involving chemical and biological reactions within the soil, and physical transport of N out of the soil. The method of N application, N source, soil pH, soil cation exchange capacity (CEC), and weather conditions influence ammonia emissions from applied N. Conditions favoring volatilization are surface applications, N sources containing urea, soil pH above 7, low CEC soils, and weather conditions favoring drying. Precise estimates of ammonia emissions are only possible with direct local measurements. Depending on application conditions, general ranges would be 2 to 50% emissions for soil pH > 7 and 0 to 25% emissions for soil pH < 7. If the N source is mixed into an acid soil, the emissions are usually greatly reduced (0 to 4% lost) (Meisinger and Randall, 1991).

Ammonia volatilization is a major pathway of N loss from livestock slurries following their application to land. The total ammonia emission in Europe, for example, is estimated to be 6.4 Mt of NH_3/yr with a major contribution (81%) from livestock wastes (van den Abbeel et al, 1989). Ammonia is lost rapidly after spreading on land and total emissions are very variable.

Currently, the only precise way to accurately predict volatilization is through a detailed research investigation at a given site. Therefore, they are usually estimated based on broad generalizations of the main controlling factors, as shown in Table 5.1 (Meisinger and Randall, 1991). Values in the table are offered as preliminary estimates, which could be used as default values if no other information is available.

Table 5.1. Approximate ammonia emissions of land-applied manure. These value are rough estimates of the percent of applied N lost; actual values depend on weather conditions after application, type of manure, ammonia content, etc. (Meisinger and Randall, 1991).

Manure application method	Type of manure	Short-term fate			Long-term fate	
		Percent of N				
		Lost	Retained		Lost	Retained
Broadcast no incorporation	Solid	15-30	70-85		25-45	55-75
	Liquid	10-25	75-90		20-40	60-80
Broadcast immediate incorporation	Solid	1-5	95-99		1-5	95-98
	Liquid	1-5	95-99		1-5	95-98
Knifed	Liquid	0-2	98-100		0-2	98-100
Sprinkler irrigated	Liquid	15-35	65-85		20-40	60-80

From experiments in the UK and the Netherlands, Pain and Thompson (1989) reached the following conclusions: a) Following application of slurry to land, a large proportion of the total ammonia emission occurred within a few hours (70% or more of the total emission occurred within 24 hours of application but emissions continued for over 15 days), b) Slurry composition, as influenced by dilution or the method of management prior to land spreading appeared to have a major influence on the total amount of volatilization while environmental and management factors had a smaller influence, c) Emissions during spreading were generally less than 1% of those which occurred following spreading (the fastest rates of loss occurred during the first hour after spreading), d) Injection or acidification of slurry prior to spreading reduced ammonia volatilization, e) Reducing volatilization increased loss of N through denitrification.

Attempts to utilize slurry as a fertilizer for grassland and arable crops have been often characterized by low and variable recoveries of N (crop uptake). In production agriculture, the injection or incorporation of slurry would be expected to reduce ammonia loss and increase denitrification. Thompson et al. (1987) conducted two field experiments in the UK commencing in winter (December) and spring (April) to determine the fate of nitrogen in cattle slurry following application to grassland. In each experiment, three methods of application were used: surface application, injection, and injection plus nitrification inhibitor. Slurry was applied at a rate of 80 t/ha (about 250 kg N/ha). From slurry applied to the surface, total ammonia volatilization was 77 and 53 kg N/ha respectively for the winter and spring experiments. Injection reduced the total volatilization to about 2 kg N/ha. Following surface application, denitrification was 30 and 5 kg N/ha for the two experiments. Larger denitrification emissions were observed for the injected treatments. In the winter experiment, denitrification from the injected slurry without nitrification inhibitor was 53 kg N/ha, and 23 kg N/ha with the inhibitor. Total denitrification for the corresponding injected treatments in the spring experiment were 18 and 14 kg N/ha. Leaching losses were negligible, reflecting the large and more immediate gaseous emissions of N and the subsequent utilization of nitrate by the crop.

Compared to volatilization, denitrification emissions in agricultural systems are much lower. For these systems, emissions of N_2O were found to be lower than 5 to 7 % of the applied N, even at high application rates of 680 kg N/ha/yr (Ryden and Lund, 1980). Similarly, Mosier et al. (1986) reported that, on well drained clay-loam soil sown with corn in 1982, 2.5% of the 200 kg N/ha applied as $(NH_4)_2SO_4$ was lost as N_2O or N_2. The following year, only a loss of 1% could be measured from the same soil sown with barley. Denitrification from land treated with anaerobically digested sewage sludge at rates of 16.7 t/ha and 83.5 t/ha were slightly higher and could reach 7% and 5% respectively. Measurements by van den Abbeel (1989) showed that most of the slurry N volatilizes directly as NH_3. Their results showed that up to 60% of the NH_4-N added can be volatilized in the four days immediately following the application. The losses attributed to denitrification represented only 7% of the amount of NH_4-N.

Nitrogen emissions by denitrification have a different meaning for production agriculture than for land application systems for processed water recycling. The objective in production agriculture is to maximize crop use of the applied fertilizer. Thus management of denitrification-related factors in this industry emphasizes minimizing emissions. The converse is true for land application systems designed to maximize N removal from organic waste.

Denitrification emissions are usually small during much of the year with periodic major events occurring when rainfall or irrigation rewet the soil. Some generalized figures for denitrification are given in the following table, which was developed under the assumption that low oxygen is the major factor influencing field denitrification and that oxygen supply is primarily controlled by soil water content (Meisinger and Randall, 1991).

Table 5.2. Approximate N denitrification estimates for various soils. (Meisinger and Randall, 1991). See footnote for adjustments due to tillage, manure N, irrigation, drainage, and special soil conditions

soil organic		Soil drainage classification			
matter content	Excessively well-drained	Well-drained	Moderately well-drained	Somewhat poorly drained	Poorly drained
%		% of inorganic N (fert., precip.) denitrified*			
<2	2-5	3-9	4-14	6-20	10-30
2-5	3-9	4-16	6-20	10-25	15-45
>5	4-12	6-20	10-25	15-35	25-55

*Adjust for tillage, manure, irrigation, and special soils as follows: for no-tillage use one class wetter drainage; for manure N double all values; for tile-drained soils use one class better drainage; for paddy culture use values under poorly drained; for irrigation or humid climates use value at upper end of range; for arid or semiarid non-irrigated sites use values at lower end of range; for soils with compacted very slowly permeable layer below plow depth, but above 4-ft deep, use one class wetter drainage.

The factors that determine whether denitrification occurs are the presence of adequate supply of NO_3-N, denitrifying organisms, a suitable carbon substrate for them, and an anaerobic atmosphere (Altman et al., 1995). One of the main rate-determining factors is soil temperature. There are indications that denitrification does not occur below about 6-8 ^{o}C, but other data have suggested that it can occur at close to 0 ^{o}C and that denitrifying populations adapt to the local climate. Maximum denitrification rates occur at 40 ^{o}C (Jacobson and Alexander, 1980). In addition to temperature, the other main determinant of denitrification rate is the amount of carbon substrate available. Goulding and Webster (1989) investigated if there was any difference on denitrification if the carbon source was from fresh organic material or stable organic matter, and found the former to be more effective.

Many studies that measured denitrification potential indicate that denitrification rates were low or negligible with depth (Ambus and Lowrance, 1991; Lowrance, 1992a). In row crops there was evidence of denitrification as deep as 0.42 m (Lowrance, 1992b). Groffman et al. (1992) also observed a large drop in denitrification enzyme activity from the ground surface (0-0.15m) to the top of the seasonal high water table. Ambus and Lowrance (1991) determined that 68% of the denitrification potential in loamy sand and fine loamy sand occurred in the top 0.01 m of the soil. Relatively high rates of denitrification may result to a depth of 0.25 to 0.30 m under the right conditions (Ambus and Lowrance, 1991). In contrast to these studies, Smith et al. (1991) measured the maximum rate of denitrification at 4.7 m below the water table in a sand and gravel aquifer. Nitrate can also be reduced with the oxidation of pyrite when there is not an organic C source (Postma et al., 1991). This may play a role on reducing N content of groundwater. This is discussed in a later section.

Stimulation of denitrification by the addition of decomposable organic material to soil has been widely reported (Firestone, 1982; Fillery, 1983). When slurries are applied to soil, the additional organic material may promote conditions conducive to denitrification as inferred from higher rates of N_2O emission from soils treated with cattle slurry (Thompson and Pain, 1989). From a study conducted in England, these authors drew the following conclusions: a) Approximately 30% of the NH_4-N from autumn-winter surface applications of cattle slurry to grassland on a freely drained soil was lost by denitrification, b) Reducing NH_3 volatilization loss by injection or acidification appreciably increased denitrification from autumn/winter applications of cattle slurry to a freely drained soil, c) Denitrification was small from surface applications of cattle slurry in the spring to a freely drained soil, d) denitrification was negligible from autumn and spring applications of cattle slurry made to a poorly drained soil that remained saturated throughout the winter (this is probably due to nitrification inhibition), e) denitrification from autumn/winter applications of cattle slurry to a freely drained soil continued throughout the winter despite soil temperatures that were generally less than 6 ^{o}C. The length of the period between the initial nitrification of slurry ammonium-N and depletion of soil nitrates by crop growth in the spring was a major determinant of total denitrification.

Hill (1986) found that, under good agronomic practices and application of N as NH_4NO_3 in potatoes in a sandy loam soil, denitrification was significant. Using incubations he showed that 8-20% of the initial NO_3-N was denitrified over a 14-day period in surface soil. The potential for denitrification at greater soil depth was very low.

Olson (1982) indicated that after fall application of 80 kg N/ha in winter wheat, denitrification of 10 to 18% of the applied N occurred soon after the application (broadcast application of $(NH_4)\ SO_4$.). Tindall et al. (1995), working under controlled conditions, found that denitrification ranged between 0.5 to over 10% of the applied N.

Goulding et al. (1993) studied the fate of 222 kg N/ha applied in spring as $K^{15}NO_3$ to winter wheat. They measured maximum rates of denitrification of over 1 kg N/ha/d following heavy rain. After N application and anthesis, accumulated emissions were in the range of 5.3% to 3.6% of the applied N. Ryden (1983) found rates of denitrification around 2 kg N/ha/d, from a loam soil under grassland that had received 500 kg N/ha in early spring. Such high rate occurred only when heavy rain followed the application of N and the temperature of the soil was increasing. Colbourn (1984) estimated that, in a wet spring, >30% of the 100 kg N/ha applied to a winter wheat crop on a clay soil was denitrified at rates up to 1 kg N/ha/d.

At Derio, Bizkaia, Estavillo et al. (1996) found denitrification figures of 15% to 40% of the total N applied in a poorly drained clay loam soil with surface applied slurry and high precipitation conditions (1234 and 1686 mm). Jarvis et al. (1987) found denitrification emissions from surface-spread slurry that were equivalent to 12% and 2% of the total N added (248 and 262 kg N/ha) for winter and spring applications, respectively.

In Denmark, four years of application of pig slurry or inorganic fertilizer to a sandy loam soil cropped with barley showed that there existed a large potential for denitrification. These emissions occurred during periods in the spring of alternating frost/thaw or in periods with frequent rainfall. During dry periods, denitrification was largest from soil treated with large amounts of pig slurry (320 kg N/ha/yr plus 100 kg organic N/ha/yr) (Maag, 1989).

Under conditions of high carbon availability (No-till systems or manure-amended soils) denitrification is higher, and it is sustained deeper in the soil profile. Irrigation with processed water would also promote deeper penetration of carbon and deeper denitrification. Research results (Kimble et al., 1972) showed that more nitrate was lost by leaching when N was applied as NH_4NO_3 than when applied as dairy manure, both because there was more nitrate in the profile and because it was less susceptible to denitrification.

Effects of dairy manure and N fertilizer were studied on plots that had received two levels of manure (0 and 66 metric tons/ha) applied every spring for 6 years. Laboratory incubation studies using soil profile samples showed potential denitrification to be greater in soil from the manure treated plots than in plots receiving either inorganic N or no N. The amount decreased with depth to 96 cm, below which energy for anaerobic microbial activity appeared to be limiting (Kimble et al., 1972).

Loro et al (1997) found that denitrification and N_2O production were enhanced following manure application compared with fertilizer application, but not in subsurface soil. Manure provides mineral N (mostly NH_4^+) and C substrate for denitrifiers and, if applied as a slurry (instead as solid manure) limited oxygen supply enhances denitrification. They also found that denitrification does not occur at 40 cm depth or deeper into the soil at a rate high enough to consume significant quantities of nitrate. This will leave nitrates free to be leached to groundwater.

Addiscot and Powlson (1992) analyzed and partitioned the N losses (leaching losses and gaseous emissions) reported for 13 winter wheat field experiments where nitrogen was applied in spring. They concluded that denitrification seemed to be the more important pathway. On average, the total loss was 15.7% of the total applied, of which denitrification contributed 10% and leaching 5.7%. Rainfall in the first three weeks after application ranged between 12 and 112 mm.

The presence of shallow water tables or perched water tables due to abrupt soil textural discontinuities may favor denitrification. Application of organic wastes with high biological oxygen demand (BOD) will further enhance anaerobic conditions leading to denitrification. In a study conducted by Smith (1976) at a potato processing plant in Idaho, the BOD and the total N and nitrate concentrations in the processed water and in the soil solution at several depths in a treatment field where the processed water was applied were studied for a 2-year period. Application rates of 1,635 and 1,080 kg N/ha were applied in the first and second year, well in excess of the 320-kg N/ha removed by a grass crop. Leaching losses and crop uptake accounted for only part of the applied N, while most of the applied N in the season remained unaccounted for. The soil N accumulation was not directly measured. However, the author hypothesis was that a sizeable fraction of applied N was denitrified rather than accumulated in the soil. Plentiful carbon availability, a water table ranging from 90 to 150 cm below the soil surface in the summer, and excessive irrigation make this interpretation plausible. Although this may represent an extreme condition, management of denitrification as a means of N removal from land-applied organic processed water should be further investigated for conditions at Washington State.

5.1.2. Leaching losses.

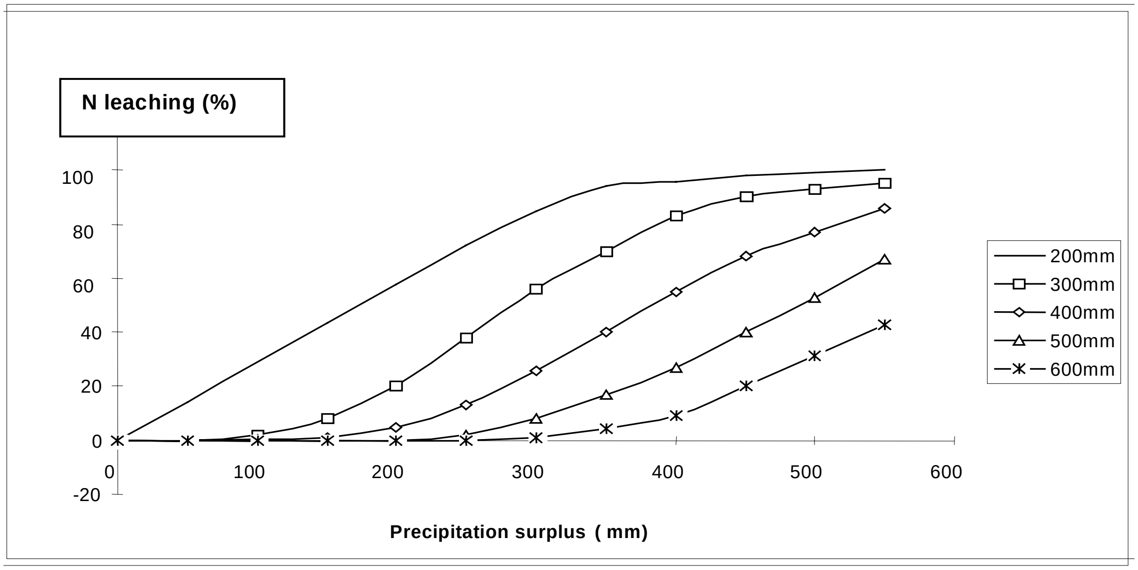
Since nitrates are soluble in water and water tends to percolate downward through soil in response to gravitational forces, nitrate leaching is a natural process that preceded agriculture. Deep water percolation will take place when rainfall (or irrigation) exceeds water loss by evapotranspiration. The amount of nitrogen lost with percolating water depends on the nitrate concentration in the soil profile. This nitrate concentration is strongly influenced by N land application methods and management.

The production of drainage water will depend not only on climatic factors such as rainfall (total amount and distribution over the year) and temperature, but also on soil type, depth of groundwater table, and the characteristics of the local irrigation management (in irrigated areas). These factors make it difficult to compare research findings of nitrogen losses by leaching collected under different environmental conditions. Under West European conditions, for example, water surplus (drainage) ranges from 0-500 mm/year, mainly in autumn and winter when temperature and crop growth are low (Kolenbrander, 1981). In Washington State, average annual percolation rates fluctuate from 50-125 mm in dryland Eastern Washington, to more than 250 mm in irrigated Central Washington (Ryker and Jones, 1995), to 50-500 mm and more in Western Washington (Ronald Hermanson, personal communication).

Perhaps the greatest uncertainty when measuring or predicting deep water percolation and associated nitrate leaching in soil deals with the heterogeneous pore distribution in the root zone where microbial N cycling can greatly alter N availability for leaching. Large pores created by shrinking and swelling of clays, decomposition of roots, and faunal activity can accelerate water movement (two to five times higher for soils without obvious macropores, and as much as twenty times for soils with cracks). This increased water movement will have different effects on nitrate leaching depending on N concentration of those areas of the soil "bypassed" by infiltrating water, the rate of water application, the N concentration of infiltrating water, and other factors. The net result, however, is generally one of increased N amounts being transported beyond the reach of crop roots. Aschmann et al. (1992) detected flushes of nitrate and other ions and they attributed them to preferential flow through the profile. Sidle and Kardos (1979) showed that, owing to macropore flow associated with root channels, NO_3-N leaching can occur more rapidly in soils than hydraulic equations would predict.

The concentration of nitrate does not only depend on the amount of nitrate in the profile but also on the amount of water. This effect of water content in the soil profile on leaching is demonstrated in Fig. 5.1 (Kolenbrander, 1981), taken from calculations by Rijtema (1978). This figure shows that, with the same water surplus, the percentage of nitrate lost in autumn and winter increases as the saturated water content of the profile decreases. This means that, under the same climatic conditions, the leaching loss on a peat soil is lower than on sandy soil due to lower drainage and a lower nitrate concentration in the soil water.

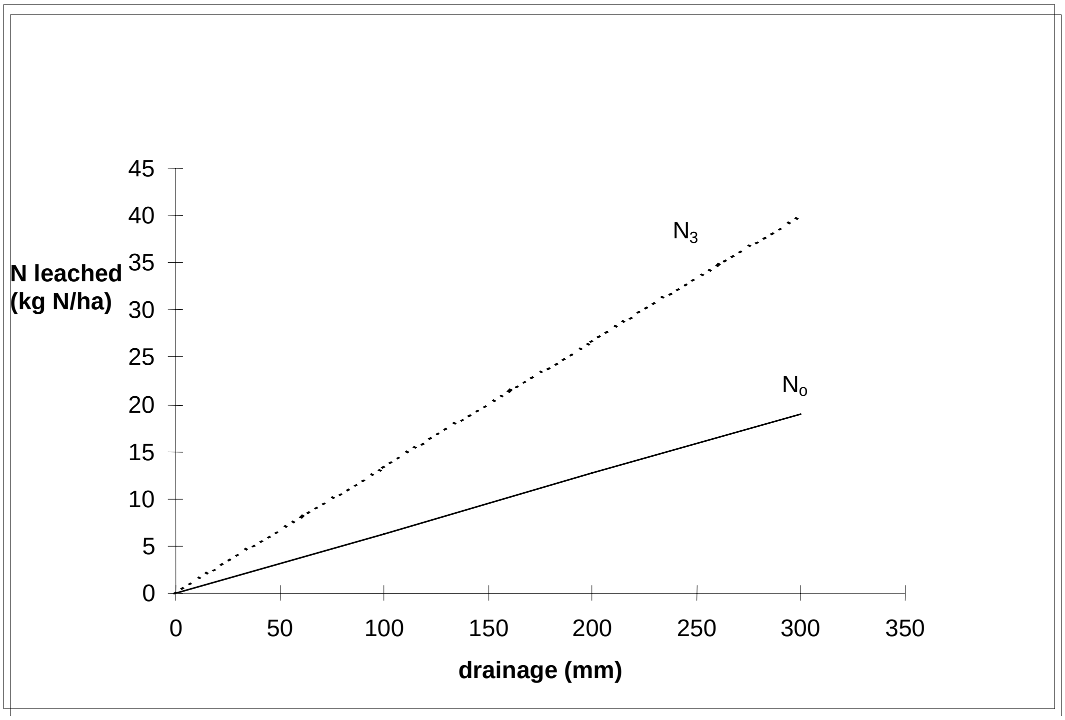
Fig 5.1. Relationship between precipitation surplus and percent nitrogen leached in autumn and winter in a water-saturated soil profile. Curves represent different water contents of the saturated profile (Kolenbrander, 1981)



For comparisons, it is also important that N leaching losses are compared at the same level of drainage water production. Figure 5.2. shows that there is a clear linear relationship between N-leaching loss and drainage water production in the same soil.

Randall and Iragavarapu (1995) also showed that the amount of N leaching is related to the amount of percolating water. They conducted a study on a poorly drained clay loam in Minnesota with continuous corn and N fertilization rates of 200 kg N/ha for several years (fertilizer N was applied as one dose in the spring before planting). They found that annual losses of NO_3-N in the tile water ranged from 1.4 to 139 kg/ha. In dry years, losses generally were equivalent to less than 3% of the fertilizer N applied, whereas in the wet years, losses ranged from 25 to 70% of that applied. Pang et al (1997), in an irrigation quantity and uniformity study, concluded that N leaching was very low when the N application was close to crop N uptake and slightly higher when the uniformity coefficient of the irrigation was 90%. When N application exceeded N uptake, N leaching increased dramatically for all uniformity levels.

Fig. 5.2. Relationship between drainage water production and N losses by leaching. N_0 and N_3 refer to two treatments with and without nitrogen (Kolenbrander, 1969).



Given the fact that crop N uptake constitutes a significant fraction of the N balance in croplands where N applications are managed according to agronomic rates, the nature of the crop (vegetation) on a given area plays a role in determining N leaching. Kolenbrander (1981) analyzed data sets from Germany, the Netherlands, and the United Kingdom, normalizing N losses to a standard drainage level of 300 mm/ha/year. From this study, the author concluded that, at very low rates of application, the leaching levels of arable land are significantly higher than on grassland. This is caused by the different nature of the N-uptake pattern of the crop. On grassland, however, a strong increase in N-leaching occurs at rates higher than 200 kg N/ha/year. At very high rates (higher than 800 kg N/ha/year), the nature of the crop will no longer play an important role in determining the rate of leaching.

Bergstrom et al. (1987) conducted an experiment where leaching of nitrate with drainage water from tile-drained field plots and from three types of lysimeters was estimated during a 4-yr period. Treatments included barley with and without N-fertilizer, a grass, and alfalfa. The maximum amount of nitrate leached was 36 kg N/ha/yr for barley fertilized with $Ca(NO_3)_2$ (120 kg N/ha/yr). For unfertilized barley the corresponding amount was 5 kg N/ha during the same period. The nitrate fluxes from the grass and alfalfa were mostly below 5 kg N/ha/yr. However, after the grass was plowed, considerable leaching occurred, reaching 42 kg N/ha during 20 weeks following plowing. Weather conditions had a strong influence on the temporal distribution of leaching losses.

Legumes have the ability to fix N and are sometimes used to supply N in a legume-grass mixture (Owens, 1990). Not only is mineral N fertilizer rarely applied to legumes, but also legumes can supply a portion of the N for the succeeding year's crop. However, few NO_3-N concentration data are available for leachate or groundwater under legumes. In a 3-yr Swedish study (Bergstrom, 1987), 0 to 6 mg/L and 0 to 18 mg/L of NO_3-N were observed in lysimeter leachate and tile plots, respectively, from alfalfa. In Ohio tile drainage, 1.5 mg/L NO_3-N was observed in leachate under alfalfa in a 2-yr study while 4.9 to 32.8 mg/L (8.9 mg/L weighted average) was measured under soybean (Logan et al., 1980). Using soil extracts, 3 to 15 mg/L NO3-N was contained in soil solution under irrigated alfalfa plots in Idaho (Robbins and Carter, 1980).

Owens (1990) observed that NO_3-N concentrations in the percolate resulting from alfalfa-grass mixture were below the 10-mg/L level. Most of the levels were below 5 mg/L, in strong contrast to the normal range of 20 to 40 mg/L NO_3-N in the leachate from corn. The nature of the crops helps to produce such differences. Corn is an annual crop with a limited root system, especially in the early growing season, and is planted in widely spaced rows. Therefore, corn intercepts not all the NO_3-N in the soil solution. Alfalfa is a perennial with a longer growing season and has closely spaced plants. The root system for alfalfa is more extensive and deeper than that for corn and does not allow as much percolation. Alfalfa utilizes soil N if available, and it is able to intercept and utilize most available N passing through the soil.

Also, as shown in Table 5.3, N leaching in heavier soils (clay) is lower than in light soils, both on arable land and grassland.

Table 5.3. Mean leaching losses for different soils and landuse

	Arable land	Grassland
Mean fertilization level	170 kg N/ha	250 kg N/ha
Leached: sandy soil	100 " "	12 " "
clay soil	42 " "	9 " "

Gaines and Gaines (1994) indicated that soil texture affects NO_3-N leaching. In coarser soils, NO_3-N will leach faster than from finer ones. The addition of peat in sandy soils helps in reducing the velocity of N leaching. Tindall et al (1995), in a laboratory analysis, indicated that leaching of NO_3-N was significant in both clay and sandy soils. They concluded that in clay soils leaching occurred less rapidly than in sandy soils. Nevertheless, after enough time, 60% of the NO_3-N was leached from the clay soils.

Due to different water holding capacities and associated transport velocity, all other factors constant, N leaching will be apparent first in sandy than clay soils. Jansson et al. (1989) reported that, from a simulation study, it was found that a sandy soil was generally more sensitive to variation in factors like climate, form and timing of applied N, and composition of manure than was a clay soil. Nitrogen leaching could often be described with linear functions of applied N for the sandy soil, where more or less clear thresholds were seen in the response function for clay soils.

5.2. N losses during the non-growing season

The quantity of nitrate passing from arable land to aquifers is often determined by the nitrate content of the soil just before winter leaching begins (Powlson et al, 1986). Nitrate present in arable soils in the fall is available for denitrification or at risk of leaching during the winter. The presence of N in the soil in the fall is derived mainly from unused N at the end of the cropping season plus mineralization of organic N derived from humus, crop residues or organic waste.

The nitrate fluxes depend on drainage volume and nitrate concentration. The nitrate concentration of drainage water tends to reach a long-term equilibrium for a particular crop/land N application management. The yearly variations in off-season nitrate fluxes mostly reflect varying drainage volumes. There are several investigations showing a strong dependence between mass emission and drainage volume (Golton et al., 1970; Letey et al., 1977).

5.2.1. Gaseous emissions.

Conditions for gaseous emissions are usually more favorable during the non-growing season. Organic waste and ammonium-based inorganic fertilizers are applied in advance of crop planting to allow time for mineralization and/or nitrification. Wet conditions during fall and winter contribute to denitrification. Ammonia volatilization occurs rapidly after application of manure.

Fall application of N for corn is common in the western Corn Belt. Nearly 21% of the N applied to corn is fall-applied, and nearly 24% of corn receives at least some of its N during the previous fall (Taylor and Vroomen, 1989).

Animal wastes are often applied in the fall. Injection is often the preferred application method if reduced volatilization is desired (production agriculture). Liquid injection of manure may increase denitrification by creating an anaerobic quality, abundant in inorganic N and oxidizable C (Comfort et al, 1988). The storage of animal wastes in slurry form and subsequent application to land has the advantage of more flexibility in application times, lower labor requirements, less potential for runoff and surface water pollution.

5.2.2. Leaching losses.

There will generally be less percolation from single rainfall events when a crop is growing than the situation without a crop. The latter is more significant during winter when soil evaporation is low. Therefore, given equal rainfall, geographical locations that receive peak rainfall during the cropping season should have less percolation than locations that have peak rainfall at times when no crop is growing. Likewise, peak rainfall timing relative to crop development causes year-to-year differences in percolation at a given location. Williams and Kissel (1991) illustrated this point using simulation results for corn production at Caldwell County, Kentucky. They compared the simulations from two years that had nearly identical rainfall but differed greatly in the timing of the rains. Although both years had about 1,092 mm of total annual rainfall, one year received 62% of the rain in the first 6 months of the year, whereas the other year received only 27% of the total rainfall in the first 6 months. The effect on percolation was pronounced. The year with early rain had 315 mm of percolation, whereas the year with later peak rainfall had 218 mm of percolation. Also, since a considerable portion of the percolation from the early rain simulation was just following N fertilizer application, but before peak crop use of N, leaching loss of N in percolate was substantial (86 kg/ha). Loss of N from the late rain was much less at 15 kg/ha. These authors concluded that rainfall timing with respect to crop growth and time of N application can greatly influence percolation amounts and N loss by leaching (Williams and Kissel, 1991).

For spring N applications, the water balance will become negative or will show small excess due to the high rate of evapotranspiration. The chances of losses by leaching will therefore be small. Organic wastes are often applied during fall and winter for economic reasons (better spreading of work over the season, smaller storage capacity). This may result in increased likelihood of nitrate losses due to leaching.

In Delaware, where one of the most concentrated poultry industries is located, approximately 250 millions of broilers produce > 200,000 t of manure each year. At currently recommended rates (about 6 to 9 t/ha) poultry manure alone could provide most of the N required by the 68,000 ha of maize grown annually in Delaware. Due to different factors, local excess of manure often exists, and manure application often occurs in winter or early spring, when crop uptake is low (or nonexistent) and precipitation is highest. These factors enhance the likelihood of NO_3-N leaching to groundwater (Sims et al., 1995).

In production agriculture, leaching of N after the application of slurry is typically higher than after application of mineral N fertilizer. This is due to a) a high proportion of the slurry being spread in autumn and b) the rates of slurry nitrogen applied being usually higher than the rates of fertilizer N applied per hectare.

Vetter and Steffens (1981) conducted a field experiment where they applied 30 m^3/ha of slurry in August, October, December and February/March on humus sands and clayey silts. These treatments were compared with unmanured plots. The N concentrations in the shallow groundwater after spreading slurry at different dates showed clearly that the amount of N leached decreased as the date of application of the slurry came closer to the date of the start of crop growth. The highest N leaching was found after spreading the slurry in August and the lowest after spreading in February/March. When slurry was applied in February/March, the N concentrations in the shallow groundwater were only slightly higher than in the unmanured treatments. The yields of cereals grown after the spreading increased as the date of application of the slurry approached springtime. Soil analyses for nitrate and ammonium also indicated that the amount of mineral N increased as the date of the application of the slurry approached springtime.

These same authors (Vetter and Steffens, 1981) carried out field trials for 4 years where treatments with increased rates of pig slurry were applied in the autumn (rates of 0, 30, 60, 90 m^3/ha). After 4 years, there was an almost linear increase in the N content of shallow groundwater from 30 mg N/L (unmanured plots) to 80 mg N/L (plots with 90 m^3/ha). The almost linear increase in the N concentrations indicates that where slurry is spread in autumn a certain percentage of the added slurry N will be leached independently of the slurry amount. This means that even relatively low slurry dressings in autumn can lead to increased leaching of N.

Owens (1990) found experimentally that most of the NO_3-N moved during the winter and spring periods, regardless of crop. This was the combined result of higher N concentrations and much greater percolate volumes. The seasonal variation of percolate volumes resulted from much lower evapotranspiration rates during the dormant periods than during the growing season.

Precipitation is one of the major factors affecting the patterns of N transport and its transformations. Hill (1986), working in sandy loam soils with a potato crop with fertilization rates ranging between 160 to 200 kg N/ha, reported that most of the N leaching occurred in fall and early spring. This author found peaks of N concentration in the groundwater during early summer and early winter that suggested that NO_3-N movement to the aquifer occurred during the autumn and early spring periods of groundwater recharge.

Olson (1982) reported that, after fall application of N fertilization to winter wheat at agronomic rates (80 kg N/ha nitrogen fertilization), leaching is expected when there is enough precipitation between the time of application and the period of rapid spring growth to cause appreciable drainage. In this set of experiments, drainage during late October and the end of March carried out about 47 kg N/ha.

Jokela and Randall (1989), conducted a study for three years on two non-irrigated southern Minnesota soils with different nitrogen rates fluctuating between 75 and 300 kg N/ha in corn. They found residual NO_3-N values in the 1.5 m profile ranging from 150 to 400 kg N/ha for most treatments in the fall but was 50 to 70% lower the following spring. This was attributed in part to leaching beyond the root zone.

Martin et al. (1994), working with lysimeters and irrigation strategies in a sandy loam soil in Michigan, concluded that most of the nitrate loss occurred between the harvest date and the subsequent planting date. Jokela (1992) reported changes in soil nitrate between the fall and spring sampling dates working with several treatments involving N fertilizer and manure applied in corn. Little or no loss (15 kg N/ha or less) occurred if <60 kg/ha of NO_3-N remained in the profile at the time of the fall sampling. Profile nitrate with the only manure treatment was similar to the inorganic fertilizer treatment suggesting that off-season leaching potential from manure is equal or slightly less than from agronomically equivalent rates of fertilizer N.

In the early 70's, Jones et al. (1974), working with different combinations of pastures and fertilization applied in the autumn, reported that of the total N leached, 94% was in the fall, 6% in the winter and less than 1% in the spring. They also reported that, of the applied N, 38 to 50% remained unaccounted for at the end of the study. Part was probably lost by denitrification during the wet winter, and some probably remained in the soil, fixed in undecomposed roots and organic matter.

Peralta et al. (1997), using simulation techniques, demonstrated that non-growing season N leaching was the major contributor to total N leaching of irrigated potato rotations (potato/wheat/maize) in the Pasco area of the Pacific Northwest. This is an area with average precipitation of 175 mm, mostly concentrated in the winter and early spring.

Bergstrom et al. (1987) indicated that, under Swedish conditions, leaching of nitrate from arable lands occurs mainly during the autumn (September-November), which is characterized by high precipitation and low evapotranspiration (Bergstrom and Brink, 1986). During this period, levels of inorganic N in the soil are often high, and the soils are commonly bare.

Regardless of the management objective (production agriculture or processed water recycling), the amount of soil nitrate during the off-season period should be minimized. Rainfall typically exceeds evapotranspiration (greater percolation) and N leaching losses are typically observed to be more predominant during this period.

Cover crops may significantly immobilize this supply of soluble N (MacLean, 1977; Andersson et al., 1984), and thereby reduce nitrate leaching. Francis et al. (1994), in a experiment using rotations with legume and no legume crops and spring crops, reported that the use of leguminous crops producing large amounts of low N content residues (e.g., lupins) has advantages in reducing autumn/winter leaching losses through intensive net immobilization of soil N in the autumn. The authors also indicated that the use of winter cover crops after grain legumes, established in the autumn, could take up much of the mineral N remaining in the soil at harvest or produced through subsequent net N mineralization. The apparent leaching losses over the winter/spring period were greater following leguminous (mean 72 kg N/ha) than following non-leguminous (mean 37 kg N/ha) grain crops. This is because leguminous crops (except lupins) supply some of their N by symbiotic fixation, so less soil N is taken up by the plants.

McCracken et al. (1994), in a study to evaluate different sources of N and cover crops, concluded that cover cropping with rye can be a powerful tool for reducing over-winter leaching of nitrate. Losses with no cover crop and cover crop were 37.3 kg N/ha and 1.5 kg N/ha, respectively.

5.3. The role of mineralization on N leaching

Mineralization of nitrogen from stable organic matter occurs throughout the year, with peak amounts when temperature and moisture conditions are suitable for the microbial activity responsible for the process. This mineralized nitrogen may lead to N leaching if not accounted for when N application decisions are made and when mineralization is occurring during the period where plants are not actively absorbing nitrogen.

Mineralization of organic to inorganic N depends on the soil organic matter content and environmental conditions such as soil moisture and temperature. Macdonald (1989), working with N-labeled fertilizer, demonstrated that for soil growing winter wheat and contrasting soil types and fertilization rates, almost all of the nitrate at risk of leaching over the winter period came from mineralization of organic nitrogen, not from unused fertilizer applied in spring. Unused fertilizer may also be a significant contributor if N amounts in excess of demand are applied to the precedent crop.

Sieling et al (1996), in Germany, indicated that application of slurry in the fall increases N leaching. A hot and dry summer and a mild winter with rainfall above normal, lead to intense N mineralization and subsequent N leaching during the winter.

Continuous application of inorganic fertilizers seems to increase long-term N mineralization rates. Glendining et al (1996) demonstrated that long-term fertilizer treatments (over 135 years) have increased N mineralization due to the build-up of soil organic N.

Hart et al (1993), working with labeled-N in winter wheat, indicated that most of the labeled-N was presumably mineralized during the fall and winter when the losses are high and crop demand is low. They concluded that leaching of NO_3-N from cereals comes predominantly from mineralization of organic N, not from residual unused N. Olson (1982), after working in the fate of N applied in the fall using labeled-N and agronomic rates in winter wheat, found that from all the leaching produced during the winter time, only about 10% of it came from the fertilizer nitrogen.

This build up of nitrate by mineralization after significant uptake by the crop during the growing season has ceased is a challenge for N management. Subsequent excess percolation during fall, winter, and early spring will increase the risk of leaching. The use of cover crops may be a necessary element to minimize N leaching losses.

5.4. The role of cropping systems and tillage method on N leaching

Cropping systems may be a major factor in regulating nitrate movement below the root zone and toward the water table. Rooting depth, water requirement, water-use rate, N-uptake rate, and time of water and N uptake are all factors involved in nitrate leaching that can be affected by choice of cropping system. For nitrate leaching to occur, appreciable concentrations of nitrates must be present in the root zone at the time that water is percolating. If, by changing crops, we can reduce either nitrate concentrations or quantity of water percolating through the soil, we can reduce the potential for groundwater contamination (Peterson and Power, 1991).

Rate and depth of crop rooting are major factors affecting the time, quantity, and depth from which water and nitrates may be removed from the soil. Also, a crop may be more effective in controlling nitrate leaching if the rate of water and N uptake is relatively high at the time of the year when nitrate leaching is likely to occur, or if the crop roots have greatly depleted stored water and nitrates earlier.

It is known from experiments with mineral N fertilizers that different cropping systems can influence the rate of leaching of N. Generally, the leaching of N is lower on grassland than on tillage land and is lower for plants with a longer vegetation period than those with a shorter vegetation period. At very low rates of application, the leaching levels of arable land are significantly higher than on grassland. This is caused by the different nature of the N-uptake pattern of the crop. On grassland, however, a strong increase in N-leaching occurs at rates higher than 200 kg N/ha/yr (Kolenbrander, 1981).

Because essentially all work has shown that zero-till management results in greater infiltration, it is often assumed that greater leaching should also occur. However, this assumption is not always correct. Kanwar et al. (1985), working on a loam soil in Iowa observed much less leaching of N in no-till (NT) plots than in moldboard plow plots. Other results showed that plots under no-till maintained significantly higher NO_3-N amounts in the 0- to 30-cm layer, with 40% of the NO_3-N initially present still there after 12.7 cm of rain and 33% remaining after the additional 6.35 cm of rain. The corresponding numbers for the moldboard-plow plots were 19 and 9%. The amount of NO_3-N leached from the 150-cm profile with 12.7 cm of rain was also less (29 kg/ha) for the no-till compared with moldboard-plowed plots (122 kg/ha) (Kanwar et al., 1985). Gilliam et al. (1987) contend that different results are explained by the tendency of water to move in large pores in the NT areas. This allows water that contains fertilizer N to move deeper in the soils so that deeper N movement is observed. In the Iowa experiments, much of the nitrate was present in the soil before fertilization. Thus the water which moved in the large pores bypassed much of the N present in the profile so that less nitrate leaching occurred. These results point out the importance of proper consideration of soil characteristics before any generalizations can be made.

5.5. Optimum crop yield and N leaching

Crop yield is not of direct concern in land application systems designed for management of organic wastes. However, maximizing N removal is correlated with maximum biomass production and yields. Therefore, unless these systems are managed for less than maximum crop removal, most of the discussion that follows is pertinent.

Typical experiments of crop yield response to N indicate rapid yield increase with increased applied N at the low end of N application rates. However, the rate of increase decreases with larger N application rates until the yield response to N reaches a plateau with minor to negligible changes. Normally, a fairly broad range of N rates can be chosen without affecting yields significantly (Pratt, 1979).

A procedure for calculating N-rate requirements include the following parameters: a) unit N requirements, i.e. the aboveground N crop uptake per unit of yield, b) fraction of N applied taken up by aboveground crop (N fertilizer recovery fraction), c) realistic yield goal, and d) credit for non-fertilizer sources of N (Bock and Hergert, 1991). Table 5.4 provides general guidelines for estimating N fertilizer recovery fractions when using N rates for maximum or near maximum yield. Values in this table are not the same as N uptake efficiency because residual N uptake is not considered. However, both indices should be closely related. The table emphasizes that timing of N applications and crop types are significant factors.

Altman et al. (1995) reported NO_3-N losses from crops amounting to 24 to 55% of the N applied at economic optimum rates (typically providing for near maximum crop yields). In Pennsylvania, the apparent recovery of N fertilizer (ammonium nitrate) applied at the economic optimum N rate in 42 experiments averaged 55% (Fix and Piekielek, 1983). Thus, even when using optimum fertilization rates, a potential exists for fertilizer N to accumulate in the soil with subsequent risk of loss through leaching.

Overall crop management should be improved to maximize crop uptake of applied N (see Table 5.4).

Table 5.4. General guidelines for estimating N fertilizer recovery fraction when using N rates for maximum or near maximum yield[1] (Bock and Hergert, 1991).

Relative efficiency of N-application timing	Perennial grasses	Upland cereal grains	Shallow-rooted crops	Flooded crops
Low[2]	0.55	0.45	0.35	0.25
Medium[3]	0.70	0.60	0.50	0.40
High[4]	0.80	0.70	0.60	0.50

[1] N fertilizer recovery fraction values assume medium-to-high nitrate loss potential as determined by soil type and moisture regime and no or negligible NH3 volatilization losses

[2] One N application (without nitrification inhibitor) well in advance of the growing season. When nitrate loss potential is low due to soil type or moisture regime, use nitrogen-use efficiency values for medium to high efficiency of N application timing.

[3] One N application near beginning of growing season.

[4] Multiple N applications with first application near beginning of growing season; use of nitrification inhibitor may substitute or partially substitute for splitting N applications.

Schroder et al. (1993) concluded that pollution risks from maize can be reduced by adding N at rates below economically optimum levels. Improved management practices such as N placement (Maddux et al., 1991; Sawyer et al., 1991), conditional post emergence N dressings (Magdoff, 1991) and winter cover crops (Schroder et al., 1992), seem necessary to ensure that economic and environmental goals can both be realized.

Using manure to supply N at near optimum economic rates may lead to higher losses than using inorganic fertilizers as the N source. A substantial quantity of inorganic N may be produced from mineralization of organic N after the crop has ceased to absorb N. This manure-derived nitrate may be subject to leaching during the winter and spring (Schepers and Fox, 1989). Sims (1987) found that at near optimum N rates, even with poultry manure that has a high proportion of its N available, only 36% of the N was removed by a maize crop, compared to 56% of inorganic fertilizer N applied. Saint-Fort et al. (1991), analyzing a number of investigations, also concluded that using manure to supply N at near economically optimum rates may result in significantly higher leaching loss of nitrate than when inorganic N fertilizer is applied. This increase is thought to be due to late fall or early spring mineralization of manure. The concept that manure N will not all be available for crop uptake and that mineralization will increase soil nitrate accumulation applies the same if N rates are intended for maximum or less than maximum yields.

Jemison et al. (1994) indicated that excessive N application increases the potential for nitrate leaching, but not much research has evaluated nitrate leaching from corn (*Zea mays* L.) receiving economic optimum N rates (EON). Their study assessed a) flow-weighted average concentration and mass of NO_3-N leached from non-manured and manured corn treated with five fertilizer N levels and at EON, and b) the relationship between NO_3-N mass in the 1.2 m soil profile following harvest and the flow-weighted average leachate concentrations. Following application of liquid dairy manure each April, the field was chiseled and disked prior to planting. Ammonium nitrate was broadcast at planting (0-200 kg N/ha in 50 kg increments and 0-100 kg N/ha in 25 kg increments) in non-manured and manured corn. Zero-N plots had 3-yr average flow-weighted leachate concentrations less than 10mg NO_3-N/L. At EON, the 3-yr averages were 18.8 and 19.3 mg NO_3-N/L for non-manured and manured corn. The mass of NO_3-N leached was 107kg/ha or 36% of the N applied at EON.

In a typical manured field there are uncertainties about the quantity of manure N applied, the amount of ammonia N volatilized, the proportion of manure organic N mineralized in a growing season, and the amount denitrified. Therefore, it is difficult to use an N balance approach (Schepers and Fox, 1989). Managing organic wastes to supply crops at recommended agronomic rates is challenging because organic wastes are a slow-release source of N, often with effects beyond the growing season of the application. These factors emphasize the need for careful budgeting and monitoring in the management of organic waste application to land.

6. FATE OF N WHEN APPLIED AT RATES LARGER THAN RECOMMENDED AGRONOMIC RATES OR WHEN APPLIED DURING THE NON-GROWING SEASON

Summary

Nitrogen will accumulate in the soil when additions exceed crop uptake. This accumulation will proceed at a rate dependent on leaching and gaseous N emissions, processes that will tend to deplete soil excess N. The dynamics of soil N accumulation and losses will depend on the N source, soil type, and weather conditions. For a given cropping system and N application rate, a long-term equilibrium soil N content and N leaching rate will be established, with year-to-year fluctuations in response to weather.

Volatilization and denitrification are possible pathways for excess N. Management can enhance these emissions. Volatilization occurs rapidly after application if measures are not taken to minimize it. Denitrification can be significant when a shallow or a perched water table are present. The frequency of water applications could be managed to enhance anaerobic conditions leading to denitrification. Processed water containing important amounts of organic matter (high biochemical oxygen demand) also helps in generating the anaerobic conditions that are required for denitrification.

Careful water management can reduce significantly the amount of in-season nitrate leaching even under excess N application. The overall annual leaching, however, will still be important in regions with significant winter precipitation. Under variable winter precipitation regimes, years with low and high N leaching will occur. At the beginning of the winter, soils usually contain substantial amounts of nitrate if excess N application rates were previously used. It is during this period that the greatest quantities of nitrate are leached from arable soils, not in the spring following the main application of N.

Conditions that increase soil organic matter content, as is the case with excess organic waste application, will lead to greater mineralization of N. Some nitrate will be formed during spring, when crop uptake is at a maximum, and it will be used efficiently. However, some nitrate will also be formed during late summer, autumn or early winter when, even in the presence of a crop, uptake is small. This nitrate will be at risk of being leached during the following winter.

Organic wastes are frequently spread in autumn because storage capacity is insufficient to allow postponement until the next spring. The long residence time of autumn-spread organic waste may result in more nitrogen being lost through runoff, volatilization, leaching and denitrification.

The amount of nitrate stored in the soil before winter (residual nitrate) depends on three main factors: the type of crop grown during the previous growing season, the

date of the harvest, and the amount of N applied to this crop. The importance of residual nitrate has been recognized in other countries. To protect groundwater against nitrate leaching from agricultural soils, changes in management practices have been proposed. The amount of residual soil nitrate in late fall has been considered as a quantity that reflects the previous management of a field. Since this quantity is also rather easily measured, it is regarded as a possible indicator of a land user's environmental performance. The amount of late-fall soil nitrate that should reflect the site-specific risk of leaching losses is variable and must consider soil, weather, and agronomic conditions.

As discussed in previous sections, N will tend to accumulate in the soil when added in excess to crop requirements. This accumulation will proceed at a rate dependent on N leaching and gaseous N emissions, which will tend to deplete the soil of excess N. The dynamics of soil N accumulation and losses will depend on the N source, soil type, and weather conditions. For a given cropping system and N application rate, a long-term equilibrium soil N content and N leaching rate will be established, with year-to-year fluctuations in response to weather.

Excess N application in production agriculture may result from lack of information of crop N requirements or incomplete or inaccurate accounting of the overall soil N budget (Power and Broadvent, 1989). Land application of organic wastes, even when not intended to maximize agricultural output, may also result in applications exceeding recommended agronomic rates. For example, Smith and Peterson (1982) reviewed research showing that potato processors applied from 160 to 490 cm of processed water annually, which supplied from 1,080 to 2,200 kg N/ha. This is substantially more than the rate of 300 to 350 kg N/ha/year that grass crops grown on these fields could remove. Potatoes are processed most of the year and large amounts of processed water are discharged from the processing plants. More recent reports (Cook, 1996) have found a much more improved situation among potato processing facilities operating within the Columbia Basin. In general, long processing seasons may result in excessive N applications to the land used for processed water discharge. Vegetables such as peas, green beans, sweet corn, tomatoes, and brussels-sprouts are processed for a much shorter season each year than potatoes.

6.1. N losses during the growing season

Results of long term continuous corn studies on tile drained Webster loam in southwest Minnesota show that annual N applications up to 70% greater than N removed in grain are required for maximum yields (and probably maximum N removal by the crop). In a study by Gast et al. (1974), nitrate and chloride accumulations and distributions were determined in a Webster loam and Waldorf silty clay loam profiles after long term N applications for continuous corn. Concentrations in the profiles were determined at 0.3-m depth intervals and at increasing distances from tile lines. They found that downward leaching losses were apparently minimal leaving denitrification and/or incorporation into organic matter as the mechanisms largely responsible for disappearance of the unused fertilizer-N. Due to the high soil moisture conditions, denitrification is probably the main factor involved.

For conditions of well-drained soils, experiments applying N in excess of crop requirements would show nitrate leaching as the most significant component of N loss if sufficient percolating water is available. Otherwise, most of the excess nitrate will accumulate temporarily in the soil until percolating water is available for transport below the root zone of crops.

6.1.1. Gaseous emissions.

Volatilization and denitrification have been discussed previously in the context of N application rates approaching recommended agronomic rates. While these gaseous emissions are part of the normal fate of N in agricultural systems, they can be minimized or enhanced if so desired. When N is applied in excess of recommended rates, a greater amount is available to be lost as gas through the same mechanisms previously discussed. If gaseous emissions are minimized through management or due to soil/weather conditions, nitrates will rapidly accumulate in the soil and will be available for leaching.

6.1.2. Leaching losses.

The same concept discussed for N gaseous emissions applies for N leaching losses. They will be only augmented by N applications above agronomic rates.

Therefore, all the literature on nitrate leaching losses presented previously is also valid for this section. Some additional literature review follows to further emphasize the needs of closely matching soil N availability to crop requirements.

Jarvis et al (1987) indicated that, in general, there is a linear increase in the N contents of groundwater with increasing slurry applications on arable land. In application of slurry equivalents to 540 kg N/ha, it was found that between 20 and 30% of the N applied in autumn was leached (Vetter and Steffens, 1981).

Over the last 50 years, it is estimated that increased fertilizer N use on intensive wheat in the UK has resulted in an increase of 36 kg N/ha/yr leachable nitrate (Davies and Sylvester-Bradley, 1995). Olsen et al. (1970) indicated that annual applications of more than 168 kg/ha of fertilizer N for 3 or more years on corn in a silt loam soil in Wisconsin might be considered a potential hazard in the pollution of underground water. Rates of N fertilizer above amounts required by the crop will lead to large leaching of N. For example, only 19% of the applied N was recovered by the crop in one experiment.

Walters and Malzer (1990), working with denitrification inhibitors and two N rates (90 and 180 kg N/ha) of urea for corn growing on a sandy loam soil in Nebraska, found that the twofold N application rate resulted in an average of 3.4 times more fertilizer-N leached over three years. They also found that nitrogen leaching losses increased in each successive year of the experiment and averaged 20, 34.7 and 92.8 kg N/ha, respectively.

Vinten et al. (1994) studied nitrate leaching on a field scale from a sandy and a clay loam soil using several N fertilization rates (0 to 210 kg N/ha) in spring barley. This author found that the effect of the fertilizer rate was small, at both sites, with the exception of the highest rate (210 kg N/ha) which lost 105 kg N/ha in the last of three years of experimentation.

Watts et al. (1991) conducted a 3-yr experiment in West Central Nebraska to evaluate water and nitrate leaching losses from irrigated orchardgrass (*Dactylis glomerata* L.) seeded on a fine sand soil. Three irrigation levels (slight deficit, slight excess, and excess) and four N amounts (0, 112, 224, and 336 kg ha^{-1}) were applied. All irrigation treatments had more deep percolation than expected, as the crop water demand estimated for irrigation scheduling proved to be too large, a problem that may easily occur under commercial field conditions if careful control is not exerted. The deficit irrigation treatment served as a "close management" treatment since percolation was minimal and yield was not reduced by water stress. During the first 2 years of operation, in-season percolation losses averaged 7, 28, and 47 cm/yr for low, medium, and high irrigation levels, respectively. Total in-season nitrate-N leaching loss for the same period ranged from 6 to 228 kg/ha, depending on N and irrigation amount. Winter and early spring N leaching losses, as estimated by soil sampling, were a significant part of total N loss. Under reduced in-season drainage and a N rate commensurate with 80 to 85% of maximum production, a minimum annual N leaching loss of 35 kg/ha can be expected. Greater losses are probable under average water and N applications and average management skills. These findings emphasize that careful in-season water and N management can reduce significantly the amount of nitrate leaching. The overall annual leaching, however, may still be important.

Leaching losses of nitrate have been well documented for irrigated corn (*Zea mays* L.) (Watts, 1977; Watts and Martin, 1981; Hergert, 1986; Timmons and Dylla, 1981). Continuous corn production on sandy soils will inevitably lead to increases in groundwater nitrate content.

Robbins et al. (1980) evaluated the nitrate contribution to subsurface drainage water by irrigated alfalfa in crop rotations by measuring the soil water flux and nitrate-N concentration below the root zone of alfalfa and crops following alfalfa with and without additional nitrogen fertilization. Under alfalfa grown on a silt loam soil, 44 kg NO_3-N/ha/yr moved below the root zone at concentrations between 3 and 15 ppm. During the growing season following alfalfa, 85-96 kg NO_3-N/ha/yr moved below the root zone under nonfertilized bean (*Phaseolus vulgaris*) crops at concentrations between 1 and 83 ppm. The second growing season after alfalfa, 17-29 kg NO_3-N/ha/yr at 3-15 ppm NO_3-N moved below the root zone of nonfertilized bean and wheat (*Triticum aestivum* L.) crops. A field planted to corn (*Zea mays* L.) and fertilized with 200 and 170 kg N/ha the first and second year after alfalfa lost 153 and 108 kg NO_3-N/ha, respectively, from leaching. Leachate N concentrations varied from 1 to 64 ppm. Unfertilized corn lost 60 to 17 kg NO_3-N/ha the first and second year after alfalfa, respectively, at leachate concentrations of 1-31 ppm.

As discussed previously, nitrate leaching rates are a function of irrigation and precipitation rate and timing, N application rate and timing (Adriano et al., 1972; James, 1975), and the crops grown (Olsen et al., 1970). Alfalfa removes water and nitrate-N from deeper in the soil profile than other crops, and is an excellent nitrate scavenger for reducing the amount of nitrate-N leaching following a high N fertilized crop, or where alfalfa crops have received excessive N applications. This characteristic has been utilized in renovating high N processed water.

However, when an alfalfa crop is plowed under, the plant roots are killed and N is mineralized from the decomposing plant material. A 225-kg/ha ammonium nitrate-N application produced about the same results on corn (*Zea mays* L.) yield as did N released from a 3-year-old alfalfa stand with about 0.1 m of early spring growth, plowed under just prior to planting the corn crop. The aboveground early spring growth and surface residue accounted for only half of the N taken up by the corn. The remainder apparently came from the roots and other N added to the soil during the 3 years of alfalfa growth (Boawn et al., 1963). However, no data are available for the nitrate-N concentration in the soil solution moving below the root zone following the termination of an alfalfa crop.

Subsequent crops will often have shallower root profiles than alfalfa - initially and possibly during the entire growing season. These crops will not extract nitrate throughout the original alfalfa root profile during the entire growing season, increasing the potential for leaching. Therefore, the rate of organic waste application to alfalfa must be as carefully managed as with any other crop.

The increased production of sewage sludge in the USA has led many municipalities to consider the application of sludge to agricultural land as a means of nutrient recycling. A long-term field study was initiated by Lerch et al. (1990) in 1982 in Adams County, Colorado, with the objective of evaluating the effects of sewage sludge on gross income, yields, grain protein, and elemental content of dryland hard red winter wheat compared to commercial NH_4NO_3 fertilizer. Sludge rates ranged from 0 to 18 dry ton/acre, and N fertilizer rates ranged from 0 to 120 lb N/ac. Sludge application resulted in greater soil NH_4-N and NO_3-N before the end of the crop vegetative period (this is, before grain filling) compared to the N fertilizer treatments over the last three years. Because of the potential for nitrate contamination of groundwater due to oversupply of N (and the potential for metal build-up in the soil) by 12 and 18 ton/acre rates, the lower sludge rate of 3 ton/ac was recommended for this dryland wheat production system.

An experiment was conducted in Southern Alberta (Chang and Entz, 1996) to determine the long-term effects of annual applications of cattle manure (long term N concentration of 1%) on nitrate accumulation and movement, and to assess the environmental impact of such a practice. Different rates of manure applications were used (0, 1, 2 and 3 times the maximum recommended rate of 60 t/ha) under a non-irrigated and an irrigated well-drained clay loam soil. Under non-irrigated conditions, no leaching loss of nitrate-N was expected because the precipitation was not enough to produce the wetting front to move beyond the 150-cm depth. Nevertheless, N accumulation was detected, which may pose a potential groundwater pollution problem during high precipitation years. The net nitrate-N accumulation in the soil suggests net mineralization of applied manure and soil organic matter occurred. For irrigated conditions, after the fifth year, the annual leaching losses of nitrate-N were estimated as 93, 224, and 341 kg N/ha, for the 60, 120, and 180-t/ha rates of manure application, respectively. Under irrigation, the leaching losses of nitrate-N were high even at the recommended rate of 60 t/ha. So, over the long term, the maximum recommended rate is too high for annual applications. A sustainable annual application must be in agreement with crop N uptake.

Timm et al. (1976) applied large quantities of tomato processing waste solids to fields at rates from 448 to 1,792 metric ton/ha. This applied 1,461 to 5,844 kg N/ha, well in excess of barley requirements, creating a severe accumulation of nitrates in the soil and potential for leaching. Smith et al. (1975) studied waste disposal at five potato processing wastewater irrigation systems in Idaho. N applications ranged from 800 to 2,200 kg/ha annually. These values were higher than the grass crops grown on the fields can be expected to utilize, likely causing an increase of soil nitrate and pollution groundwater under the fields.

6.2. N losses during the non-growing season

When N application exceeds agronomic rates, N losses during the non-growing season are likely to be significant. The mechanisms and processes leading to gaseous emissions and leaching losses of nitrogen are the same previously discussed.

6.2.1. Gaseous emissions.

N application in excess of agronomic rates may lead to augmented volatilization and denitrification emissions compared to fertilization/organic N application rates in better agreement with crop needs. The need to minimize or enhance these emissions will depend on the objectives associated with the application of nitrogen to land.

Despite excessive N application, volatilization can be largely controlled by application practices and timing. Denitrification will mainly depend on climatic and soil conditions, but can also be affected by management. If these conditions and/or management are conducive to an anaerobic environment in the topsoil, denitrification will be more significant. Denitrification from organic sources and ammonium-based fertilizers can be somewhat reduced through the use of nitrification inhibitors. In Central and Eastern Washington, winter low temperatures and frozen soils will reduce denitrification rates. All mechanisms leading to reduced rates of gaseous emissions, either managed or natural, will increase soil N accumulation and the risk of leaching under excessive N application rates.

6.2.2. Leaching losses.

In arable cropping systems with annual crops receiving N applications in excess of agronomic rates, leaching of nitrate during winter is difficult to avoid under many conditions where sizable precipitation is available during the non-growing season. Soils may contain substantial amounts of nitrate during this period, but crop uptake will be small and rainfall will exceed evaporation. It is during this period that the greatest quantities of nitrate are leached from arable soils, not in the spring following the main application of N. Under Northern Europe conditions, this has been demonstrated by measurements of nitrate concentration and water flow in field drains (Harris et al., 1984; Goss et al., 1988) and by monitoring the leachate from lysimeters. It has also been demonstrated by applying 15N-labelled nitrate to soils either in autumn or spring; losses of autumn-applied 15N were much greater than of that applied in spring and were correlated with winter drainage (Powlson et al., 1989).

Cropping systems that increase soil organic matter content, as is the case with excess organic waste application, generally lead to greater mineralization of N. Some nitrate will be formed during spring, when crop uptake is at maximum, and will be used efficiently. However, some will also be formed during late summer, autumn or early winter when, even in the presence of a crop, uptake is small. This nitrate will be at risk to leaching during the winter. Large quantities of nitrate can be formed by mineralization in autumn, more than can be absorbed by an autumn-sown crop over the winter period, increasing the risk of leaching.

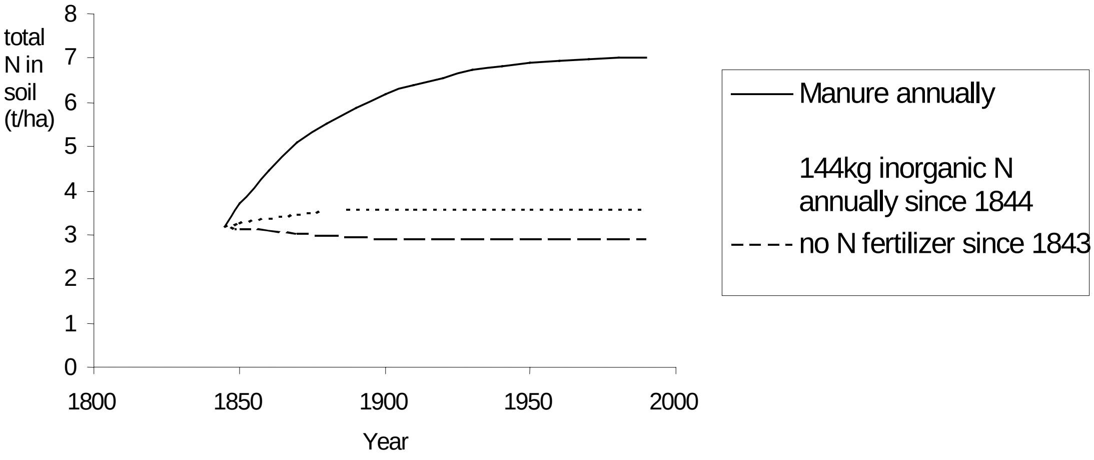
Organic wastes are frequently spread in autumn because storage capacity is insufficient to allow postponement until the next spring. The long residence time of autumn-spread of organic wastes may result in more nitrogen being lost through runoff, volatilization, leaching and denitrification (Schroder et al., 1993).

6.3. The role of soil nitrate accumulation and soil storage capacity on N leaching

The question may arise if significant amounts of N from organic wastes (or inorganic fertilizer) can be applied and stored in the soil profile without leaching. Results from long-term experiments in England (about 140 years) on a silty clay loam at Rothamsted and a sandy loam at Woburn showed that more than 100 kg N/ha/yr were lost from soils when large applications of farmyard manure, sewage sludge, and composts were applied during this long period. Such losses occurred even when the soils were accumulating organic matter rapidly (Johnston et al., 1989). The soils at Rothamsted are silty clay loam and winter wheat has been grown since 1843. Three of the most contrasted treatments are unmanured, annual inorganic fertilizer supplying 144 kg N/ha, and farmyard manure at 35 t/ha, supplying 225 kg N/ha/yr on average. Yields in both treatments supplying N have been similar. Figure 6.1 shows the effect of these treatments on total N content of the soil.

Animal manure and other organic wastes applied to soil can supply large quantities of N to arable soils but they also increase the amount of nitrate at risk to leaching. As excess N is applied to crop/soil systems, soil accumulation increases and so does the mean N leaching rate until reaching a dynamic equilibrium (steady state) condition where changes are modulated by weather variability and cropping sequence.

Fig 6.1. Effect of manure, N fertilizer or no fertilizer on the total nitrogen content of soil during more than 140 years at Broadbalk, Rothamsted (Johnson et al., 1989).



The Rothamsted long-term experiments may represent an extreme case where the quantity of manure applied is in excess of crop needs and has been applied continuously for many years. However, the results illustrate some of the principles underlying the assessment of nitrate leaching risk. The problem is, in part, one of timing: the production of nitrate from the mineralization of soil organic mater is not necessarily synchronized with crop uptake so a large amount of nitrate can accumulate in soil and be leached later. This lack of synchronization is exacerbated if organic manure, or other N-rich organic materials, is applied to soils in autumn or if much organic matter is mineralized because past organic inputs have been large. Similar effects on mineralization, and the consequent leaching risk, have also been observed where organic materials have been applied for much shorter periods (Powlson et al., 1989).

There is consensus that the amount of nitrates remaining in the soil following harvest is an important factor that reflects the nitrate leaching potential (Chichester, 1977). Nitrogen applications above crop requirements can result in an accumulation of soil nitrate (Hahne et al., 1977; Olsen et al., 1970; Nelson and MacGregor, 1973; Jolley and Pierre, 1977; MacGregor et al., 1974; Herron et al., 1968; Linville and Smith, 1971; Meisinger et al., 1982). Jokela and Randall (1989), in a study with corn conducted for three years on two non-irrigated southern Minnesota soils with different nitrogen rates fluctuating between 75 and 300 kg N/ha, found residual nitrate values in the 1.5 m profile ranging from 150 to 400 kg N/ha for most treatments in the fall.

In a study by Roth et al. (1990), total soil nitrate accumulation varied considerably among sites. Total accumulation averaged over all N treatments ranged from 36 to 295 kg NO_3-N/ha. This variation suggests that field history has a large impact on soil nitrate accumulation. Changes in the soil nitrate concentrations between fall and spring were quite variable. In general, the largest decreases in soil nitrate levels were associated with the highest fall accumulation, although this was not consistent. Bundy and Malone (1988) also observed greater over-winter changes in soil nitrate where fall soil nitrate accumulation was high. Results of a study by Roth et al. (1990) confirmed that nitrate accumulation and the potential for loss increased when N inputs were increased above the needs of the crop.

Under conditions of soil nitrate accumulation, N leaching could be reduced if the amount of water percolation was small. This only works to a certain extent, because large accumulations of N in the soil will lead to a significant increase of leachate N concentrations. Also, infrequent large precipitation events may produce substantial leaching. In Washington State, average annual percolation rates are significant, fluctuating from 50-125 mm in dryland Eastern Washington, to more than 250 mm in irrigated Central Washington (Ryker and Jones, 1995), to 50-500 mm and more in Western Washington (Ronald Hermanson, personal communication).

Nitrate leaching beneath the crop root zone may occur if a significant pool of nitrate accumulates at times when it is likely that water percolation may occur. In most regions, likelihood for significant water percolation is usually at a minimum during periods of active crop growth when evapotranspiration requirements are high. Likelihood for water percolation is usually greatest during non-crop periods or for the first few weeks after planting a crop. To minimize nitrate leaching, soil and crop management practices should be selected so that significant soil nitrate pools are not present during these periods of the season.

The amount of residual N in the soil before winter depends of three main factors: the date of the harvest, the crop grown during the previous growing season, and the N application rates applied to this crop. The more time elapses between harvesting and the beginning of the winter, the more mineral N is released by mineralization. Crops that are harvested late leave the soil when the conditions for mineralization are less advantageous, especially with respect to temperature. Leguminous crops tend to leave a larger amount of residual N than other crops at harvest.

A common reason for nitrate accumulation is the application of more N than is required by the crop. This often results from N application recommendations that are not based on well-calibrated field data on crop response to available N. Results from 50-location years of data in Nebraska showed that fertilization according to well calibrated fertilizer recommendations based on the nutrient replacement concept resulted in equal irrigated maize yields. However, N application recommendations based on calibrated field tests resulted in 40 kg/ha less applied N. Excess N is left over as residual soil N and may be subject to leaching (Power and Broadbent, 1989). Numerous California studies (reviewed by Pratt, 1984) have demonstrated that, in situations where roots have access to the entire soil solution, little nitrate is leached until excess N is applied or the soils are over-irrigated.

Liang et al. (1989) worked with corn and two N application rates, high (400 kg N/ha) and normal (170 kg N/ha). They found that the high application rate significantly increased soil nitrate during the growing season, and a residual effect of excess N application in soil nitrate was found in 2 of 3 years during the non-growing season. Losses of soil nitrate over winter also occurred in 2 of 3 years.

Alcoz et al. (1993), working in Texas with two N rates in wheat, found that nitrate concentration increased significantly with increasing fertilizer N application in the surface 30 cm (75 and 150 kg N/ha). Chaney (1989), using several N application rates (applied at 0 to 280 kg N/ha) in winter wheat, found that the residual soil nitrate did not increase in proportion to the amount of N applied. Residual N only increased when the optimum agronomic N rate was exceeded.

Using six N application levels and three texture-contrasted soils, Isfan et al. (1995) reported that high amounts of nitrate-N may remain in the soil at harvest and may be available to losses by leaching and denitrification during subsequent months. Either in a light soil (sandy) or a heavy clay soil, these authors found a positive correlation between added N at planting and soil nitrate at harvest. For the sandy soil, when the application was from 0 to 200 kg N/ha, the residual N fluctuated between 33.7 up to 74.5 kg N/ha. In the heavy clay, these figures were from 37.5 up to 145.5 kg N/ha, denoting some accumulation of NO_3-N in the clayey soil due to slower leaching.

Management practices affecting residual nitrates also include cropping systems and irrigation practices. Cropping systems regulate to a large extent the quantity of N applied, and therefore opportunities for residual nitrates to accumulate. Monoculture of grain crops probably offer the greatest opportunity for accumulation of residual nitrate because usually N rates are large and mechanisms for utilizing residual nitrates are least active for such systems. The crop-fallow system (such as wheat-fallow) is a special type of monoculture. Many publications have documented that nitrates may accumulate to relatively high concentrations in fallowed soils (Power and Broadbent, 1989).

The type of preceding crop is important in determining the amount of residual N during fall. Francis et al (1994), in a experiment using rotations with legume and no legume crops and spring crops, reported that the amount of mineral N remaining in the soil profile in the autumn after harvest of barley and rapeseed crops was relatively low (mean of 52 kg N/ha). After leguminous crops, the residual N was generally larger (mean of 80 kg N/ha).

Timing and rate of irrigation are additional factors that may affect residual nitrate accumulation. A viable irrigation system must include provisions for periodic leaching to prevent an accumulation of salts from occurring. If appreciable amount of nitrate is present in the soil profile when leaching occurs, these nitrates will move beneath the root zone. Therefore, one wants to avoid residual nitrates in irrigated soils to the extent possible to minimize nitrate leaching. Unless poor irrigation practices are used, most of the leaching occurring in irrigated agriculture occurs either in the seedling stage or during non-crop periods (Martin et al., 1982).

Johnson and Raun (1995) indicated that the soil-plant system was able to buffer against soil accumulation of inorganic N after 23 years of N application at different rates in wheat. They did not find inorganic N accumulation in the soil profile until N rates exceeded the recommended rates. They mentioned that increased plant protein, plant N volatilization and denitrification in soil have major buffering mechanisms. These buffering mechanisms allow applying more N than needed without a risk to groundwater quality. They indicated removal of inorganic N by increasing protein in wheat to values of 20% of maximum yield requirements.

Westfall et al. (1996) reviewed the concept of soil-plant N buffering proposed by Raun and Johnson (1995). In this review, they emphasize that some flexibility in N application rates may exist without necessarily having an adverse environmental impact in semi-arid environments. Buffer capacities of about 21 to 50 lb/ac have been reported under annual dryland cropping conditions. However, it is important to remark that these plant buffering capacities are mechanisms that help to reduce soil N accumulation, but they represent only a limited amount of nitrogen. When N application rates plus mineralization exceed crop N uptake (including excess or "buffer" consumption) and gaseous emisions, the remainder accumulates in the soil and leaches off the root zone when percolating waters are available for transport.

The water storage of the soil is also important to determine N accumulation and leaching, as seen previously. In general, the higher the water storage capacity of the soil the lower is the amount of N leached for similar water inputs. Soil N accumulation is determined to a high degree by the clay content of the soil. Vetter and Steffens (1981) showed experimentally that N concentrations in shallow groundwater increased to higher levels on sandy soils than in clay soils after 4 years of application of pig slurry. Spallacci (1979) also found in lysimeter experiments with slurry than N leaching was higher on sand than on loamy sand, loamy sand higher than on loam, and loam higher than on clay.

Olsen et al. (1970) showed that, on the Plano soil in Wisconsin, nitrate accumulated in the profile over a 3-year period when excess N was continually added to corn. The downward rate of nitrate movement was 30 to 40 cm per year. While it would require a number of years for most of the unused nitrate added in a given year to reach the groundwater, this nitrate load would be more or less continuous after a period of time. The lag time will depend on the travel time of the nitrate front and the depth to groundwater (Randall, 1985). Nitrate moves slower in clay loam and clay soils.

Determination of plant-available N in the soil prior to N application requires soil testing for nitrate within the root zone. Ammonium may also be significant at times during the year. Assuming that a representative soil sample or series of samples is collected by depth increments to the bottom of the root zone, the amount of residual soil N can be calculated by multiplying the nitrate-N concentration times the depth increment of the sample. Estimating residual N within the root zone based only on a surface sample (15 to 30 cm) is extremely risky and should be avoided. Reasons are that subsoil residual soil N may represent a significant portion of the plant-available N. For example, the surface 30 cm of soil from 138 farms over a 4-year period in the Platte River Valley of Central Nebraska contained only 32% of the plant-available N found in the upper 1.2 m of soil (Schepers and Mosier, 1991).

The importance of residual nitrate has been recognized in countries such as Germany. To protect groundwater against nitrate leaching losses from agricultural soils, changes in management practices have been proposed. To evaluate their environmental impact, the amount of residual soil nitrate in late fall has been considered as a quantity that reflects the previous management of a field. Since this quantity is also rather easily measured, it is regarded as a possible indicator to evaluate a land user's environmental performance. Not clear so far is which amount of late-fall nitrate should reflect the site-specific risk of seepage and leaching losses (Van Der Ploeg et al., 1995).

Van der Ploeg et al. (1995) pointed out that care should be exercised before setting limits to recommended levels of soil nitrates in late fall. A given value, chosen somewhat arbitrarily and applied statewide, regardless of local soil, climate, or aquifer conditions is not a desirable approach.

7. POTENTIAL TO AFFECT GROUNDWATER WHEN N IS APPLIED AT RECOMMENDED AGRONOMIC RATES

Summary

Problems with nitrate in groundwater are found in all countries with high levels of agricultural production. The implementation of measures controlling the problem is managed according as to a) how far drinking water resources are endangered, and b) how far the interests of water management and agriculture can be brought into line. Some studies seem to suggest that it is unrealistic to expect water from intensively used agricultural areas to meet drinking-water quality standards. However, proper water and nitrogen management should be encouraged to minimize the impact.

Nitrate-N reaching the groundwater may result from point sources such as feedlots and sewage disposal systems, from non-point sources such as land application of N or from naturally occurring sources of nitrogen. The amount of nitrate leaching will depend on the availability of soluble N and the vertical transport of leachate through the soil profile. The nitrate loading impact on groundwater quality largely depends on whether the aquifer system is confined or unconfined and if unconfined, at what depth. Confined aquifers often are hydrologically, chemically, and biologically much more isolated than are unconfined aquifers.

Success in mitigating groundwater quality problems can only be expected in the long term. One reason is the long duration of groundwater transport in most catchment areas. The main factors influencing impact to groundwater are: a) The kind of soil use, b) the depth of the groundwater table, c) the groundwater recharge dependent on soil use, d) land N application rate and soil cultivation, e) soil characteristics which influence the efficiency of N transformation.

In most catchment areas, models using information on land use, soils, and fertilization and water infiltration regime can estimate the average nitrate concentration in percolation water. However, other sources of recharge (e.g., canal leakage) with different nitrate concentration may also be significant in some areas. The nitrate concentration in percolation water would be similar to the concentration reaching groundwater, if no nitrate decomposition takes place between the boundary of the root zone and the aquifer.

Problems with nitrate in groundwater are found in all countries that have a high level of agricultural production. The implementation of measures controlling the problem is managed more or less intensively according to a) how far drinking water resources are endangered, and b) how far the interests of water management and agriculture can be brought into line. Studies in Germany suggest that it is unrealistic to expect water from intensively used agricultural areas to meet drinking-water quality standards (Walther, 1989).

The main factors influencing impact to groundwater are: a) the depth of the groundwater table, b) the groundwater recharge, c) the kind of soil use, d) N load and soil cultivation, e) soil characteristics which influence the efficiency of N transformation, such as the ratio of organic carbon to organic N and pH value.

In most catchment areas, the average nitrate concentration in percolation water can be estimated by models using information on land use, soils, N application rates, and water infiltration regime. However, other sources of recharge (e.g. canal leakage) with different nitrate concentration may also be significant in some areas (e.g. South Columbia Basin Irrigation District). The nitrate concentration in percolation water would be similar to the concentration reaching groundwater, if no nitrate decomposition takes place between the boundary of the root zone and the aquifer (Walther, 1989).

The intermediate vadose zone (IVZ) is the subsurface material bounded by the root zone and water table. This root zone boundary has physical and chemical significance because it defines the lower boundary for the processes controlling nitrate and water entry to the IVZ: water extraction by plant transpiration, N extraction (plant uptake or denitrification), N addition (N fixation or fertilization), root or root pathway influences on preferential saturated flow, and released of N and C by plant decomposition. Often, the IVZ is viewed as a transmission zone where the nitrate concentration may be changed substantially due to dispersion or dilution enroute, but the nitrate load delivered to the water table is basically that draining from the soil root zone (Pionke and lowrance, 1991). The IVZ is recognized as a nitrate storage zone, with the detention time being based primarily on the water holding capacity, flow, and climatic properties of the system. For example, a thick fine-textured IVZ in an arid climate, might require decades to centuries before nitrate-containing percolate from the overlying soil enters the water table, whereas a thin, coarse-textured or fractured IVZ subject to a humid climate or irrigation might transmit on a time scale of hours to months. The same response times for improvement are required when practices reducing nitrate loading are implemented.

The nitrate loading impact on groundwater quality largely depends on whether the aquifer system is confined or unconfined and if unconfined, at what depth. Confined aquifers often are hydrologically, chemically, and biologically much more isolated than are unconfined aquifers. In contrast, the unconfined aquifer directly contacts the IVZ, is generally closer to the land surface, and receives recharge directly from the root soil zone (Freeze and Cherry, 1979). The unconfined shallow aquifers, particularly those that penetrate the root zone, can be especially active biologically due to an abundance of microorganisms, organic C, and nutrients compared to deeper unconfined or confined aquifers. Nitrate-N fate and transport in any aquifer depends on a combination of geochemical, physical, and biological factors. Nitrate-N entering shallow aquifer systems, especially those with rapidly fluctuating or controllable water tables, has a good chance for removal by denitrification (Pionke and lowrance, 1991). Once nitrate reaches a complex regional aquifer system, the processes that reduce nitrate concentrations can be difficult to distinguish. Where large spatial scales or travel times on the order of centuries to millenia separate source and impact areas, the effects of dilution Vs. denitrification may be difficult to separate, and dilution may well dominate. Denitrification does occur at this scale, but denitrification rates are extremely slow.

The effect of dilution depend on the relative positioning of the source (field of concern) and impact zone (groundwater of concern). Dilution affects nitrate concentration but not loads. Dilution will be minimal when the groundwater sources represent similar land use and N management. For example, the nitrate contribution from one potato field in a watershed totally filled with potato fields that are similarly managed is unlikely to be diluted irrespective of position. Dilution is likely to be minimal when the groundwater table is shallow, or the field source and groundwater zone of concern are close together and the field occupies the highest position of the landscape. The deeper the water table position below the field the more likely that the unsaturated overburden draining directly to that water table will be a larger volume, possibly including much more than the field. For the situation where the groundwater impact zone is at considerable difference in depth and distance from the field, the dilution of nitrate draining one field can be totally dominating and mask that field's contribution (Pionke and lowrance, 1991)

When water from the vadose zone joins underlying groundwater, it tends to stay at the top of the (unconfined) aquifer. This vertical "stacking" occurs where the density of total dissolved salt content of the water in the vadose zone does not exceed that of the water in the aquifer, as can be expected in humid areas. The deep percolation water from irrigated land in relatively dry climates tends to have salt contents on the order of 2,000 to 5,000 mg/L. If this water reaches an aquifer with good quality water, it could "sink"deeper into the aquifer and eventually reach the lower boundary. This would cause more complex mixing with the original groundwater (Bouwer, H., 1989). A more complex mixing is more typical of conditions at the Columbia Basin (J. Ebbert, USGS, personal communication).

Nitrate in groundwater is subjected to a variety of physical, chemical, and biological processes which lead to changes in concentration or mass of nitrate solution. Biological and chemical denitrification are important in many aquifers for removing nitrate. Biological denitrification rates are controlled by redox conditions, available carbon and denitrifier populations. Denitrification will lead to increases in dissolved dinitrogen gas or nitrous oxide in groundwater. Dissimilatory nitrate reduction and immobilization are also of potential importance in reducing the mass of nitrate. Once nitrate has entered groundwater, heterogeneity within the aquifer can decrease either concentration or mass. Recharge by water with lower nitrate concentration causes dilution. Movement into confined aquifers can lead to chemical evolution of the groundwater towards oxygen depletion and more reduced conditions. Movement into less permeable areas or carbon-rich portions of the aquifer can promote nitrate reduction through denitrification. Case studies of regional aquifers systems have demonstrated that nitrate disappearance occurs in contaminated aquifers although numerous interpretations of removal mechanisms are possible. Most studies used indirect measurements to indicate that biological denitrification does or can reduce nitrate levels in groundwater. The restoration of nitrate contaminated aquifers may be accomplished under certain conditions by enhancing biological or chemical denitrification rates. Increased dissolved organic carbon and other nutrients in a contaminated aquifer would probably increase denitrification due both to the increased carbon supply and more anaerobic conditions (Lowrance and Pionke, 1989).

Nitrate unused by crops will accumulate in the soil, leach when percolation water is available, to reach eventually groundwater. Baker et al. (1975) and Baker and Johnson (1981) in Iowa measured losses of 41 to 55% of N applications into subsurface drains 1.2m deep. Average concentrations of nitrate from study sites, principally Webster (fin-loamy, mixed, mesic Typic Haplaquolls) and Nicollet (fine-loamy, mixed, mesic Aquic Hapludolls) soils, planted to corn (Zea mays L.) were 20 to 40 mg/L, depending on application rate (56 or 116 kg/ha). An application of 28 kg/ha N to bahiagrass (*Papalum notatum* Fluegge) produced a maximum concentration of 35 mg/L of nitrate in leachate 27 d after application. Magette et al. (1990) in Maryland in a study of Sassafras sandy loam (fine-loamy, siliceous, mesic Typic Hapludults) or Elkton silt loam (clayey, mixed, mesic Typic Ochraquults) observed nitrate-N (applied to both grains and legumes) in wells about 8 m deep in concentrations 15 to 18 mg/L. They suggested that NO_3 concentrations measured in shallow unconfined groundwater beneath well-drained soil might be somewhat higher than those measured in groundwater below poorly drained soil. Kladivko et al. (1991) in Indiana measured NO_3-N leaching through Clermont silt loam (fine-silty, mixed, mesic Typic Ochraquals) planted to corn into drains (5-40 m spacing) 0.75 m deep. Nitrate-N losses averaged 18 to 70 kg/ha (6-25% of application), and concentrations, seldom less than 10 mg/L, averaged 20 to 30 mg/L. Drury et al. (1993), in a tillage study on Brookston clay loam (clayey, mixed, mesic Typic Haplaquolls) planted to corn in Ontario, observed concentrations of nitrate-N in drains 0.95 m deep that averaged 12 to 17 mg/L. Nitrogen leaching amounted to 8 to 16% of application (179 kg N/ha) over a 2-yr investigation.

Saint-Fort et al. (1991) reported that the average total nitrate-N loading in the vadose zone to a depth of 9.50 m associated with feedlot, native grassland, irrigated corn fields, and urban lawns was 1403, 183, 1116, and 235 kg/ha, respectively. The data indicated that the potential for groundwater pollution was great for feedlots and land under irrigated corn receiving manure and fertilizer N applications.

Stewart et al. (1967) investigated the vertical distribution of nitrate-N from soil surface to the water table or bedrock for sites of differing land uses. Average values of cumulative NO_3-N to a depth of 6.1 m in transit to the water table varied widely with land use: alfalfa, 88; native grassland, 101; cultivated dryland, 292; irrigated fields not in alfalfa, 567; and corrals, 1608 kg/ha. They further acknowledged that care must be exercised in the interpretation of the results due to extreme variability within land-use classes. In that regard, they observed that the amount of nitrate-N under feedlots varied from virtually none to more than 5600 kg/ha in a 6.1 m profile. They ascribed this difference to low oxygen levels in these soil profiles that probably resulted in higher N loss by denitrification. Their data also indicated that irrigated lands contributed to more nitrate-N to groundwater than did feedlots, although a higher concentration of nitrate-N per unit area was found under feedlots.

Irrigated corn fields in southwestern Nebraska appear to represent a significant source of nitrate in groundwater. Significantly higher nitrate-N concentrations were observed below the zone of 1.5 m depth under irrigated corn fields compared to any of the other various kinds of landuse. Typical N application rates of 90 to 130 kg/ha of fertilizer N for the area are complemented with an estimate of 15 t/ha/yr of feedlot manure (Saint-Fort et al., 1991). A number of investigations have indicated that using manure to supply N at recommended agronomic rates may result in significantly higher leaching loss of nitrate than when inorganic N fertilizer is applied (Sims, 1987). Typically, about 30% of the organic matter is mineralized during the first cropping season. Manure would therefore act as a slow-release fertilizer N and mineralized N released either in the spring of the fall after harvest (when plants are not actively growing) would be susceptible to leaching to groundwater.

Madison and Brunett (1985) showed the northeastern USA as a problematic area for nitrate contamination of groundwater. In this area, intensive livestock operations coexist with relatively dense rural populations that limit availability of agricultural land. Nitrogen availability on many dairy farms exceeds amounts required for corn production. Manure applications to perennial forages on dairy farms would increase the land area available for spreading, thereby decreasing the application rate, improving the N balance, and thus lessening the potential of nitrate leaching. Alfalfa is usually grown in succession with corn and is the preferred perennial forage legume among dairy farmers in the northeastern USA. Schuman and Elliott (1978) reported that N removal by alfalfa was 2.5 to 3 times greater than that by corn. Various researchers have shown that alfalfa removes water and nitrate from deep in the soil (Mathers et al., 1975; Schertz and Miller, 1972; Olsen et al., 1970; Stewart et al., 1968; Brown et al., 1963). Despite these qualities, careful management of N rates is important, just like with any other crop. Excess N applications will unavoidably lead to increased N pollution of groundwater. Also, N management after alfalfa must be careful due to the N supply from mineralization of alfalfa residues and roots.

8. POTENTIAL TO AFFECT GROUNDWATER WHEN N IS APPLIED AT RATES LARGER THAN RECOMMENDED AGRONOMIC RATES

Summary

Application of N at rates larger than recommended agronomic practice will lead to increased N concentrations of groundwater in most regions. Nitrate-N moves readily through soil, and in areas receiving high N application rates, there is ample evidence of substantial groundwater impact.

Research has found that denitrification is potentially important in removing nitrate from the intermediate vadose zone, particularly when shallow water tables are present. Despite its beneficial role in removing nitrates from groundwater under some conditions, this mechanism can not compensate for poor management. Denitrification can not be regarded as a natural treatment for N loading to groundwater resulting from excess application of fertilizer or organic wastes. At best, it may provide some mitigation.

Application of N at rates larger than recommended agronomic practice will lead to increased N concentrations of groundwater in most regions.

Ronen and Magaritz (1985), studying the water-table region of a 25-m deep phreatic sandstone aquifer in Israel, lying under fields irrigated with sewage effluents for up to 22 years, found that the average concentrations of NO_3-N were up to 225 mg/L. The area studied received a very high nitrogen load from fertilization and the use of sewage effluents for irrigation.

Nitrate-N moves readily through soil, and in areas receiving high N application rates, it has been collected and analyzed in subsurface water samples collected by a variety of means. Logan et al. (1980) reported nitrate-N concentrations ranging from 5.0 to 120.0 Mg/L in tile lines under corn (*Zea mays* L.) in Iowa, Minnesota, and Ohio. In Iowa tile lines, Baker et al. (1975) and Baker and Johnson (1981) observed nitrate-N levels of 10 to 70 mg/L under corn rotated with oat (*Avena sativa* L.) or soybean (*Glycin max* L.). Other tile line analyses revealed 3.4 to 51.4 mg/L NO_3-N under a multiple cropping system in New York state (Zwerman et al., 1972); 4.0 to 20.4 mg/L NO_3-N under a mineral soil cropped to corn in Ontario (Miller, 1979); and 13 to 81 mg/L NO3-N under continuous corn in Minnesota (Gast et al., 1978).

In the Georgia coastal plain, Hubbard et al. (1984) used wells in intensive multiple cropping systems with center pivot irrigation. Nitrate-N concentrations in the wells ranged from <1 to 133 mg/L with a mean of 20 mg/L. In a Nebraska study with irrigated corn, the average annual flow-weighted nitate-N concentrations in extracted soil water ranged from 28.3 to 75.2 mg/L (9). Burwell et al. (1976) collected subsurface discharge from four corn watersheds in Iowa and found monthly average water weighted concentrations of nitrate-N as high as 40 mg/L. In eastern Ohio, a small corn watershed received N fertilizer, which was treated with a nitrification inhibitor. Seasonal nitrate-N concentrations in subsurface discharge from this watershed ranged between 10 and 32 mg/L (Owens, 1987). In percolate from non-weighing lysimeters in Minnesota, which were planted to corn, seasonal nitrate-N concentrations ranged from 14 to 212 mg/L and flow weighted annual means were 19 to 118 mg/L (Timmons, 1984; Timmons and Dylla, 1981). When high rates of N fertilizer were applied to corn on weighing lysimeters in Ohio, seasonal average nitrate-N concentrations in percolate ranged from 15 to 80 mg/L (Chichester, 1977).

Nitrogen movements in deep loess soil and in subsurface discharge were measured on watersheds in southwestern Iowa (Schuman et al., 1975; Burwell et al., 1976). During a 3-year period, the quantity of NO_3-N present below the root zone was substantially higher for the watershed fertilized with 448 kg N/ha/yr than for the one fertilized with 168 kg/ha/yr.

Long-term research in Minnesota (MacGregor et al., 1974) showed that considerable nitrate-N accumulated in the upper 8 m soil depth (most below the root zone) for corn (*Zea mays* L.) fertilized with a high N rate. Gast et al. (1978) determined nitrate-N losses in tile outflow after applications of N to continuous corn and found that average annual losses ranged from 14 to 60 kg/ha, depending on N fertilizer rate. For irrigated corn on a sandy loam soil, Gerwing et al. (1979) reported that ground-water nitate-N concentrations were increased about 7 and 10 ppm by early September for on-time applications of 179 and 269 kg N/ha, respectively.

Lysimeter studies throughout the United States have shown that N leaching losses vary widely depending on experimental treatments (Owens, 1960; Pratt et al., 1967; Endelman et al., 1974; Jones et al., 1974; Kissel et al., 1974; Tyler and Thomas, 1977; Chichester and Smith, 1978). Results of these studies showed that leaching of applied fertilizer N can be substantial, and that nitrate-N can move rapidly in light soils under intensive irrigation.

Weil et al.(1987) conducted a study to determine the vertical and seasonal patterns of nitrate leaching under irrigated coastal plain soils treated with poultry manure (Columbia aquifer in Maryland). Four commercially-farmed corn (*Zea mays* L.) fields were studied, two receiving only fertilizer N (240 to 360 kg N/ha over a 2-yr period) and two with a continuing history of poultry manure applications (25-29 t/ha over 2 yr). In each field, a transect of four monitoring wells was installed 4 to 8 m deep (1 m below the seasonally low water table). Three additional wells were installed in forestland adjacent to three of the fields. Under the unmanured field, groundwater nitrate-N concentrations averaged 15.1 mg/L during August through November 1986, while the corresponding figure for the manured fields was not significantly different at 18.3 mg/L. Two months after spreading manure in November and December, as much as 104 mg/L nitrate-N was measured in the groundwater under the manured fields. From December 1986 through September 1987 the groundwater under the manured fields had significantly higher NO_3-N concentrations than did that under the unmanured fields (43.7 vs. 18.1 mg/L, respectively). The forestland groundwater always contained <1mg NO_3-N/L, and high Cl to NO_3-N ratios, suggesting that NO_3 in the cropland groundwater was lost after entering the forested areas, and that forests may therefore protect waterways from subsurface N contamination.

8.1. The role of denitrification

Denitrification is potentially important in removing nitrate from the intermediate vadose zone (IVZ). Denitrification requires microbiological activity, a C source, and very low O_2 contents or redox potentials. Denitrification losses of the nitrate-N load can be significant where the vadose zone is subject to very shallow or fluctuating shallow water tables (e.g., Englund and Haldorsen, 1986; Jacobs and Gilliam, 1985). The manager or modeler cannot readily estimate the impact of IVZ on nitrate-N delivery to groundwater without collecting substantial data or information on IVZ properties. Where such information is not available, the deep IVZ is best considered as a transmission zone where denitrification is insignificant. In shallow vadose zones, losses by denitrification may be major, particularly where high organic C contents, high microbial populations, high temperatures, and low O_2 or redux status exist (Pionke and lowrance, 1991).

Research has concluded that nitrate concentration in shallow groundwater shows a positive correlation with the mean depth of the groundwater table. Smaller depths, increased moisture content in the root zone and decreased oxygen content enhance denitrification, thus reducing nitrate flux into the groundwater (Krajenbrink et al., 1989).

Despite the loss of considerable fertilizer N in drainage waters of agricultural fields of the North Carolina coastal plain, low concentrations of nitrate are found in the groundwater beneath the poorly-drained soils of this area. Denitrification has been proposed as the major loss mechanism (Jacobs and Gilliam, 1985). Numerous studies on the fate of nitrate below organic waste disposal sites (food processing waste lagoons, manure lagoons, feed yard, sewage sludge and effluent septic tank drainfields) have indicated significant denitrification in the vadose zone (Keeney, 1981; Smith and Peterson, 1982).

Land application of organic wastes, especially concentrated wastes such as poultry manure, can lead to nitrate accumulation in the profile and groundwater pollution (Jackson et al., 1977; Smith and Peterson, 1982). Because of the presence of readily degradable organic matter, denitrification also may occur with high organic waste loading (Smith and Peterson, 1982).

Gast et al. (1974) studied nitrate-N accumulation and distribution in a fertilized tile-drained Webster clay loam soil in south central Minnesota and concluded that there was relatively little loss of NO_3-N from tile drains and that most of the unaccounted for fertilizer N applied over that removed by the crop was lost by denitrification.

Variations in the natural abundance of stable nitrogen isotopes can semi-quantitatively differentiate inorganic from waste sources of nitrate in groundwater. Stable nitrogen isotopes also can be used to validate denitrification in aquifers (Mariotti et al., 1988; Smith et al., 1991). This natural remediation process is the inferred dominant cause of nitrate stratification in shallow aquifers (Hallberg, 1989; Gillham, 1991).

Researchers have reported a large variation in denitrification rates in groundwater. Trudell et al. (1986) measured denitrification rates of 0.0078 - 0.13 g NO_3-N/m^3/h during an in situ experiment in a shallow sand aquifer. Vogel et al. (1981) reported a much slower rate of denitrification in a large flow system in the Kalahari. They estimated that it took about 14 000 years to denitrify 22 mg/L NO_3-N. Smith et al. (1991) used transport times from the source to the monitoring well to estimate minimum denitrification rates in a sand and gravel aquifer on Cape Cod. Denitrification of a 15 mg/L NO_3-N plume had to occur within 2 years.

Spalding et al. (1993) conducted an investigation to isotopically characterize nitrate contamination in the groundwater from a dispersed waste source, namely, aerobically digested sewage sludge applied to crop-land, to test for the occurrence of denitrification using stable isotope methodology, and to estimate the persistence of nitrate in shallow aquifers. They concluded that denitrification in the deeper zones is occurring in modern groundwater. The rates of denitrification as suggested by the small isotopic enrichment factor for these samples further support the hypothesis that the process has occurred in a relatively short period of time (years). This relatively rapid denitrification rate is in agreement with groundwater flow estimates that indicate that nitrate transport from the source to its present location is less than 6 years.

Weil et al.(1987) conducted a study in Maryland to compare nitrate-N in groundwater and in the soil profile under center-pivot irrigation to that under adjacent forestland. Since nitrate-N reached high concentrations in the groundwater under the crop fields, but was very low under the forest, it may be hypothesized that it was lost by denitrification in the groundwater environment itself. Such denitrification has been reported in the literature, but under rather different circumstances. For example, work in Germany has shown that sulfide in groundwater can provide the needed energy source for certain denitrifiers (Bottercher et al., 1985). However, the sulfide and sulfate levels were very low in this study. Sulfate-S ranged from 1 to 22 mg/L, but the variation was unrelated to nitrate-N levels. Other studies (e.g., Lowrance et al., 1984; Gambrell et al., 1975) have reported substantial denitrification in very shallow groundwater of certain riparian forests and poorly drained soils.

Recent work by Parkin and Meisinger (1989) supports the concept that denitrification activity is closely related to organic C supply. Both the numbers of denitrifying organisms and denitrification enzyme activity were undetectable below the 2-m depth in the vadose zone in their study on a Maryland Coastal Plain soil. However, they did not measure denitrification below the water table and a small increase in denitrifiers just above the water table leaves open the possibility of significant denitrification in the groundwater itself.

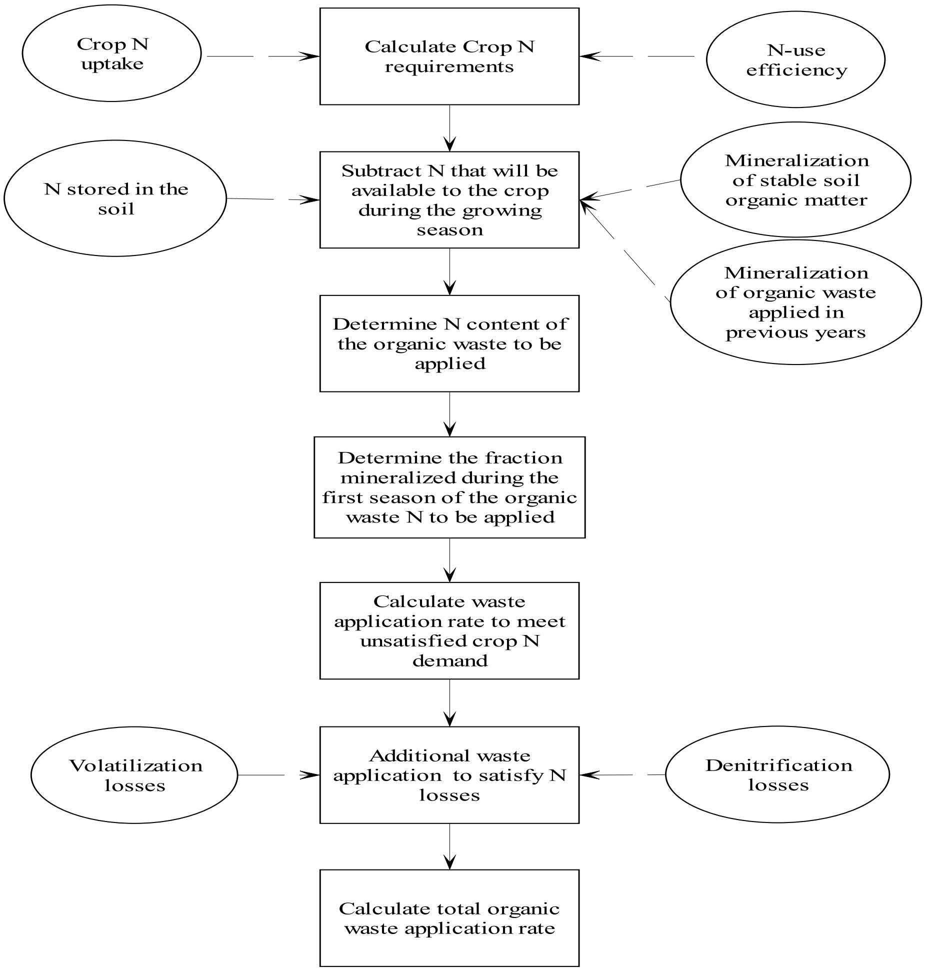
9. RESEARCH RECOMMENDED TO CUSTOMIZE CURRENT KNOWLEDGE ON NITROGEN FATE TO CONDITIONS IN THE STATE OF WASHINGTON

As explained in this report, the fate of nitrogen in agricultural soils cannot be understood, regulated or managed without consideration of the interactions among the components of the soil-plant-atmosphere-water system that affect the soil nitrogen and water balance. This is the case regardless of the source of the nitrogen applied to the soil. However, more pathways are involved in the fate of nitrogen supplied by organic sources. This must be considered when processed water containing organic nutrients is applied to farmlands primarily as a way of disposal.

Figure 9.1 shows the basic steps for calculating organic waste application rates in land application systems. This diagram was used to identify research required before specific recommendations are made to properly manage and mitigate the environmental impact (particularly N leaching) of land application systems in Washington State. From the analysis of the steps required for calculating N application rates, the following questions require answer for customization of this approach to the State of Washington:

1. What is the expected mineralization (inorganic N release) rate derived from the stable organic fraction of the main agricultural soils in the state?
2. What is the expected mineralization rate over several seasons of common organic wastes?
3. What is the expected uptake efficiency of the N derived from common organic wastes in the state?
4. What are the volatilization and denitrification rates typical of these wastes under various application procedures and conditions?
5. What are the maximum allowable soil nitrate levels before significant leaching rates are at risk for the main soils, weather conditions, and cropping systems of the state?
6. What is the risk of nitrate leaching from land application systems across the state for given organic waste application rates, soils, weather, and cropping systems?

Figure 9.1. Basic steps for calculating organic waste application rates in land application systems.



Questions 1 through 4 can be answered using conventional experimental procedures. Some of them can be partially addressed using estimates or extrapolations from the literature. However, uncertainty will be introduced by using such approach. The level of uncertainty in these quantities will be transferred to the decision making process associated with the disposal of organic wastes. Ultimately these uncertainties will limit the feasibility of disposing organic wastes while simultaneously a) maximizing N removal from waste and b) minimizing the risk of nitrate leaching to groundwater. One of these two objectives will need to be relaxed.

The development of a suitable knowledge data base as called for by questions 1 through 4 will lead to the need of formulating a sound computer program, able to calculate organic waste application rates for land application systems in the state, which will allow scheduling disposal procedures with minimized uncertainty.

Questions 5 and 6 cannot be addressed using conventional experimental procedures. An effort of this nature will pose unfeasible resource demands. To evaluate all the necessary variable combinations throughout the state is a gigantic task. In addition, the analysis of risk will require performing these evaluations over a period of 30 or more years in order to adequately capture weather variability and provide sufficient time for cumulative effects to develop. In fact, questions 5 and 6 can only be addressed using computer simulation technology.

Members of our team have developed computer-based technologies for this kind of analyses (Stockle, 1996). These include cropping systems simulators, weather generators, and interface programs for simulation models and geographic information systems (GIS). The cropping systems simulator, CropSyst (Stockle et al., 1994; Stockle, 1996; Stockle and Donatelli, 1996; Stockle and Nelson, 1997), is able to simulate the growth and yield of crops and crop rotations as well as the environmental impact (nitrate leaching, pesticide leaching, erosion) of cropping systems in response to soil, weather, and N application rates. A weather generator, ClimGen (Stockle, 1996; Ndlovu, 1994; Castellvi et al., 1997), is able to develop a comprehensive weather database for the state. Another program, ArcCS (ArcInfo-CropSyst cooperator) allows users to interface GIS data bases with CropSyst simulations and develop analyses of regional scope, and display output results in maps. This suite of programs have been thoroughly tested an applied in the state (Peralta et al., 1997; Pannkuk et al., 1998) and worldwide (e.g. Ferrer and Stockle, 1995; Donatelli et al., 1996; Pala et al., 1996; Stockle et al., 1997; Stockle and Debaeke, 1997; Badini et al., 1997).

Details required to conduct any of the research activities outlined in this section are beyond the scope of this literature review, but they can be provided to DOE upon specific request. As the above models are refined to better simulate field conditions, field data will need to be taken to verify that we are realistically estimating N movement within our complex cropping systems. These data may be obtained from both field scale experiments and whole farm and watershed analyses. The above listed activities will improve our ability to manage land application systems of organic wastes while providing critical environmental protection.

LIST OF REFERENCES

Section 2

Hubbard, R. K., L.E. Asmussen, and H.D. Allison. 1984. Shallow groundwater quality beneath an intensive multiple-cropping system using center pivot irrigation. J. Environ. Qual. 13:156-161.

Keeney, D. R. 1986. Nitrate in Ground Water - Agricultural Contribution and Control. pp.329-351. In: Proceedings - Conference on Agricultural Impacts on Ground Water. Omaha, NE. 11-13 Aug. National Water Well Assoc., Dublin, OH.

Keeney, D. R. 1989. Sources of Nitrate to Ground Water. p. 23-34. In: R. F. Follett (ed.) Nitrogen Management and Ground Water Protection. Elsevier Science Publishing Co. Inc., New York, NY.

Meisinger, J.J. 1976. Nitrogen application rates consistent with environmental constraints for potatoes on Long Island. Search Agric. 6:1-14

Nelson, D.W. 1982. Gaseous losses of nitrogen other than through denitrification. In: F.J. Stevenson (ed.) Nitrogen in agricultural soils. Agronomy 22:327-364.

Peralta, J.M. 1997. Longterm evaluation of nitrogen available for contamination from potato systems in the Quincy-Pasco area of Central Washington. M.S. Thesis, Department of Biological Systems Engineering, Washington State University, Pullman, Washington.

Power, J. F. and F. E. Broadbent. 1989. Proper Accounting for N in Cropping Systems. p.159-181. In: R. F. Follett (ed.) Nitrogen Management and Ground Water Protection. Elsevier Science Publishing Co. Inc., New York, NY.

Ryker, S.J. and J.L. Jones. 1995. Nitrate concentrations in ground water of the Central Columbia Plateau. U.S. Geological Survey Open-File Report 95-445.

Stewart, S., C. Cogger, C. Smith, and C.F. Feise. 1994. The State of our groundwater: A report on documented chemical contamination in Washington. Cooperative Extension Washington State Univer., Washington Toxics Coalition EB1756A. Pullman, WA.

US Geological Survey. 1992. Surface water quality assessment of the Yakima River Basin, Washington: Analysis of available water quality data through 1985 water year. Open-File Report 91-453.

Section 3

Abbes, C., L.E. Parent, A. Karam, and D. Isfan. 1995a. Onion response to ammoniated peat and ammonium sulfate in relation to ammonium toxicity. Can. J. Soil Sci. 75:261-272.

Abbes, C., L.E. Parent, A. Karam, and D. Isfan. 1995b. N uptake and recovery by onions from peat-mineral fertilizers. Can. J. Soil Sci. 75:273-280.

Abd El-Latif, L.I., El-Sarengawy, N.M. and G.G.D. Salamah. 1984. Growth, yield and nitrogen uptake by barley under different levels of nitrogen in sandy soil. Annals of Agric. Sc., Moshtohor. 20:203-211.

Abernathy, R.H., and W.H. Bohl. 1987. Effects of forage legumes on yield and nitrogen uptake by a succeeding barley crop. Applied Agricultural Research.

Addiscott, T.M. and R.J. Darby. 1991. Relating the nitrogen fertilizer needs of winter wheat crops to the soil's mineral nitrogen. Influence of the downward movement of nitrate during winter and spring. Journal of Agricultural Science. 117: 241-249.

Ahmadi, M., W.J. Wiebold, and J.E. Beuerlein. 1988. Effect of seeding rate and time of N application on oat grain yield. J. Prod. Agric. 1:242-246.

Alessi, J., J.F. Power, and L.D. Sibbitt. 1979. Yield, quality and nitrogen fertilizer recovery of standard and semi-dwarf spring wheat as affected by sowing date and fertilizer rate. J. Agric. Sci. 93:87-93.

Alkanani, T. and A. F. MacKenzie. 1996. Banding urea and lignosulfate in corn Zea mays L.) production and 15N recovery. Can. J. Soil Sci. 76:365-371.

Anda, A. and L. Pinter. 1994. Sorghum germination and development as influenced by soil temperature and water content. Agronomy J. 86:621-624

Anderson, W.K., and R. McLean. 1989. Increased responsiveness of short oat cultivars to early sowing, nitrogen fertilizer and seed rate. Aust. J. Agric. Res. 40:729-744.

Armstrong, M.J., G.F.J. Milford, T.O. Pocock, P.J. Last, and W. Day. 1986. The dynamics of nitrogen uptake and its remobilization during the growth of sugar beet. J. Agric. Sci. Camb. 107:145-154.

Aulakh, M. S., J. W. Doran, D. T. Walters, A. R. Mosier and D. D. Francis. 1991. Crop residue type and placement effects on denitrification and mineralization. Soil Sci. Soc. Am. J. 55:1020-1025.

Baker, A. S. and W. P. Mortensen. 1974. The interaction of fertilizer band leaching and fertilizer source on growth and NPK uptake by sweet corn. p. 40-50, Proceedings of the 25th Annual Pacific Northwest Fertilizer Conference, Richland, WA, Northwest Plant Food Association, Portland, OR.

Baker, J. T., P. J. Pinter, Jr., R. J. Reginato and F. T. Kanemasu. 1986. Effects of temperature on leaf appearance in spring and winter wheat cultivars. Agronomy J. 78(4):605-613.

Barber, L.D., B.C. Joern, J.J. Volence, and S.M. Cunningham. 1996. Supplemental nitrogen effects on alfalfa regrowth and nitrogen mobilization from roots. Crop Sci. 36:1217-1223.

Barbour, N.W., and C.F. Murphy. 1984. Field evaluation of seedling root length selection in oats. Crop Sci. 24:165-169.

Bartz, J. K., and R. L. Jones. 1983. Availability of nitrogen to sudangrass from ammonium-saturated clinoptilolite. Soil Sci. Soc. Am. J. 47:259-262.

Batal, K.M., K. Bondari, D.M. Granberry, and B.G. Mullinix. 1994. Effects of source, rate, and frequency of N application on yield, marketable grades and rot incidence of sweet onion (Allium cepa L. cv. Granex-33). J. Hort. Sci. 69:1043-1051.

Bauer, A. 1980. Responses of tall and semidwarf hard red spring wheats to fertilizer nitrogen rates and water supply in North Dakota 1969-1974. North Dakota Agricultural Experiment Station, North Dakota State University.

Bergersen, F. J., G. L. Turner, R. R. Gault, M. B. Peoples, L. J. Morthorpe, and J. Brockwell. 1992. Contributions of nitrogen in soybean crop residues to subsequent crops and to soils. Aust. J. Agric. Res. 43:155-169.

Biemond, H., and J. Vos. 1992. Effects of nitrogen on the development and growth of the potato plant. 2. The partitioning of dry matter, nitrogen and nitrate. Ann. Bot. 70:37-45.

Bock, B.R., and G.W. Hegbert. 1991. Fertilizer nitrogen management. In R.F. Follett, D.R. Keeney and R.M. Cruse (eds.) Managing nitrogen for groundwater quality and farm profitability. Soil Sci. Soc. Am., Madison, WI. p.139-164.

Boman, R.K., R.L. Westerman, W.R. Raun, and M.E. Jojola. 1995. Time of nitrogen application: effects on winter wheat and residual soil nitrates. Soil Sci. Soc. Am. J. 59:1364-1369.

Bowen, J., L. Jordan, and D. Biehle. 1991. Economics of no-till corn planted into winter cover crops. p. 181-182. In W.L. Hargrove (ed.) Cover crops for clean water. Proc. W. Tenn. Exp. Sta. April 9-11, 1991. Jackson, TN. Soil and Water Conservation Society. Ankeny, IA.

Bowman, D.C., and J.L. Paul. 1988. Uptake and assimilation of NO3- and NH4+ by nitrogen-deficient perennial ryegrass turf. Plant Physiol. 88:1303-1309.

Bowman, D.C., and J.L. Paul. 1992. Foliar absorption of urea, ammonium, and nitrate by perennial ryegrass turf. J. Amer. Soc. Hort. Sci. 117:75-79.

Bowman, D.C., J.L. Paul, W.B. Davis, and S.H. Nelson. 1989. Rapid depletion of nitrogen applied to Kentucky bluegrass turf. J. Amer. Soc. Hort. Sci. 114:229-233.

Brar, G.S., and A. J. Palazzo. 1995. Shoot and root development of tall and hard fescues in two different soils. J. Environ. Qual. 24:777-781.

Bremer, E. and C. van Kessel. 1992. Plant-available nitrogen from lentil and wheat residues during a subsequent growing season. Soil Science Society of Am. J. 56:1155-1160.

Brinkman, M.A., and Y.D. Rho. 1984. Response of three oat culltivars to N fertilizer. Crop Sci. 24:973-977.

Brinsfield, R.B. and K.W. Staver. 1991. Use of cereal grain cover crops for reducing groundwater nitrate contamination in the Chesapeake Bay region. p. 79-82. In W.L. Hargrove (ed.) Cover crops for clean water. Proc. W. Tenn. Exp. Sta. April 9-11, 1991. Jackson, TN. Soil and Water Conservation Society. Ankeny, IA.

Broadbent, F.E. 1984. Plant use of nitrogen. In: Hauck, R.D. (ed.) Nitrogen in crop production. ASA, CSA, and SSSA, Madison, WI.

Brown, B.D., A.J. Hornbacher, and D.V. Naylor. 1988. Sulfur-coated urea as a slow-release nitrogen source for onions. J. Amer. Soc. Hort. Sci. 113:864-869.

Bulman, P., and D.L. Smith. 1993. Accumulation and redistribution of dry matter and nitrogen by spring barley. Agron. J. 85:1114-1121.

Bulman, P., and D.L. Smith. 1994. Post-heading nitrogen uptake, retranslocation, and partitioning in spring barley. Crop Sci. 34:977-984.

Bushnell, John. 1941. Exploratory tests of subsoil treatments inducing deeper rooting of potatoes on Wooster silt loam. J. Amer. Soc. Agron. 33:823-828.

Cao, W. and D. N. Moss. 1991. Phyllochron change in winter wheat with planting date and environmental changes. Agron. J. 83(2):396-401.

Cao, W. and D. N. Moss. 1994. Sensitivity of winter wheat phyllochron to environmental changes. Agron. J. 86(1):63-66.

Carrow, R.N., and A.M. Petrovic. 1992. Effects of traffic on turfgrass.. In: Waddington, D.V., Carrow, R.N., and Shearman, R.C. (eds) Turgrass - Agron. Monogr. 32. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. Madison, WI. p. 285-330

Carter, J.N., and D.J. Traveller. 1981. Effect of time and amount of nitrogen uptake on sugarbeet growth and yield. Agron. J. 73:665-671.

Cassman, K.G. and R.E. Plant. 1992. A model to predict crop response to applied fertilizer nutrients in heterogeneous fields. Fert. Res. 31:151-163.

Cattanach, A.W., A.G. Dexter, and E.S. Oplinger. 1991. Sugarbeets. p.1-11. In Altenative Field Crops Manual. University of Minnesota Ctr. for Alternative Plant and Animal Products and the Minnesota Extension Service.

Cerrato, M.E., and A. M. Blackmer. 1990. Comparison of models for describing corn yield response to nitrogen fertilizer. Agron. J. 82:138-143.

Chalifour, F-P., and L. M. Nelson. 1987. Effects of continuos combined nitrogen supply on symbiotic dinitrogen fixation of faba bean and pea inoculated with different rhizobial isolates. Can. J. Bot. 65:2542-2548.

Chaney, K. 1990. Effect of nitrogen fertilizer rate on soil nitrate nitrogen content after harvesting winter wheat. J. Agric. Sci. 114:171-176.

Cherney , J.H. and J.M. Duxbury. 1994. Inorganic nitrogen supply and symbiotic dinitrogen fixation in alfalfa. J. Plant Nutr. 17:2053-2067.

Chhillar, R.K. 1980. Effect of levels of nitrogen and phosphorus on the yield of oat in sodic soils. Indian J. Agron. 25:512-515.

Christensen, N.W., G. Gingrich, and J. Hart. 1995. Fertilizer rate, source and placement of enhanced nitrogen use by hops to protect groundwater quality. Final research report, ODA Ground Water Research and Development Fund.

Clark, A.J., A.M. Decker, J.J. Meisinger, F.R. Mulford, and M.S. McIntosh. 1995. Hairy vetch kill date effects on soil water and corn production. Agron. J. 87: 579-585.

Cumbus, I.P. and Nye, P.H.. 1985. Root zone temperature effects on growth and phosphate absorption in rape Brassica napus cv. Emerald. J. Exp. Bot. 36: 219-227.

Darby, R. J., and D. P. Yeoman. 1994. Effects of methods of cereal straw disposal, seedbed preparation and sowing method on the establishment, yield and oil content of winter oilseed rape (Brassica napus). J. Agric. Sci. 122:393-304.

Das, S. K., G. S. Reddy, K. L. Sharma, K. P. R. Vittal, B. Venkateswarlu, M. N. Reddy and Y. V. R. Reddy. 1993. Prediction of nitrogen availability in soil after crop residue incorporation. Fert. Res. 34:209-215.

De Nobili, M., S. Santi, and C. Mondini. 1992. Fate of nitrogen (15N) from oxamide and urea applied to turf grass: a lysimeter study. Fert. Res. 33:71-79.

Deckard, E.L. Tsai, and C.Y. Tucker, T.C. 1984. Effect of nitrogen nutrition on quality of agronomic crops. In Hauck, R.D. (ed.) Nitrogen in crop production: proceedings, symposium, 25-27. Sheffield, Alabama, May 1982. Am. Soc. Agron., Madison, WI. p. 601-615.

Dev, G., and D.A. Rennie. 1979. Isotope studies on the comparative efficiency of nitrogenous sources. Aust. J. Soil Res. 17:155-162.

Ditsch, D.C. Alley, M.M. Kelley, K.R., and Lei, Y.Z.. 1993. Effectiveness of winter rye for accumulating residual fertilizer N following corn. J. Soil Water Cons. 48: 125-132.

Douglas, C. L. Jr. and R. W. Rickman. 1992. Estimating crop residue decomposition from air temperature, initial nitrogen content and residue placement. Soil Sci. Soc. Am. J. 56:272-278.

Dow, A.I. 1980. Critical nutrient ranges in northwest crops. Washington State Univ. Irrigated Agriculture Research and Extension Center. Ext. Bull. EB-0757.

Dow, A.I., and A.R. Halvorson. 1980. Fertilizer Guide: Irrigated field beans for Central Washington. Washington State University, Coop. Ext. Public. FG-5.

Dow, A.I., K.J. Morrison, and A.R. Halvorson. 1976. Fertilizer Guide: Alfalfa (irrigated) for Central Washington. Washington State University, Coop. Ext. Public. FG-3.

Dow, A.I., K.I. Morrison, C.E. Nelson, D.W. James, and A.R. Halvorson. 1979a. Fertilizer guide: Irrigated field corn for grain or silage in Central Washington. Washington State University, Coop. Ext. Public. FG-6.

Dow, A. I., R. Parker, W. W. Heinemann, D. W. Evans, and A. R. Halvorson. 1979b. Fertilizer guide: Irrigated pasture for Central Washington. Washington State University, Coop. Ext. Public. FG-4.

Dow, A.I., K.I. Morrison, C.E. Nelson, D.W. James, and A.R. Halvorson. 1970a. Fertilizer guide: Irrigated hops for Central Washington. Washington State University, Coop. Ext. Public. FG-11.

Dow, A.I., C. E. Nelson, D.W. James, J.W. Berry, and A.R. Halvorson. 1970b. Fertilizer guide: Irrigated sweet corn for Central Washington. Washington State University, Coop. Ext. Public. FG-35

Dow, A. I., D.W. James, C. E. Nelson, and A. R. Halvorson. 1970c. Fertililizer guide: Sugar beets for Central Washington. Washington State University, Coop. Ext. Public. FG-10.

Dubert, F., A. Skoczowski and J. Biesaga-Koscielniak. 1994. The long-term effect of cold on the metabolism of winter wheat seedlings. I. Growth and hydration of seedlings at in vitro conditions. J. Therm. Biol. 19(2):103-110.

Durieux, R.P., Eugene J. Kamprath, William A. Jackson, and Robert H. Moll. 1994. Root distribution of corn: The effect of nitrogen fertiliation. Agron. J. 86:958-962.

Eck, H.V. and S.R. Winter. 1992. Soil profile modification effects on corn and sugarbeet grown with limited water. Soil Sci. J. Am. 56:1298-1304.

Edwards, L. M. and J. M. Sadler. 1992. Growth vigor of some crop species and cultivars when fall-seeded as winter cover in the Atlantic region of Canada. Can. J. Plant Sci. 72:421-429.

Ells, J.E., A.E. McSay, P.N. Soltanpour, F.C. Schweissing, M.E. Bartolo, and E.G. Kruse. 1993. Onion irrigation and nitrogen leaching in the Arkansas Valley of Colorado, 1990-1991. HortTechnology. 3:184-187.

Engle, C.F., F.E. Koehler, K.J. Morrison, and A.R. Halvorson. 1975. Dry land wheat nitrogen needs (with moisture and nitrate tests) for eastern Washington. Washington State Fertilizer Guide, FG-34.

Evans, J., N.A. Fettell, G.E. O'Connor, D.J. Carpenter, and P.M. Chalk. 1997. Effect of soil treatment with cereal straw and method of crop establishment on field pea (Pisum sativuum) fixation. Biol. Fertil. Soils. 24:87-95.

Ervin, E.H. and A.J. Koski. 1998. Drought avoidance aspects and crop coefficients of Kentucky bluegrass and tall fescue turfs in the semiarid west. Crop Sci. 38: 788-795.

Fanning, C. D. A. R. Halvorson, K. J. Morrison, and F. E. Koehler. 1976. Fertilizer guide: Improved pasture and hay for Eastern Washington. Washington State University, Coop. Ext. Public. FG-37.

Fawcett, J.A. and Frey, K.J. 1982. Nitrogen harvest index variation in Avena sativa and Avena sterilis Oats. Proc. Iowa Acad. Sci. 89:155-159.

Fenn, L.B., R.M. Taylor, M.L. Binzel, and C.M. Burks. 1991. Calcium stimulation of ammonium absorption in onion. Agron. J. 83:840-843.

Ferguson, G.A., I.L. Pepper, and W.R. Kneebone. 1986. Growth of creeping bentgrass on a new medium for turfgrass growth: clinoptilolite zeolite-amended sand. Agron. J. 78:1095-1098.

Fiez, T.E., B.C. Miller and W.L. Pan. 1994a. Assessment of spatially variable nitrogen fertilizer management in winter wheat. J. Prod. Agric. 7:56-93.

Fiez, T.E., B.C. Miller and W.L. Pan. 1994b. Winter wheat yield and grain protein across varied landscape positions. Agron. J. 86:1026-1032.

Fiez, T. E., W. L. Pan, and B. C. Miller. 1995. Nitrogen efficiency analysis of winter wheat among landscape positions. Soil Sci. Soc. Am. J. 59:1666-1671.

Follett, R.F., M.J. Shaffer, M.K. Brodahl, and G.A. Reichman. 1994. NLEAP simulation of residual soil nitrate for irrigated and nonirrigated corn. J. Soil Water Cons. 49(4):375-382.

Fox., R.H., J.M. Kern, and W.P. Piekielek. 1986. Nitrogen fertilizer source, and method and time of application effects on no-till corn yields and nitrogen uptakes. Agron. J. 78:741-746.

Francis, D.D., J.S. Schepers, and M.F. Vigil. 1993. Post-anthesis nitrogen loss from corn. Agron. J. 85:659-663.

Frye, W.W. Smith, W.G. Williams, R.J.. 1985. Economics of winter cover crops as a source of nitrogen for no-till corn. J. Soil Water Cons. 40: 246-248.

Gao, S. 1995. Wheat root growth, distribution and nitrogen uptake in response to an enhanced ammonium supply. Ph.D. Dissertation, Washington State University, Pullman WA. 97 p.

Gascho, G.J. and J.E. Hook. 1991. Development of a fertigation program for sprinkler-irrigated corn. J. Prod. Agric. 4: 306-312.

Gass, W.B., G.A. Peterson, R.D. Hauck, and R.A. Olson. 1971. Recovery of residual nitrogen by corn (Zea mays L.) from various soil depths as measured by 15N tracer techniques. Soil Sci. Soc. Am. Proc. 35:290-294.

Gately, T.F., and D.M. McAleese. 1976. Effects of fertilizer N and number of years in tillage on the protein and non-protein content of feeding barley grain (cv. Nessa) and on N uptake and recovery. J. Agric. Sci. Camb. 87:243-249.

Geist, J.M. 1976. Orchardgrass growth on nitrogen and sulfur fertilized volcanic ash soil. Journal of Range Management. 29:415-418.

George, T., and P.W. Singleton. 1992. Nitrogen assimilation traits and dinitrogen fixation in soybean and common bean. Agron. J. 84:1020-1028.

Ghosh, D.C. 1985. Influence of nitrogen, phosphorous and cutting on growth and yield of oat. Indian J. Agron. 30:172-176.

Glenn, B.P., D.G. Ely, S. Glenn, L.W. Douglass, L.P. Bush, and R.W. Hemken. 1985. Effects of ammonium nitrate and potassium sulfate fertilization on nitrogen and sulfur composition of tall fescue and orchardgrass. Journal of Plant Nutrition. 8:15-38.

Goss, R. L., K. J. Morrison, A. R. Halvorson. 1982. Fertilizer guide: home lawns, playfields and other turf. Washington State University, Coop. Ext. Public. FG-24.

Greig, W.S. Blakeslee, L. 1988. Potatoes: optimum use and distribution with comparative costs by major regions of the U.S. Washington State University, Cooperative. Ext. Bull. 1495.

Griffith, M. and H. C. H. McIntyre. 1993. The interrelationship of growth and frost tolerance in winter rye. Physiol. Plant. 87:335-344.

Griffith, M., P. A., D. S. C. Yang, W. Hon and B. A. Moffat. 1992. Antifreeze protein produced endogenously in winter rye leaves. Plant Physiol. 100:593-596.

Guillard, K., and D.W. Allinson. 1985. Legume growth and residual effects on oat (Avena sativa L.) production. Commun. in Soil Sci. Plant Anal. 16:375-383.

Guillard, Karl, Gary F. Griffin, Derek W. Allinson, M. Moosa Rafey, William R. Yamartino, and Stephen W. Pietrzyk. 1995. Nitrogen utilization of selected cropping systems in the U.S.

Northeast: I. Dry matter yield, N uptake, apparent N recovery, and N use efficiency. Agron. J. 87:193-199.

Halvorson, A.R. 1977. Nitrogen fertilizer use during drought in the summer fallow wheat area of eastern Washington. Washington State Univ. Cooperative. Ext. Bull. EM-4264.

Halvorson, A. R., F.E. Koehler, W.L. Pan, C.F. Engle, K.J. Morrison, and E.T. Field. 1986. Winter wheat fertilizer guide. Washington State University Coop. Ext., EB-1390.

Hammond, M.W. and R. Neilan. 1992. Research for reduction of nitrate leaching into Columbia Basin Groundwater: Final report. Upper Grant Conservation District. Ephrata, WA.

Hanks, R.J. 1983. Yield and water-use relationships: An overview. p. 393-412. In H.M. Taylor,W.R. Jordan and T.R. Sinclair (eds.) Limitations to efficient water use in crop production. Am. Soc. Agron., Madison, WI.

Harms, C. L. and B. B. Tucker. 1973. Influence of nitrogen fertilization and other factors on yield, prussic acid, nitrate, and total nitrogen concentrations of sudangrass cultivars. Agron. J. 65:21-26.

Harper, J.E., and A.H. Gibson. 1984. Differential nodulation tolerance to nitrate among legume species. Crop Sci. 24:797-801.

Hart, P. B. S., D. S. Powlson, P. R. Poulton, A. E. Johnston and D. S. Jenkinson. 1993. The availability of the nitrogen in the crop residues of winter wheat to subsequent crops. J. Agric. Sci. 121:335-362.

Hedge, D.M. 1986. Growth analysis of onion (Allium capa L.) in relation to irrigation and nitrogen fertilization. J. Agron. Crop Sci. 157:227-234.

Heichel G.H., D.K. Barnes, and C.P. Vance. 1981. Nitrogen fixation of alfalfa in the seeding year. Crop Sci. 21:330-335.

Hellstrom, A. 1994. Growth analysis in Brassica using a mechanistic growth model. Swedish J. of Agric. Research 24:57-65.

Henriksen, K. 1987. Effect of N- and P- fertilization on yield and harvest time in bulb onions (Allium capa L.). Acta Horticulture. 198:207-215.

Hensel, D.R., and J.R. Shumaker. 1992. Evaluation of cultural practices, nitrogen rates, and cultivar selection for sweet onion production in northeast Florida. Proc. Fla. State Hort. Soc. 105:338-340.

Hermanson, R.E., A.C.S. Rao, W.L. Pan, K.F. Duncan, and M.A. Wright. 1995. Manure nutrient balancer manual, ver. 1.0. Cooperative Ext. Washington State Univ.

Hills, F.J. and A. Ulrich. 1971. Nitrogen nutrition. In R.T. Johnson et al. (eds.), Advances in sugarbeet production: Principles and practices. The Iowa State University Press, Ames.

Hills, F.J., F.E. Broadbent, and M. Fried. 1978. Timing and rate of fertilizer nitrogen for sugarbeets related to nitrogen uptake and pollution potential. J. Environ. Qual. 7:368-372.

Hodgson, D.R., G.M. Whiteley, and A. E. Bradnam. 1989. Effects of waterlogging in the spring on soil conditions and the growth and yield of spring barley in three cultivation systems. J. Agric. Sci. Camb. 112:265-276.

Honeycutt, C. W., L. J. Potaro and W. A. Halteman. 1991. Predicting nitrate formation from soil, fertilizer, crop residue and sludge with thermal units. J. Environ. Qual. 20:850-856.

Hoyt, G.D. and R.L. Mikkelsen. 1991. Soil nitrogen movement under winter cover crops and residues. p. 91-94. In W.L. Hargrove (ed.) Cover crops for clean water. Proc. W. Tenn. Exp. Sta. April 9-11, 1991. Soil and Water Conservation Society, Ankeny, IA.

Huang, Y. D.H. Rickerl, and K.D. Kephart. 1996. Recovery of deep-point injected soil nitrogen-15 by switchgrass, alfalfa, ineffective alfalfa, and corn. J. Environ. Qual. 25:1394-1400.

Huang, Z.T., and A.M. Petrovic. 1994. Clinoptilolite zeolite influence on nitrate leaching and nitrogen use efficiency in simulated sand based golf greens. J. Environ. Qual. 23:1190-1194.

Huett, D.O. and E. Belinda Dettmann. 1992. Nutrient uptake and partitioning by zucchini squash, head lettuce, and potato in response to nitrogen. Aust. J. Agric.

Huggins, D.R. 1991. Redesigning no-tillage cropping systems : alternatives for increasing productivity and nitrogen use efficiency. Ph.D. Dissertation, Pullman WA. 235 p.

Huggins, D.R., and W.L. Pan. 1992. Nitrogen efficiency component analysis: an evaluation of cropping system differences in productivity. Agron J. 85:898-905.

Huggins, D.R., and W.L. Pan. 1993. Nitrogen efficiency component analysis: an evaluation of cropping system differences in productivity. Agron. J. 85:898-905.

Huggins, D.R., W.L. Pan, and J.L. Smith. 1989a. Improving yield, percent protein and N use efficiency of no-till hard red spring wheat through crop rotation and fall N fertilization. Proc. Far West Regional Fertilization Conference, Coeur d'Alene, ID. 23-25 July. 1989.

Huggins, D. R., W. L. Pan, and J. L. Smith. 1989b. Management considerations for yield, percent protein, and N use efficiency of hard red spring wheat. In STEEP Progress Report, p. 96-98, Annual STEEP Conference, Portland, Oregon.

Hummel, Jr., N.W. 1989. Resin-coated urea evaluation for turfgrass fertilization. Agron. J. 81:290-294.

Humphreys, D. Gavin, Donald L. Smith, and Diane E. Mather. 1994. Nitrogen fertilizer application and seeding date effects on oat grain milling quality. Agron J. 86:838-843.

Ifenkwe, O.P., and E.J. Allen. 1983. Nitrogen and potassium uptake by high-yielding potato crops. J. Agric. Sci. Camb. 101:103-111.

Incerti, M., and G.J.O. Leary. 1990. Rooting depth of wheat in the Victorian Mallee. Aust. J. Exp. Agric. 30:817-824.

Jackson, T.L., H.M. Reisenauer, and G.M. Horner. 1952. Nitrogen recommendations for wheat production in eastern Washington, Stations Circular No. 179. Inst. of Agricultural.

Jackson, W. A., W. L. Pan, R. H. Moll, and E. J. Kamprath. l986. Uptake, translocation, and reduction of nitrate. In C. A. Neyra, ed., Biochemical Basis of Plant Breeding. CRC Press, Boca Raton, Florida.

Jackson, G.D., R.K. Berg, G.D. Kushnak, T.K. Blake, and G. I. Yarrow. 1994. Nitrogen effects on yield, beta-glucan content, and other quality factors of oat and waxy hulless barley. Commun. Soil Sci. Plant Anal. 25:3047-3055.

Jacobsen, J.S., D.L. Tanaka, and J.W. Bauder. 1993. Spring wheat response to fertilizer placement and nitrogen rate with limited moisture. Commun. Soil Sci. Plant Anal. 24: 187-195.

Jacquot, H.D. 1953. Annual cropping with nitrogen in the intermediate rainfall areas of eastern Washington, Stations Circular No. 214. Inst. of Agricultural Sciences, State College of Washington.

Janzen, H.H., T.L. Roberts, and C.W. Lindwall. 1991. Uptake of point- injected nitrogen by winter wheat as influenced by time of application. Soil Sci. Soc. Am. J. 55:259-264.

Jensen, E. S. 1994. Availability of nitrogen in 15N-labelled mature pea residues to subsequent crops in the field. Soil Biol. Biochem. 26(4):465-472.

Jensen, E.S. 1996. Nitrogen acquisition by peas and barley and the effect of their crop residues on available nitrogen for subsequent crops. Biol. Fert. Soils. 23:459-464.

Joern, B.C., and M.L. Vitosh. 1995. Influence of applied nitrogen on potato. Part II: Recovery and partitioning of applied nitrogen. Am. Pot. J. 72:73-84.

Johnson, G.V., and W.R. Raun. 1995. Nitrate leaching in continuous winter wheat: use of a soil-plant buffering concept to account for fertilizer nitrogen. J. Prod. Agric. 8(4):486-491.

Kahn, G. M., S. K. Agawal. 1983. Effect of moisture stress, sowing methods and nitrogen on nutrient content and their uptake by mustard (Brassica juncea Coss.). Indian J. Agronomy 28:425-431.

Karlen, D.L., P.G. Hunt, and T.A. Matheny. 1996. Fertilizer 15nitrogen recovery by corn, wheat, and cotton grown with and without pre-plant tillage on Norfolk Loamy sand. Crop Sci. 36:975-981

Kairudin, N., and K.J. Frey. 1988. Soil N Availability and nitrogen harvest index of oats. Jour. Iowa Acad. Sci. 95:73-78.

Kanneganti, V. R. and S. D. Klausner. 1994. Nitrogen recovery by orchardgrass from dairy manure applied with or without fertilizer nitrogen. Commun. Soil Sci. Plant Analysis 26(15-16):2771-2783).

Kanyama-Phiri, G.Y., C.A. Raguse, and K.L. Taggard. 1990. Responses of a perennial grass-legume mixture to applied nitrogen and differing soil textures. Agron. J. 82:488-495.

Kessavalou, Anabayan and Daniel T. Walters. 1997. Winter rye as a cover crop following soybean under conservation tillage. Agron. J. 89:68-74.

Khanif, Y.M., O. Van Cleemput, and L. Baert. 1984. Field study of the fate of labelled fertilizer nitrate applied to barley and maize in sandy soils. Fert. Res. 5:289-294.

Kleinkopf, G.E. 1994. Nitrogen requirements of russet burbank potatoes. Spud Topics. vol. 36(21), Washington State Potato Commission, Moses Lake, WA.

Kleinkopf, G.E. and R. E. Ohms. 1977. Nitrogen and time of application in potato yield and quality. Proc. Idaho Potato School. p. 15-17.

Kleinkopf, G.E. and R.B. Dwelle. 1978. Effect of nitrogen fertilization on tuber set and tuber size. Proc. Idaho Potato School. p. 26-28.

Kleinkopf, G.E. and D. T. Westermann. 1980. Effects of N and cultural practices on potato growth and quality. Proc. Idaho Potato School. p. 12-18.

Kleinkopf, G.E. and D. T. Westermann. 1986. Petiole testing for efficient nitrogen management. Proc. Univ. Idaho Winter Commodity Schools. 18:163-165.

Klepper, B., and R. W. Rickman, C. M. Peterson. 1982. Quantitative characterization of vegetative development in small cereal grains. Agron. J. 74:789-792.

Klepper, B., and R. W. Rickman. 1990. Modelling crop root growth and function. Adv. Agron. 44:113-132.

Klepper, B., R. K. Belford, and R. W. Rickman. 1984. Root and shoot development in winter wheat. Agron. J. 76:117-122.

Koehler, F.E. 1960. Nitrogen uptake and moisture use by wheat. Proc. Fertilizer Conference of the Pacific Northwest, Salt Lake City, UT. 13-15 July. 1960.

Koenig, R.T. 1993. Morphological development, productivity and nutrient use by spring wheat in response to an enhanced ammonium supply. Ph.D. Dissertation, Washington State University, Pullman WA. 194p.

Krenzer, E. G., Jr., T. L. Nipp and R. W, McNew. 1991. Winter wheat mainstem leaf appearance and tiller formation vs. moisture treatment. Agron. J. 83:663-667.

Kucey, R.M.N. 1986. Effect of fertilizer form, method and timing of application on barley yield and N uptake under dryland conditions in southern Alberta. Can. J. Soil Sci. 66:615-621.

Kucey, R.M.N. 1989a. Contribution of N2 fixation to field bean and pea N uptake over the growing season under field conditions in southern Alberta. Can. J. Plant Sci. 69:695-699.

Kucey, R.M.N. 1989b. The influence of rate and time of mineral N application on yield and N2 fixation by field bean. Can. J. Plant Sci. 69:427-436.

Kuchenbach, R. O., and S.A. Barber. 1987. Yearly variation of root distribution with depth in relation to nutrient uptake and corn yields. Commun. in Soil Sci. Plant Anal. 18(3):255-263.

Kunelius, H.T., and M. Suzuki. 1977. Response of orchard grass to multiple harvests and rates of nitrogen in post-seeding years. Can. J. Plant Sci. 57:763-770.

Kuo, S. 1985. Nitrogen and phosphorus requirements for sweet corn in western Washington. Agric. Res. Ctr. College of Agric. and Home Econ. Washington State Univ.

Kuo, S., U.M. Sainjo, and E. Jellum. 1996. Winter cover cropping influence on nitrogen mineralization, pre-sidedress soil nitrate test, and corn yields. Biol Fertil Soils. 22:310-317.

Ladd, J. N. and M. Amato. 1986. The fate of nitrogen from legume and fertilizer sources in soils successively cropped with wheat under field conditions. Soil Biol. Biochem. 18(4):417-425.

Ladd, J. N., M. Amato, R. B. Jackson and J. H. A. Butler. 1983. Utilization by wheat crops of nitrogen from legume residues decomposing in soils in the field. Soil Biol. Biochem. 15(3):231-238.

Lamb, J.F.S., D.K. Barnes, M.P. Russelle, C.P. Vance, G.H. Heichel, and K.I Hanjum. 1995. Ineffectively and effectively nodulated alfalfas demonstrate biological nitrogen fixation continues with high nitrogen fertilizer. Crop Sci. 35:153-157.

Lang, N.S. and R.G. Stevens. 1997. Survey of central Washington Fertilizer recommendations. Proc. 1997 Wash. Potato Conf., Moses Lake, WA. pg 73-82.

Lang, N.S., R.G. Stevens, R.E. Thornton, W.L. Pan, and S. Victory. 1997. Irrigated potato nutrient management guide for central Washington. Proc. 1997 Wash. Potato Conf., Moses Lake, WA. pg 47-72.

Larrson S., and A.G. Gorny. 1988. Grain yield and drought resistance indices of oat cultivars in field rain shelter and laboratory experiments. J. Agron.Crop Sci. 161:277-286.

LaRue, T. A., and T.G. Patterson. 1981. How much nitrogen do legumes fix? Adv. Agron. 34:15-38.

Lauer, D. A. 1985. Russet Burbank yield response to sprinkler-applied nitrogen fertilizer. Am. Pot. J. 63:61-69.

Lauer, D.A. 1984. Response of Russet Burbank potatoes to sprinkler-applied N fertilizer on sandy soils. Proc. Wash. State Potato Conf. p. 39-49.

Lauer, D.A. 1986. Russet burbank yield response to sprinkler-applied nitrogen fertilizer. Am. Pot. J. 63:61-69.

Law, A. G., K. J. Morrison, A. R. Halvorson and C. D. Fanning. 1975. Fertilizer guide: Grass seed for Eastern Washington. Washington State University, Coop. Ext. Public. FG-38.

Lawlor, D.J. Kanemasu, E.T. Albrecht, W.C. III Johnson, D.E.. 1990. Seed production environment influence on the base temperature for growth of sorghum genotypes. Agron. J. 82: 643-647.

Leggett, G.E. 1959. Relationships between wheat yields, available moisture, and available nitrogen in eastern Washington dry land areas, Bulletin 609. Inst. of Agricultural Sciences, State College of Washington.

Leggett, G.E., and W.L. Nelson. 1960. Wheat production as influenced by cropping sequence and nitrogen fertilization in the 10 to 15 inch rainfall area of eastern Washington, Bulletin 608. Inst. of Agricultural Sciences, State College of Washington.

Lesczynski, D. B., and C. B. Tanner. 1976. Seasonal variation of root distribution of irrigated, field-grown Russet Burbank potato. Am. Potato J. 53: 69-78.

Levin, A., D. B. Beegle, and R. H. Fox. 1987. Effect of tillage on residual nitrogen availability from alfalfa to succeeding corn crops. Agron. J. 79: 34-38.

Lewis, C. E. and C. W. Knight. 1987. Yield response of rapeseed to row spacing and rates of seeding and N-fertilization in interior Alaska. Can. J. Plant Sci. 67:53-57.

Liang, B.C. and A.F. MacKenzie. 1994. Corn yield, nitrogen uptake and nitrogen use efficiency as influenced by nitrogen fertilization. Can. J. Soil Sci. 74: 235-240.

Linford, K., and R. E. McDole. 1977. Survey to investigate potato rooting in southern Idaho soils. p. 109-114. Proc. Annu. Pac. Northwest Fertilizer Conference, Twin Falls, ID., Plant Food Assoc., Portland, OR.

Loffler, C. M., T. L. Rauch, and R. H. Busch. 1985. Grain and plant protein relationships in hard red spring wheat. Crop Sci. 25: 521-524.

Lory, J.A., G.W. Randall, and M.P. Russelle. 1995. Crop sequence effects on response of corn and soil inorganic nitrogen to fertilizer and manure nitrogen. Agron. J. 87: 876-883.

Lucero, D.W., D.C. Martens, J.R. McKenna, and D.E. Starner. 1995. Poultry litter effects on unmanaged pasture yield, nitrogen and phosphorus uptakes, and botanical composition. Commun. Soil Sci. Plant Anal. 26:861-881.

Macduff, J. H., M. J. Hopper, A. Wild and F. E. Trim. 1987. Comparison of the effects of root temperature on nitrate and ammonium nutrition of oilseed rape (Brassica napus L.) in flowing solution culture. J. Expt. Botany 38(192):1104-1120.

Mahler, R. L. and G. A. Murray. 1989. Northern Idaho fertilizer guide: winter rapeseed. CIS 785. Cooperative Extension Service, Agricultural Experiment Station, University of Idaho.

Mahler, R.L., D.F. Bezdicek, and R.E. Witters. 1979. Influence of slope position on nitrogen fixation and yield of dry peas. Agron. J. 71:348-351.

Mahler, R.L., F.E. Koehler, and L.K. Lutcher. 1994. Nitrogen source, timing of application, and placement: effects on winter wheat production. Agron. J. 86:637-642.

Maier, N.A., A. P. Dahlenburg, and T.K. Twigden. 1990. Effect of nitrogen on the yield and quality of irrigated onions (Allium capa L.) cv. Cream Gold grown on siliceous sands. Aust. J. Exp. Agric. 30:845-851.

Malone, M. 1993. Rapid inhibition of leaf growth by root cooling in wheat: Kinetics and mechanism. J. Exp. Bot. 44(268):1663-1669.

Marshall, H.G., F.L. Kolb, and G.W.Roth. 1987. Effects of nitrogen fertilizer rate, seedling rate, and row spacing on semidwarf and conventional height spring oat. Crop Sci. 27:572-575.

Maskina, M.S., J.F. Power, J.W. Doran, W.W. Wilhelm. 1993. Residual effects of no-till crop residues on corn yield and nitrogen uptake. Soil Sci. Soc. Am. J. 57:1555-1560.

Mason, M. G. and I. C. Rowland. 1992. Effect of amount and quality if previous crop residues on the nitrogen fertilizer response of a wheat crop. Aus. J. Expt. Agric. 32:363-370.

McCracken, D. V., S. J. Corak, M. S. Smith, W. W. Frye, and R. L. Blevins. 1989. Residual effects of nitrogen fertilization and winter cover cropping on nitrogen availability. Soil Sci. Soc. Am. J. 53:1459-1464.

McEwen, J., R. J. Darby, M. V. Hewitt, and D. P. Yeoman. 1989. Effects of field beans, fallow, lupines, oats, oilseed rape, peas, ryegrass, sunflowers and wheat on nitrogen residues in the soil and on the growth of a subsequent wheat crop. J. Agric. Sci. 115:209-219.

McLean L.A., F.W. Sosulski, and C. G. Youngs. 1974. Effects of nitrogen and moisture on yield and protein in field peas. Can. J. Plant Sci. 54:301-305.

McMaster, G. S. and W. W. Wilhelm. 1995. Accuracy of equations predicting the phyllochron of wheat. Crop Science 35(1):30-36.

McNeal, F. H., G. O. Boatwright, M. A. Berg, and C. A. Watson. 1968. Nitrogen in plant parts of seven spring wheat varieties at successive stages of development. Crop Sci. 8: 535-537.

McNeal, F. H., M. A. Berg, P. L. Brown, and C. F. McGuire. 1971. Productivity and quality response of five spring wheat genotypes, Triticum aestivum L., to nitrogen fertilizer. Agron. J. 63: 908-910.

McTaggart, I.P., and K.A. Smith. 1995. The effect of rate, form and timing of fertilizer N on nitrogen uptake and grain N content in spring malting barley. J. Agric. Sci. Camb. 125:341-353.

Meek, B.D., D.L. Carter, D.T. Westermann, and R.E. Peckenpaugh. 1994. Root-zone mineral nitrogen changes as affected by crop sequence and tillage. Soil Sci. Soc. Am. J. 58:1464-1469.

Meisinger, J.J., W.L. Hargrove, R.L. Mikkelsen, J.R. Williams, and V.W. Benson. 1991. Effects of cover crops on ground water quality. p. 57-68. In W.L. Hargrove (ed.) Cover crops for clean water. Proc. W. Tenn. Exp. Sta. April 9-11, 1991. Jackson, TN. Soil and Water Conservation Society, Ankeny, IA.

Menelik, G., R.B. Reneau Jr., and D.C. Martens. 1994. Corn yields and nitrogen uptake as influenced by tillage and applied nitrogen. Journal of Plant Nutrition. 17(6):911-931.

Merrill, S.D., D.R. Upchurch, A.L. Black, and A. Bauer. 1994. Theory of Minirhizotron root directionality observation and application to wheat and corn. Soil Sci. Soc. Am. J. 58:664-671.

Millard, P., and B. Marshall. 1986. Growth, nitrogen uptake and partitioning within the potato (Solanum tuberosum L.) crop, in relation to nitrogen application. J. Agric. Sci. Camb. 107: 421-429.

Miller, M. H., E. G. Beauchamp and J. D. Lauzon. 1994. Leaching of nitrogen and phosphorus from the biomass of three cover crop species. J. Environ. Qual. 23:267-272.

Miltner, E.D., B.E. Branham, E.A. Paul, and P.E. Rieke. 1996. Leaching and mass balance of 15N-labeled urea applied to a Kentucky Bluegrass turf. Crop Sci. 36:1427-1433.

Mohammad, M. J. A.. 1993. Wheat growth and P uptake responses to mycorrhizal inoculation and deep P placement. Ph.D. diss. Washington State University., Pullman.

Moorby, H. and P. H. Nye. 1984. The effect of temperature variation over the root system on root extension and phosphate uptake by rape. Plant Soil 78:283-293.

Morton, J. 1976. Fertigation management of irrigated grains in light textured soils. Proc. Fertilizer Conference of the Pacific Northwest, Billings, MT. 13-15 July. 1976.

Moyer, J.L., and D.W. Sweeney. 1990. Tall fescue response to placement of urea/ammonium nitrate solution. Soil Sci. Am. J. 54:1153-1156.

Moyer, J.L., D.W. Sweeney, and R.E. Lamond. 1995. Response of tall fescue to fertilizer placement at different levels of phosphorus, potassium, and soil pH. 1995. J. Plant Nutr. 18:729-746.

Muldoon, D. K. 1985. The effect of nitrogen fertilizer on the growth, mineral composition and digestibility of a sorghum X sudangrass hybrid and Japanese barnyard millet. Aust. J. Expt. Agric. 25:411-416.

Mulla, D.J., A.U. Bhatti, M.W. Hammond, and J.A. Benson. 1992. A comparison of winter wheat yield and quality under uniform vesus spatially variable fertilizer management. Agriculture, Ecosystems, and Environment. 38: 301-311.

Narang, R. S., and S. Singh. 1985. Nitrogen management in Indian mustard. Ind. J. Agron. 30:477-482.

N'Dayegamiye, Adrien. 1996. Response of silage corn and wheat to dairy manure and fertilizers in long-term fertilized and manured trials. Can. J. of Soil Sci. 76:357-363.

Nedel, J.L., S.E. Ullrich, and W.L. Pan. 1997. Nitrogen use by standard height and semi-dwarf barley isotypes. Brasilia. 32:147-153.

Nedel, J.L., S.E. Ullrich, J.A. Clancy, and W.L. Pan. 1993. Barley semidwarf and standard isotype yield and malting quality response to nitrogen. Crop Sci. 33:258-263.

Nelson, D. P. 1990. Potato root morphology and nutrient transport to developing tubers. Ph.D. dissertation, Washington State University, Pullman, WA.

Nickel, S.E., R. Kent Crookston, and Michael P. Russelle. 1995. Root growth and distribution are affected by corn-soybean cropping sequence. Agron. J. 87:895-902.

Nielsen, N.E. and H.E. Jensen. 1986. The course of nitrogen uptake by spring barley from soil and fertilizer nitrogen. Plant Soil 91:391-395.

Nwadukwe, P.O., and V.O. Chude. 1995. Effects of nitrogen and phosphorus fertilization on seed crop of onion (Allium capa L.) in a semiarid tropical soils. Trop. Agric. 72:216-219.

Nykiforuk, C. L. and A. M. Johnson-Flanagan. 1994. Germination and early seedling development under low temperature in canola. Crop Sci. 34:1047-1054.

Oberle, S.L., and D.R. Keeney. 1990. Factors influencing corn fertilizer N requirements in the northern U.S. corn belt. J. Prod. Agric. 3(4):527-534.

Ojala, J.C., J.C. Stark, and G. E. Kleinkopf. 1990. Influence of irrigation and nitrogen management on potato yield and quality. Am. Pot. J. 67:29-43.

Olson, R.A. and L.T. Kurtz. 1982. Crop nitrogen requirements, utilization, and fertilization. In: Stevensen, F.J., J.M. Bremner, R.D. Hauck, and D.R. Keeney (eds). Nitrogen in agricultural soils. Agron. Monogr. 22. ASA,CSA, and SSSA, Madison, WI.

Olson, R.A. and D.H. Sander. 1988. Corn production. p. 639-686. In G.F. Sprague and J.W. Dudley (ed.) Corn and corn improvement. ASA Monogr. 18. ASA, Madison, WI.

Olson, R.V., L.S. Murphy, H.C. Moser, and C.W. Swallow. 1979. Fate of tagged fertilizer nitrogen applied to winter wheat. Soil Sci. Soc. Am. J. 43: 973-975.

Oquist, G., V. M. Hurry and N. P. A. Huner. 1993. Low-temperature effects on photosynthesis and correlation with freezing tolerance in spring and winter

Overman, A. R., and S.R. Wilkinson. 1995. An extended nitrogen, phosphorus, and potassium model for tall fescue. Commun. Soil Sci. Plant Anal. 26:3417-3434.

Overman, Allen R., Denise M. Wilson, and Eugene J. Kamprath. 1994. Estimation of yield and nitrogen removal by corn. Agron. J. 86:1012-1016.

Pan, W. L., J. Brunty, M. Moneymaker, R. Bolton, R. Stevens, R. Boydston, G. Santo, R. Thornton, and S. Victory. 1997. Nitrogen recycling in potato rotations. Proc. Washington State Potato Conf. and Trade Show, p. 33-40. Wash. State Potato Comm., Moses Lake, WA. p.33-39.

Pan, W.L., J.J. Camberato, R.H. Moll, E.J. Kamprath, and W.A. Jackson. 1995. Altering source-sink relationships in profile maize hybrids: consequences for nitrogen uptake and remobilization. Crop Sci. 35:836-845.

Pan, W.L. and A.G. Hopkins. 1991. Plant development and N and P use of winter barley. I. Evidence of water stress-induced P deficiency in an eroded toposequence. Plant Soil 135: 9-19.

Pan, W.L. and L.K. Hiller. 1992. Growth and development of potato root types: Implications for placement and timing strategies in fertility management. Proc. Wash. State Potato Conf. and Trade Fair. p. 105-111.

Pan, W.L., E. Lundquist, R. Bolton, and L.K. Hiller. 1994. Potato root development and N uptake. Proc. Wash. State Potato Conf. and Trade Fair, p. 107-111, Washington State Potato Commission, Moses Lake, WA.

Pan, W. L., D. P. Nelson, and S. Mohebbi. 1990. Potato root growth and function. In Proceedings of Twenty-ninth Annual Washington State Potato Conference, p. 109-112, Moses Lake, WA, Feb. 1-2, 1990.

Pare, T., F.P. Chalifour, J. Bourassa, and H. Antoun. 1992. Forage corn dry-matter yields and N uptake as affected by previous legumes and N fertilizer. Can. J. Plant Sci. 72:699-712.

Parr, J F. 1973. Chemical and biochemical considerations for maximizing the efficiency of fertilizer nitrogen. J. Environ. Qual. 2: 75-84.

Paul, J.W., and G.E. Beauchamp. 1993. Nitrogen availability for corn in soils amended with urea, cattle slurry, and solid and composted manures. Can. J. Soil Sci. 73:253-266.

Peacock, C.H., and P.F. Daniel. 1992. A comparison of turfgrass response to biologically amended fertilizers. HortScience. 27:883-884.

Pelter, G. Q., E. J. Sorensen, R. E., Thornton and R. Stevens. 1992. Dry bulb onion production in the Columbia Basin. Washington State University Cooperative Extension. EB 1693. 16pp.

Peterson, P. W., W. J. Moldovan, K. J. Morrison, S. Fransen, and C. B. Kelsey. 1984. Pasture management guide for Northeast Washington. Washington State University, Coop. Ext. Public. EB 1297.

Petrovic, A.M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. J. Environ. Qual. 19:1-14.

Phillips, R. E., R. L. Blevins, G. W. Thomas, W.W. Frye and S.H. Phillips. 1980. No-tillage agriculture. Science 208:1108-1113.

Porter, L.K. 1995. Irrigated corn 15N uptake, and NO3 carryover and leaching. Conf. Proc., Clean water, clean environment, 21st century: team agriculture, working together to protect water resources. ASAE. Mar 5-8, 1995, Kansas City, Mo. p. 171-174.

Power, J.F., D.L. Grunes, and G.A. Reichman. 1961. The influence of phosphorus fertilization and moisture on growth and nutrient absorption by spring wheat: I. Plant growth, N uptake, and moisture use. Soil Sci. Soc. Am. Proc. 25:207-210.

Power, J.F., W.W. Wilhelm, and J. W. Doran. 1986. Crop residue effects on soil environment and dryland maize and soya bean production. Soil and Tillage Res. 8:101-111.

Powlson, D.S., P.B.S. Hart, P.R. Poulton, A.E. Johnston, and D.S. Jenkinson. 1992. Influence of soil type, crop management and weather on the recovery of 15N-labeled fertiizer applied to winter wheat in spring. J.Agric. Sci. 118:83-100.

Quemada, M. and M. L. Cabrera. 1995. Carbon and nitrogen mineralized from leaves and stems of four cover crops. Soil Sci. Soc. Am. J. 59:471-477.

Raczkowski, C.W. 1984. Fate of subsurface banded (knife) and broadcast N applied to tall fescue (Festuca arundinacea Schreb.). M.S. thesis. Kansas State Univ., Manhattan.

Raczkowski, C.W., and D.E. Kissel. 1989. Fate of subsurface-banded and broadcast nitrogen applied to tall fescue. Soil Sci. Am. J. 53:566-570.

Ramsey, B. R., and A. P. L. Callinan. 1994. Effects of nitrogen fertilizer on canola production in north central Victoria. Aus. J. Exptl. Agric. 34:789-796.

Rao, E., and P.N. Arora. 1979. Studies on uptake of nitrogen by potato crop. Indian J. Agron. 24(4):442-444.

Rao, S.C., and T.H. Dao. 1996. Nitrogen placement and tillage effects on dry matter and nitrogen accumulation and redistribution in winter wheat. Agron. J. 88:365-371.

Rasmussen, P.E., and C.R. Rhodes. 1991. Tillage, soil depth, and precipitation effects on wheat response to nitrogen. Soil Sci. Soc. J. Am. 55:1221-124.

Rasmussen, Paul E., and F. Vance Pumphrey. 1977. Nutrient uptake and distribution in processing peas (Pisum sativum L.) grown under dryland and irrigated conditions in northeast Oregon. p. 147-153. Proc. 28th Annual Pacific Northwest Fertilizer Conference, Twin Falls, ID. 12 July-14 July. 1977.

Raun, W.R., and G.V. Johnson. 1995. Soil-plant buffering of inorganic nitrogen in continuous winter wheat. Agron. J. 87:827-834.

Read, J.C. and R. M. Jones. 1987. Oat silage yield as affected by time of application of nitrogen fertilizer, seeding rate, and planting date. Texas Agric. Expt. Sta., Nov. 1987, p. 29-30.

Reeves, D.W., C.W. Wood, and J.T. Touchton. 1993. Timing nitrogen applications for corn in a winter legume conservation-tillage system. Agron. J. 85:98-106.

Reisenauer, H.M., and G.E. Leggett. 1957. Eastern Washington soils need sulfur, Circular 317. Inst. Of Agricultural Sciences, State College of Washington.

Rennie, R.J., and G.A. Kemp. 1983. N2-fixation in field beans quantified by 15N isotope dilution. II. Effect of cultivars of beans. Agron. J. 75:645-649.

Rennie, R.J., and G.A. Kemp. 1984. 15N-determined time course for N2 fixation in two cultivars of field bean. Agron. J. 76:146-154.

Rickman, R.W., S.E. Waldman, and B. Klepper. 1996. MODWht3: a development-driven whaet grown simulation. Agron. J. 88:176-185.

Roberts, S., and H.H. Cheng. 1984. The use of nitrogen-15 isotope to study nitrogen nutrition of potatoes. Proc. NW Fertilizer Conference, Pasco, WA. 17-18 July. 1984.

Roberts, S., H.H. Cheng, and F.O. Farrow. 1991. Potato uptake and recovery of nitrogen-15-enriched ammonium nitrate from periodic applications. Agron. J. 83:378-381.

Salo, T. 1996. Simulated and measured nitrogen status in soil and in onion crops. Acta Horticulture. 428:193-204.

Sarrantonio, M. 1992. Opportunities and challenges for the inclusion of soil-improving crops in vegetable production systems. Hort. Sci. 27: 754-758.

Sarrantonio, M. and T. W. Scott. 1988. Tillage effects on availability of nitrogen to corn following a winter green manure crop. Soil Sci. Soc. Am. J. 52:1661-1668.

Sartain, J.B. 1992. Natural organic slow-release N sources for turfgrass. Proc. Fla. State Hort. Soc. 105:224-226.

Schomberg, H. H., J. L. Steiner and P. W. Unger. 1994. Decomposition and nitrogen dynamics of crop residues: Residue quality and water effects. Soil Sci. Soc. Am. J. 58:372-381.

Schuurman, J.J. 1980. Root and crop growth of oats as affected by the length of periods of high water-table. Neth. J. agric. Sci. 28:20-28.

Schwarz, K.U. Leon, J. Geisler, G. 1991. Genetic variability in root development of spring barley (H. vulgare L.) and oats (A. sativa L.). Dev. Agric. Managed-Forest Ecol. 24:639-646.

Sharratt, B. S. 1991. Shoot growth, root length density, and water use of barley grown at different soil temperatures. Agron. J. 83:237-239.

Sharratt, B.S., and V.L. Cochran. 1993. Skip-row and equidistant-row barley with nitrogen placement: yield, nitrogen uptake, and root density. Agron. J. 85:246-250.

Shennan, C. 1992. Cover crops, N cycling, and soil properties in semi-irrigated vegetable production systems. Hort. Sci. 27:749-755.

Shipley, P.R., J.J. Meisinger, and A.M. Decker. 1992. Conserving residual corn fertilizer nitrogen with winter cover crops. Agron. J. 84:869-876.

Singh, U.N., and R.A. Singh. 1979. Effect of nitrogen on the yield of rainfed oat and its nitrogen uptake and moisture use. Indian J. Agric. Sci. 49:945-949.

Smith, C. J., G. C. Wright, M. R. Wooroofe. 1988. The effect of irrigation and nitrogen fertilizer on rapeseed (Brassica napus) production in southeastern Australia. II. Nitrogen accumulation and oil yield. Irrig. Sci. 9: 15-25.

Smith, D.L., and D.J. Hume. 1985. Effects of irrigation and fertilizer on N2(C2H2) fixation and yield of white bean and soybean. Can. J. Plant Sci. 65:307-316.

Smith, S. J. and A. N. Sharpley. 1990. Soil nitrogen mineralization in the presence of surface and incorporated crop residues. Agronomy Journal 82:112-116.

Sollenberger, L.E., W.C. Templeton Jr., and R.R. Hill, Jr. 1984. Orchardgrass and perennial ryegrass with applied nitrogen and in mixtures with legumes. 1. Total dry matter and nitrogen yields. Grass and Forage Science. 39:255-262.

Sowers, K.E. 1992. Spring nitrogen applications with point injection or topdress to optimize nitrogen use efficiency, yield and protein in soft white winter wheat. MS Thesis. Washington State University, Pullman WA. 114p.

Sowers, K.E., W.L. Pan, B.C. Miller, and J. L. Smith. 1994. Nitrogen use efficiency of split nitrogen applications in soft winter wheat. Agron. J. 86:942-948.

Stahnke, G.K., S.E. Brauen, R.S. Byther, A.L. Antonelli, and G. Chastagner. 1997. Home lawns. Washington State Univ. Coop. Ext. Serv., Ext. Bull. 482.

Staley, T.E., W.L. Stout, G.A. Jung. 1991. Nitrogen use by tall fescue and switchgrass on acidic soils of varying water holding capacity. Agron J. 83:732-738.

Stanford, G., J.N. Carter, D.T. Westermann, and J.J. Meisinger. 1977. Residual nitrate and mineralizable soil nitrogen in relation to nitrogen uptake by irrigated sugarbeets. Agron. J. 69:303-308.

Starr, J.L. and H.C. DeRoo. 1981. The fate of nitrogen fertilizer applied to turfgrass. Crop Sci. 21:531-536.

Starrett, S.K., N.E. Christians, and T.A. Austin. 1995. Fate of amended urea in turfgrass biosystems. Commun. Soil Sci. Plant Anal. 26:1595-1606.

Staver, K. W., B. B. Brinsfield. 1995. Assessing the impact of changes in management practices on nutrient transport from coastal plain agricultural systems. Chesapeake Research Consortium Report, Project CA NPS#3.

Steen, E. and B. Lindén. 1987. Role of fine roots in the nitrogen economy of sugar beet. J. Agronomy and Crop Science. 158:1-7.

Stevens, R.G. 1988. Effect of nitrogen source, rate and timing on yield and quality of Walla Walla sweet onions. Proc. 39th Ann. Far West Preg. Fert. Conf. Bozeman, MT. July 11-13. pg. 123-132.

Stevens, R. G., and S. Roberts. 1988. Fertilizer guide: Winter wheat (soft white) Central Washington Irrigated. Washington State University, Coop. Ext. Public EB 1487..

Stevens, R.G. 1992. Assessment of the effects of current hop yard management on nitrogen cycling relative to water quality. Unpublished annual report, Hop Research Council.

Stevens, Robert G. 1997. Nitrogen management of winter onions in Washington. p. 104-113. Proc. v.2 Western Nutrient Management Conference. Potash and Phosphate Institute. Salt Lake City, UT. 6-7 Mar. 1997.

Stevens, R.G., and V.I. Prest. 1995. Eastern Washington field test. p. 48-74. In Recycled yard Debris compost growth trial results, 1993-1994. Washington State Univ. Res. Ctr.

Stevens, R.G., R.G. Evans, and S.T. Kenny. 1995. Investigation of the effect of rate and timing of nitrogen application on yield and quality of hops. Washington Hop Industry -1995 Annual Reports, Washington Hop Commission, Hop Growers of Washington, and Washington State University.

Stevens, R.G., R.G. Evans, and S.T. Kenny, and V. Prest. 1993. Investigation of the effect of rate and time of nitrogen application on yield and quality of hops. 1993 Report, Washington Hop Commission.

Stevens, R.G., R.G. Evans, and S.T. Kenny, and V. Prest. 1994. Investigation of the effect of rate and time of nitrogen application on yield and quality of hops. 1994 Report, Washington Hop Commission.

Stirling, G.D., Q.D.A. Ivory., and D.A. Ivory. 1981. Nitrogen and phosphorus fertilization of forage oats in the Maranoa region of southern Queensland. Queensland Journal of Agricultural and Animal Sciences. 38:143-153.

Stoker, R., K. E. Carter. 1984. Effect of irrigation and nitrogen on yield and quality of oilseed rape. New Zealand J. of Exptl. Agric. 12:219-224.

Stout, W.L. 1995. Evaluating the "added nitrogen interaction" effect in forage grasses. Commun. Soil Sci. Plant Anal. 26:2829-2841.

Stout, W.L., and G.A. Jung. 1992. Influences of soil environment on biomass and nitrogen accumulation rates of orchardgrass. Agron. J. 84:1011-1019.

Stute, J. K., and J.L. Posner. 1995. Synchrony between legume nitrogen release and corn demand in the upper Midwest. Agron. J. 87:1063-1069.

Taylor, A. J., C. J. Smith, I. B. Wilson. 1991. Effect of irrigation and nitrogen fertilizer on yield, oil content, nitrogen accumulation and water use of canola. Fert. Res. 29:249-260.

Tester, C. F. 1989. Tall fescue growth in greenhouse, growth chamber, and field plots amended with sewage sludge compost and fertilizer. Soil Sci. 148:452-458.

Teuber, L.R., D.A. Phillips, S. Geng, and W.F. Lehman. 1991. Predicted and actual yield and nitrogen concentration of alfalfa in different nitrogen environments. Crop Sci. 31:1459-1464.

Thornton, R. E., s.L. Victory, and M. W. Hammond. 1997. A comparison of pre-plant nitrogen best management practices on potatoes and their effect on nitrate leaching in the Columbia Basin. In S. Thornton (ed) Proceedings of the thirty-sixth annual Washington State Potato Conference, WA State Potato Commission, Moses Lake, WA.

Tillman, B.A., W.L. Pan, and S.E. Ullrich. 1991. Nitrogen use by northern-adapted barley genotypes under no-till. Agron. J. 83:194-201.

Tindall, T.A., J.C. Stark, and B.D. Brown. 1993. Nutrient management. p. 21-28. In L.D. Robertson and J.C. Stark (ed.) Idaho spring barley production guide. Univ. of Idaho Cooperative Ext. Bull. 742.

Turner, D.O. 1979. Nitrogen fertilization of orchardgrass pasture as influenced by irrigation. p. 1-15. Washington State Agriculture Research Center. Washington Agric. Res. Center. Bull. 881.

Turner, D.O.. 1976. Fertilizer guide: Sweet corn for western Washington. Washington State University Cooperative Extension Service. FG-39.

Turner, D.O., A.R. Halvorson, and M. Jarmin. 1975. Fertilizer guide: Peas for western Washington. Washington State University Cooperative Extension Service. FG-27.

Turner, D.O., W.P. Mortensen, A.R. Halvorson, and A.S. Baker. 1982. Alfalfa-grass seedlings for western Washinton. Washington State University Cooperative Extension Service. FG-16.

Turner, T. R., and N. W. Hummel, Jr. 1992. Nutritional requirements and fertilization. In: Waddington, D.V., Carrow, R.N., and Shearman, R.C. (eds) Turfrass - Agron. Monogr. 32. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. Madison, WI. Pp. 385-439.

Undersander, D. J. and S. Christiansen. 1986. Interactions of water variables and growing degree days on heading phase of winter wheat. Agricultural and Forest Meteorology 38:169-180.

Utomo, M. W. W. Frye and R. L. Blevins. 1990. Sustaining soil nitrogen for corn using hairy vetch cover crop. Agron. J. 82:979-983.

Vandecaveye, S.C., and L.V. Bond. 1936. Yield and composition of alfalfa as affected by various fertilizers and soil types. J. Am. Soc. of Agron. 28:491-504.

Vanotti, M. B. and L. G. Bundy. 1994. Frequency of nitrogen fertilizer carryover in the humid Midwest. Agron. J. 86:881-886.

Vanotti, M. B., and L. G. Bundy. 1995. Soybean effects on soil nitrogen availability in crop rotation. Agron. J. 87:676-680.

Varvel, G. E. and T. A. Peterson. 1992. Nitrogen fertilizer recovery by soybean in monoculture and rotation systems. Agron. J. 84:215-218.

Vaughan, B., D.G. Westfall, and K.A. Barbarick. 1990. Nitrogen rate and timing effects on winter wheat grain yield, grain protein, and economics. J. Prod. Agric. 3:324-328.

Vepraskas, M.J., and M.G. Wagger. 1990. Corn root distribution and yield response to subsoiling for Paleudults having different aggregate sizes. Soil Sci. Soc. J. Am. 54:849-854.

Veseth, R., R. McDole, C. Engle, and J. Vomocil. 1986. Fertilizer band location for cereal root access in no-till and minimum tillage systems. STEEP Extension Publication PNW283, U. Idaho, Washington State University, Oregon State University.

Vigil, M. F. and D. E. Kissel. 1991. Equations for estimating the amount of nitrogen mineralized from crop residues. Soil Sci. Soc. Am. J. 55:757-761.

Wagger, M. G. 1989. Time of desiccation effects on plant composition and subsequent nitrogen release from several annual winter cover crops. Agron. J. 81:236-241.

Wagger, M.G. 1989. Cover crop management and nitrogen rate in relation to growth and yield of no-till corn. Agron. J. 81: 533-538.

Wagger, M.G. and D.B. Mengel. 1988. The role of nonleguminous cover crops in the efficient use of water and nitrogen. p. 115-127. In Cropping strategies for efficient use of water and nitrogen. Special pub. no. 51. ASA-CSSA-SSSA, Madison, WI.

Walters, D.T., and G.L. Malzer. 1990. Nitrogen management and nitrification inhibitor effects on nitrogen-15 Urea: I. Yield and fertilizer use efficiency. Soil Sci. Soc. Am. J. 54:115-122.

Washington Agricultural Statistics Service. 1996. Washington Agricultural Statistics, 1995-96. Olympia, WA

Webster, C.P., R.J. Dowdell, and R.Q. Cannell. 1985. Uptake of labelled nitrate by roots of winter barley on a direct-drilled or ploughed silt loam soil. Soil and Tillage Research. 5:381-389.

Weinert, T. 1996. Cover Crops and the N Cycle in a Potato-Based Rotation. Master's Thesis, Washington State University. 123 pp.

Weinert, T. L., W. Pan, M. Moneymaker, G. Santo, R. Stevens. 1995. Green-manured winter cover crops in irrigated potato rotations. In Proceedings of the WA Potato Conference, p. 23-28, Moses Lake, WA.

Westcott, M.P., M. L. Knox, and J.L. Wraith. 1994. Kinetics of soil-plant nitrate relations in potato and peppermint: A model for derivative diagnosis. Common Soil Sci. Plant Anal. 25:469-478.

Westcott, M.P., L.E. Welty, M.L. Knox, and L.S. Prestbye. 1995. Managing alfalfa and berseem clover for forage and plowdown nitrogen in barley rotations. Agron. J. 87:1176-1181.

Westermann, D.T., and J.J. Kolar. 1978. Symbiotic N2(C2H2) fixation by bean. Crop Sci. 18:986-990.

Westermann, D.T. and R.E. Sojka. 1996. Tillage and nitrogen placement effects on nutrient uptake by potato. Soil Sci. Soc. J. Am. 60:1448-1453.

Westermann, D.T., G.E. Kleinkopf, and L.K. Porter. 1988. Nitrogen fertilizer efficiencies on Potatoes. Am. Pot. J. 65:377-386.

Westermann, D.T., G.E. Kleinkopf, L.K. Porter, and G.E. Leggett. 1981. Nitrogen sources for bean seed production. Agron. J. 75:660-664.

Whitmore, A. P. 1995. Modelling the mineralization and leaching of nitrogen from crop residues during three successive growing seasons. Ecological Modelling 81:233-241.

Wolfe, D. W., D.T. Topoleski, N.A. Gundersheim, and B.A. Ingall. 1995. Growth and sensitivity of four vegetable crop to soil compaction. J. Amer. Hort. Sci. 120:956-963.

Worzella, W.W. 1932. Root development in hardy and non-hardy winter wheat varities. Journal of the American Society of Agronomy. 24:626-637.

Wright, G. C., C. J. Smith, M. R. Woodroofe. 1988. The effect of irrigation and nitrogen fertilizer on rapeseed (Brassica napus) production in southeastern Australia. I. Growth and seed yield. Irrig. Sci. 9:1-13

Wuest, S.B., and K.G. Cassman. 1992a. Fertilizer-nitrogen use efficiency of irrigated wheat: I. Uptake efficiency of preplant versus late-season application Agron. J. 84:682-688.

Wuest, S.B., and K.G. Cassman. 1992b. Fertilizer-nitrogen use efficiency of irrigated wheat: II. Partitioning efficiency of preplant versus late-season application. Agron. J. 84:689-694.

Wyland, L. J., L. E. Jackson and K. F. Schulbach. 1995. Soil-plant nitrogen dynamics following incorporation of a mature rye cover crop in a lettuce production system. J. of Agric. Sci 124:17-25.

Section 4

Adriano, D.C., A.E. Erickson, A.R. Wolcott, and B.J. Ellis. 1974. Certain environmental problems associated with long-term land disposal of food processing wastes. In Loehr, R.C. (ed.). Processing and management of agricultural wastes. Proceedings of the 1974 Cornell Agricultural Waste Management Conference. p. 222-233. Cornell University, Ithaca, NY.

Ardern, D.A. 1976. The agricultural use of municipal sludge. In Loehr, R.C. (ed.). Land as a waste management alternative. Proceeding of the 1976 Cornell Agricultural Waste Management Conference, p. 583-601. Ann Arbor Science Publisherss Inc., Ann Arbor, MI.

ASAE Standards. 1993. Manure Production and Characteristics. 1993. ASAE Data: ASAE D384.1. American Society of Agricultural Engineers, East Lansing, MI.

Bezdicek, D.F., J.M. Sims, M.H. Ehlers, J. Conrath, and R.E. Hermanson. 1977. Nutrient budget in a dairy anaerobic lagoon - evaluation for land application. In Loehr, R.C. (ed.) Food, fertilizer and agricultural residues. Proceedings of the 1977 Cornell Agricultural

Waste Management Conference. p. 681-692. Ann Arbor Science Publishers Inc., Ann Arbor, MI.

Bock, B.R. and Hergert, G.W. 1991. Fertilizer Nitrogen Management. In R.F. Follett, D.R. Keeney, and R.M. Cruse (eds.). Managing Nitrogen for Groundwater Quality and Farm Profitability. SSSA, Madison, WI. p.139-164.

Carey, B.M. 1995. Vadose zone monitoring Deer Park, Washington: A municipal effluent land application site. Washington State Department of Ecology, Environmental Investigations and Laboratory Services Program Publication 94-148.

Carey, B.M. and J.A. Jacobson. 1994. Vadose zone monitoring at Tree Top Land Application Site in Selah, Washington, June - December 1992. Washington State Department of Ecology, Environmental Investigations and Laboratory Services Program Publication 94-148.

Chescheir, G.M. III and P.W. Westerman. 1984. Rapid Methods for Determining Fertilizer Value of Livestock Manures. ASAE Paper 84-4082. American Society of Agricultural Engineers, East Lansing, MI.

Cogger, C.G., C.F. Engle, and R.E. Hermanson. 1987. Sewage sludge guidellines for Washington. Part three: Sample problem and worksheet for calculating sludge application rates. Washington State University Cooperative Extension EB1432.

Cook, K.V. 1996. Review of six potato processing facilities in the Columbia Basin, Washington. Washington State Department of Ecology, Water Quality Program, Watershed Management Section Publication WQ-R-95-90.

Gamroth, M.J. 1991. NCALC-A Software Program for Balancing Manure Resource Use. Proceedings of the 1991 Northwest and Lower Columbia Dairy Shortcourses. Oregon State and Washington State Universities p. 97-102.

Hermanson, R.E. 1996. Manure sampling for nutrient analysis with worksheets for calculating fertilizer values. Washington State University Cooperative Extension EB1819.

Hermanson, R.E., A.C.S. Rao, W.L. Pan, K.F. Duncan, and M.A. Wright. 1995. MNB: Manure Nutrient Balancer, Version 1.0. Washington State University Cooperative Extension: MCP0026.

Hermanson, R.E., J.A. Moore, and C.F. Engle. 1983. How to Calculate Manure Application Rates in the Pacific Northwest. Washington State University Cooperative Extension PNW0239.

Jewell, W.J. 1976. Organic assimilation capacities of land treatment systems receiving vegetable processing wastewaters. In 31st Annu. Purdue Univ. Ind. Waste Conf. West Lafayette, Ind. p. 38

Jewell, W.J., and R.C. Loehr. 1975. Land treatment of food processing wastes. Paper no. 75-2513. Presented at the Winter Meeting of the Am. Soc. of Agric. Eng., Chicago, Ill. Dec. 1975.

Jones, J.L. and R.J. Wagner. 1995. Water-quality assessment of the Central Columbia Plateau in Washington and Idaho -- Analysis of available nutrient and pesticide data for ground water, 1942-92. U.S. Geological Survey Water-Resources Investigations Report 94-4258.

Kelling, K.A., Walsh, L.M., Keeney, D.R., Ryan, J.A. and A.E. Peterson. 1977. A field study of agricultural use of sewage sludge: II Effect on soil N and P. J. Environ. Qual. 6:345-352.

Krauss, G.D. and A.L. Page. 1997. Wastewater, sludge and food crops. BioCycle, Feb., p. 74-82.

Liu, D.H.F., B.G. Liptak, and P.A. Bouis. 1997 (2nd ed.). Environmental engineers' handbook. CRC Press LLC, Boca Raton, FL.

Long, F.L., Z. F. Lund, and R.E. Hermanson. 1975. Effect of Soil-Incorporated Dairy Cattle Manure on Runoff Water Quality and Soil Properties. Journal of Environmental Quality 4 (2): 163-166.

Magdoff, F.R. and F.W. Chromec. 1977. Nitrogen mineralization from sewage sludge. J. Environ. Sci. Health A12:191-201.

Magdoff, F.R. and J.F. Amadon. 1980. Nitrogen availability from sewage sludge. J. Environ. Qual. 9:451-455.

Meisinger, J.J. and G.W. Randall. 1991. Estimating Nitrogen Budgets for Soil-Crop Systems. In R.F. Follett, D.R. Keeney, and R.M. Cruse. (eds.), Managing Nitrogen for Groundwater Quality and Farm Profibablity. SSSA, Madison, WI. p. 85-124.

Midwest Plan Service. 1985. Animal Waste Utilization. In T.L. Loudon et al. (eds.), Livestock Waste Facilities Handbook, Midwest Plan Service, Iowa State University, Ames, IA.

Moore, J.A. and M.J. Gamroth. Rev. 1989. Calculating the Fertilizer Value of Manure From Livestock Operations. Oregon State University Extension Service EC1094.

Palazzo, A.J. 1976. Land application of wastewater: Forage growth and utilization of applied N, P, and K. In Loehr, R.C. (ed.). Land as a waste management alternative. Proceedings of the 1976 Cornell Agricultural Waste Management Conference p. 171-180. Ann Arbor Science Publichsers Inc., Ann Arbor, MI.

Ritter, W.F. 1987. An overview of factors affecting land application of food processing wastes. In James, L.G. and M.J. English (eds.) Irrigation systems for the 21st century. Conference proceedings p. 521-528. Portland, OR, July 28-30, 1987, ASCE.

Smith, J.H. 1986. Decomposition of potato processing wastes in soil. Journal of Environmental Quality, Vol. 15, no. 1: 13-16.

Smith, J.H. and J.R. Peterson. 1982. Recycling of nitrogen through land application of agricultural, food processing, and municipal wastes. In F.J. Stevenson (ed.) Nitrogen in agricultural soils. Agronomy 22: 791-831. American Society of Agronomy.

Smith, J.H., C.W. Robbins, J.A. Bondurant, and C.W. Hayden. 1978. Treatment and disposal of potato processing wastewater by irrigation. USDA-SEA, Conserv. Res. Rep. 22: 43.

Smith, J.H. 1976. Treatment of potato processing wastewater on agricultural land. J. Environ. Qual. 5: 113-116.

Smith, J.L. and D. B. McWhorter. 1976. Continuous subsurface injection of liquid organic wastes. In Loehr, R.C. (ed.). Land as a waste management alternative. Proceedings of the 1976 Cornell Agricultural Waste Management Conference p. 643-656. Ann Arbor Science Publishers Inc., Ann Arbor, MI.

Smith, J.H., C.W. Robbins, J.A. Bondurant, and C.W. Hayden. 1976. In Loehr, R.C. (ed.) Treatment of potato processing wastewater on agricultural land: Water and organic loading, and the fate of applied plant nutrients. Land as a waste management alternative. Proceedings of the 1976 Cornell Agricultural Waste Management Conference p. 769-780. Ann Arbor Science Publishers Inc., Ann Arbor, MI.

Smith, J. H., C.W. Robbins, and C.W. Hayden. 1975. Plant nutrients in potato processing wastewater used for irrigation. p. 159-165. In Proc. 26th Ann. Pacific Northwest Fertilizer Conf., 15-17 July 1975, Salt Lake City, Utah.

Soil Conservation Service, U.S. Department of Agriculture. 1993. Nutrient Management — Organic Nutrients. Interim Washington Standard WA590-3. U.S. Department of Agriculture.

Soil Conservation Service, U.S. Department of Agriculture. 1992. National Engineering Handbook, Agricultural Waste Management Field Handbook, Part 651. U.S. Department of Agriculture.

Sullivan, D.M. 1998. Fertilizing with biosolids. Oregon State University Extension Service. PNW 0508.

Sullivan, D.M., D.M. Granatstein, C.G. Cogger, C.L. Henry, and K.P. Dorsey. 1993. Draft. Biosolids management guidelines for Washington State. Washington State Department of Ecology Publication 93-80.

Thompson, R.B., D. Morse, K.A. Kelling, and L.E. Lanyon. 1997. Computer Programs that Calculate Manure Application Rates. Journal of Production Agriculture 10:58-69.

Tunney, H. 1979. Dry Matter, Specific Gravity, and Nutrient Relationships of Cattle and Pig Slurry. In J.C. Hawkins (ed.), Engineering Problems with Effluents From Livestock. Proc. C.E.C. Seminar, Cambridge, England Publ. C.E.C. Luxembourg, p. 430-447.

USEPA. 1983. Process design manual for land application of municipal biosolids. EPA-625/1-83-016. EPA, Cincinnati, OH.

2. Section 5

Addiscott, T. M. and D.S. Powlson. 1992. Partitioning losses of nitrogen fertilizer between leaching and denitrification. Journal of Agricultural Science, Cambridge (1992), 118:101-107.

Altman, S. J. and R.P. Parizek. 1995. Dilution of Nonpoint-Source Nitrate in Groundwater. J. Environ. Qual. 24:707-718.

Ambus, P., and R. Lowrance. 1991. Comparison of denitrification in two riparian soils. Soil Sci. Soc. Am. J. 55:994-997.

Andersson, R., T. Kindt, P.O.Johansson, and L. Maxe. 1984. An attempt to reduce nitrate in groundwater used for municipal water supply by changing agricultural practices. Nord. Hydrol. 15: 185-194.

Apsimon, H.M. and M. Kruse-Plass. 1991. The role of ammonia as an atmospheric pollutant. In: V.C. Nielsen, J.H. Voorburg, and P. L'Hermite (eds.) Odour and Ammonia Emissions from Livestock Farming. Elsevier Science Publishers, Essex, England.

Aschmann, S.G., M.S. McIntosh, J.S. Angle, and R.L. Hill. 1992. Nitrogen movement under a hardwood forest amended with liquid wastewater sludge. Agriculture, Ecosystems and Environment. 38: 249-263.

Bergstrom, Lars. 1987. Nitrate leaching and drainage from annual and perennial crops in tile-drained plots and lysimeters. J. Environ. Qual. 16:11-18.

Bergstrom, L. and N. Brink. 1986. Effects of differential applications of fertilizer N on leaching losses and distribution of inorganic N in the soil. Plant Soil. 93:333-345.

Bock, B.R., and G.W. Hergert. 1991. Fertilizer Nitrogen Management. p. 139-164. In: R. F. Follett, D. R. Keeney, and R. M. Cruse (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Science Society of America, Inc., Madison, WI.

Cabrera, M.L., S.C. Chiang, W.C. Merka, O.C. Pancorbo, and S.A. Thompson. 1994. Pelletizing and soil water effects on gaseous emissions from surface-applied poultry litter. Soil Sci. Soc. Am. J. 58:807-811.

Chaney, K. 1989. Effect of nitrogen fertilizer rate on soil nitrate nitrogen content after harvesting winter wheat. Journal of Agricultural Science, Cambridge (1990), 114:171-176.

Colbourn, P., M.M. Iqbal, and I.W.Harper. 1984. Estimation of the total gaseous nitrogen losses from clay soils under laboratory and field conditions. Journal of Soil Science. 35: 11-22.

Comfort, S.D., K.A. Kelling, D.R. Keeney, and J.C. Converse. 1990. Nitrous oxide production from injected liquid dairy manure. Soil Sci Soc. Am. J. 54:421-427.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J. 44:765-771.

Egginton, Gwen M. and K.A. Smith. 1986. Losses of nitrogen by denitrification from a grassland soil fertilized with cattle slurry and calcium nitrate. Journal of Soil Science. 37:69-80.

Estavillo, J. M., M. Rodriguez, and C. Gonalez-Murua. 1996. Nitrogen losses by denitrification and leaching in grassland. The effect of cow slurry application. Fert. Res. 43: 197-201.

Fillery, I. R. P. 1983. p.33-64. In: J. R. Freney and J. R. Simpson (eds.) Gaseous Loss of Nitrogen from Plant-Soil Systems. The Hague: Martinus Nijhoff/Dr W. Junk Publishers.

Firestone, M. K. (1982). Biological Denitrification. p.289-326, In: F. J. Stevenson (ed.) Nitrogen in Agricultural Soils. American Society of Agronomy, Madison, WI.

Fox, R.H. and W.P. Piekielek. 1983. Response of corn to nitrogen fertilizer and the prediction of soil nitrogen availability with chemical test in Pennsylvania. Pennsylvania Agric. Exp. Stn. Bull. 843.

Francis, G.S., R.J. Haynes, and P.H. Williams. 1994. Nitrogen mineralization, nitrate leaching and crop growth after ploughing-in leguminous and non-leguminous grain crop residues. Journal of Agricultural Science, Cambridge (1994). 123, 81-87. Cambridge University Press.

Gaines, T.P. and S.T. Gaines. 1994. Soil texture effect on nitrate leaching in soil percolates. Commun. Soil Sci. Plant anal. 25(13 & 14): 2561-2570.

Gilliam, J.W. and G.D. Hoyt. 1987. Effect of Conservation Tillage on Fate and Transport of Nitrogen. p. 217-240. In: T.L. Logan et al. (ed.) Effects of Conservation Tillage on Groundwater Quality: Nitrates and Pesticides. Lewis Publishers, Inc. Chelsea, Michigan.

Glendining, M.J., D.S. Powlson, P.R. Poulton, N.J.Bradbury, D. Palazzo, and X. Li. 1996. The effects of long-term applications of inorganic nitrogen fertilizer on soil nitrogen in the Broadbalk Wheat Experiment. Journal of Agricultural Science, Cambridge (1996). 127, 347-363. Cambridge University Press.

Goulding, K. W. T. and C. P. Webster. 1989. Denitrification Losses of Nitrogen from Arable Soils as Affected by Old and New Organic Matter from Leys and Farmyard Manure. p.225-234. In: J. A. Hansen and K. Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press Inc., San Diego, CA.

Goulding, K. W. T., C. P. Webster, D.S. Powlson, and P.R. Poulton. 1993. Denitrification losses of nitrogen fertilizer applied to winter wheat following ley and arable rotations as estimated by acetylene inhibition and 15N balance. Journal of Soil Science. 44:63-72.

Groffman, P.M., A.J. Gold, and R.C. Simmons. 1992. Nitrate dynamics in riparian Forests: Microbial studies. J. Environ. Qual. 21:666-671.

Hart, P.B.S., D.S. Powlson, P.R. Poulton, A.E. Johnston, and D.S. Jenkinson. 1993. The availability of the nitrogen in the crop residues of winter wheat to subsequent crops. Journal of Agricultural Science, Cambridge (1993). 121, 355-362. Cambridge University Press.

Haycock, N.E. and T.P. Burt. 1993. Role of floodplain sediments in reducing the nitrate concentration of subsurface run-off: A case study in the Cotswolds. UK. Hydrol. Proc. 7:287-295.

Hill, A.R. 1986. Nitrate and chloride distribution and balance under continuous potato cropping. Agriculture, Ecosystems and Environment. 15: 267-280.

Jacobson, S. N. and M. Alexander. 1980. Nitrate loss from soil in relation to temperature, carbon source, and denitrifier populations. Soil Biology and Biochemistry. 12:501-505.

Jansson, P.-E., R. Singh Antil, and G. Ch. Borg. 1989. Simulation of Nitrate Leaching from Arable Soils Treated with Manure. p. 150-166. . In: Jens AA. Hansen and Kaj Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press., London.

Jarvis, S. C., M. Sherwood. and J.H.A.M. Steenvoorden. 1987. Nitrogen Losses from Animal Manures: from Grazed Pastures and from Applied Slurry. p.195-212. In: H. G. v.d. Meer, et al. (eds) Animal Manure on Grassland and Fodder Crops. Martinus Nijhoff Publishers, Dodrecht, Netherlands.

Jemison, John M. Jr., and Richard H. Fox. 1994. Nitrate leaching from nitrogen-fertilized and manured corn measured with zero-tension pan lysimeters. J. Environ. Qual. 23:337-343.

Jokela, William E. 1992. Nitrogen Fertilizer and Dairy Manure Effects on Corn Yield and Soil Nitrate. Soil Sci. Soc. Am. J. 56: 148-154.

Jokela, W.E. and G.W. Randall. 1989. Corn yield and residual soil nitrate as affected by time and rate of nitrogen application. Agron. J. 81:720-726.

Jones, M.B., J.E.Street, and W.A. Williams. 1974. Leaching and uptake of nitrogen applied to annual grass and clover-grass mixtures in lysimeters. Agronomy Journal. 66: March/April 1974, 256-258.

Kanwar, R.S., J.L.Baker, and J.M. Laflen. 1985. Nitrate movement through the soil profile in relation to tillage system and fertilizer application method. Transactions of the ASAE. 26(6):November-December 1985, 1802-1807.

Kimble, J. M., R. J. Bartlett, J. L. McIntosh, and K.E. Varney. 1972. Fate of nitrate from manure and inorganic nitrogen in a clay soil cropped to continuous corn. J. Environ. Quality. 1:413-415.

Kolenbrander, G.J. 1981. Leaching of Nitrogen in Agriculture. In: J.C. Brogan (ed.) Nitrogen Losses and Surface Runoff from Landspreading of Manures. Martinus Nijhoff/Dr. Junk Publishers. The Hague.

Kolenbrander, G.J. 1969. Nitrate content and nitrogen loss in drainwater. Neth. J. Agric. Sci. 17: 246-255.

Lamb, J.A., G.A. Peterson, and C.R. Fenster. 1985. Fallow Nitrate Accumulation in a Wheat-fallow Rotation as Affected by Tillage System. Soil Sci. Soc. Am. J. 49: 1441-1446.

Letey, J., J.M. Blair, D. Devitt, L.J. Lund, and P. Nash. 1977. Nitrate-nitrogen in effluent from agricultural tile drains in California. Hilgardia. 45:289-319.

Logan, T.J., G.W. Randall, and D.R. Timmons. 1980. Nutrient content of the tile drainage from cropland in the North Central Region. NC Regional Publ. 268. Res. Bull. 1119. OARDC, Wooster, OH.

Loro, P.J., D.W. Bergstrom, and E.G. Beauchamp. 1997. Intensity and duration of denitrification following application of manure and fertilizer to soil. J. Environ. Qual. 26:706-713.

Lowrance, R. 1992a. Groundwater nitrate and denitrification in a Coastal Plain riparian forest. J. Environ. Qual. 21:401-405.

Lowrance, R. 1992b. Nitrogen outputs from a field-size agricultural watershed. J. Environ. Qual. 21:602-607.

Maag, M. 1989. Denitrification Losses from Soil Receiving Pig Slurry or Fertilizer. p.235-246. In: J. A. Hansen and K. Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press Inc., San Diego, CA

MacDonald, Andrew J., David S. Powlson. Paul R. Poulton, and David S. Jenkinson. 1989. Unused fertilizer nitrogen in arable soils—its contribution to nitrate leaching. J. Sci. Food Agric. 46:407-419.

MacLean, A.J. 1977. Movement of nitrate with different cropping systems in two soils. Can J. Soil Sci. 57:27-33.

Maddux, L.D., C.W. Raczkowski, D.E. Kissel, and P.L. Barnes. 1991. Broadcast and subsurface-banded urea nitrogen in urea ammonium nitrate appied to corn. Soil Sci. Soc. Am. J. 55:264-267.

Magdoff, F.R. 1991. Understanding the Magdoff pre-sidedress nitrate test for corn. J. Prod. Agric. 4:297-305.

Martin, E.C., T.L. Loudon, J.T. Ritchie, and A. Werner. 1994. Use of drainage lysimeters to evaluate nitrogen and irrigation management strategies to minimize nitrate leaching in maize production. Transactions of the ASAE. 37(1):79-83.

McCracken, Daniel V., M. Scott Smith, John H. Grove, Charles T. McKown, and Robert L. Blevins. 1994. Nitrate leaching as influenced by cover cropping and nitrogen source. Soil Sci. Soc. Am. J. 58: 1476-1483.

Medalie, L., W.B. Bowden, and C.T. Smith. 1994. Nitrogen leaching following land application of aerobically digested municipal sewage sludge in a northern hardwood forest. J. Environ, Qual. 23:130-138.

Meisinger, J. J. and G. W. Randall. 1991. Estimating Nitrogen Budgets for Soil-Crop Systems. p.85-124. In: R. F. Follett, D. R. Keeney, and R. M. Cruse (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Science Society of America, Inc., Madison, WI.

Mosier, A. R., W.D. Guenzi, and E.E. Xchweizer. 1986. Soil Losses of Dinitrogen and Nitrous Oxide from Irrigated Crops in Northeastern Colorado. Soil Science Society of America Journal. 50:344-348.

Olson. R.V. 1982. Immobilization, nitrification, and losses of fall-applied, labeled ammonium-nitrogen during growth of winter wheat. Agronomy Journal. 74: 991-995.

Owens, L.B. 1990. Nitrate-nitrogen concentrations in percolate from lysimeters planted to a legume-grass mixture. J. Environ. Qual. 19:131-135.

Pain, B.F., and R.B. Thompson. 1989. Ammonia Volitilization from Livestock Slurries Applied to Land. p. 202-211. In: J. A. Hansen and K. Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press Inc., San Diego, CA.

Pang, X.P., J. Letey, and L. Wu. 1997. Irrigation quantity and uniformity and nitrogen application effects on crop yield and nitrogen leaching. Soil Sci. Soc. Am J. 61:257-261.

Peralta, J.M., C.O. Stockle, K.E. Saxton, and L.G. King. 1997. Nitrogen form an irrigated crop rotation available for contaminating ground water: A long-term simulation study. Proceedings of the Conference on Best Management Practices for Irrigated Agriculture and the Environment. U.S. Committee on Irrigation and Drainage and Bureau of Reclamation. Fargo, North Dakota, July 16-19, 1997.

Peterson, G.A., and J.F. Power. 1991. Soil, Crop, and Water Management. p. 189-198. In: R.F. Follett, D.R. Keeney, and R.M. Cruse (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Sci. Soc. Am. Madison, WI.

Postma, D., C. Boesen, H. Kristiansen, and F. Larsen. 1991. Nitrate reduction in an unconfined sandy aquifer: Water chemistry, reduction processes, and geochemical modeling. Water Resour. Res. 27:2027-2045.

Powlson, D.S., P.R. Poulton, T.M. Addiscott, and D.S.McCann. 1989. Leaching of Nitrate from Soils Receiving Organic or Inorganic Fertilizers Continuously for 135 Years. p. 334-345. In: Jens AA. Hansen and Kaj Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press, London.

Pratt, P.F. 1984. Nitrogen use and nitrate leaching in irrigated agriculture. p. 319-333. In: R.D. Hauck (ed.) Nitrogen in Crop Production. Am. Soc. Agron., Madison, WI.

Pratt, P.F. 1979. Integration, discussion, and conclusions. p. 719-769. In: Final Report to the Natl. Sci. Found. For nitrate in effluents from irrigated lands. Univ. of California, Riverside.

Randall, G.W., and T.K. Iragavarapu. 1995. Impact of long-term tillage systems for continous corn on nitrate leaching to tile drainage. J. Environ. Qual. 24:360-366.

Rijtema, P.E. 1978. Een benadering voor de stikstofemissie uit het graslandbedrijf. Note 982. (gewijzigd), Inst. Cultuurtechniek en Waterhuishouding, Wageningen.

Robbins, C.W. and D.L. Carter. 1980. Nitrate-nitrogen leached below the root zone during and following alfalfa. J. Environ. Qual. 9(3):447-450.

Rolston, D.E., D.L. Hoffman, and D.W. Toy. 1978. Field measurement of denitrification: I. Flux of N2 and N2O. Soil Sci. Soc. Am. J. 42:863-869.

Roth, G.W. and R.H. Fox. 1990. Soil nitrate accumulation following nitrogen-fertilized corn in Pennsylvania. J. Environ. Qual. 19:243-248.

Ryden, J. C. 1983. Denitrification loss from a grassland soil in the field receiving different rates of nitrogen as ammonium nitrate. Journal of Soil Science. 34:355-365.

Ryden, J. C. and L. J. Lund. 1980. Nitrous Oxide Evolution from Irrigated Land. Journal of Environmental Quality. 9:387-393.

Ryker, S.J. and J.L. Jones. 1995. Nitrate concentrations in ground water of the Central Columbia Plateau. U.S. Geological Survey Open-File Report 95-445.

Saint-Fort, R., J.S. Schepers, and R.F Spaulding. 1991. Potentially mineralizable nitrogen and nitrate leaching under different land-use conditions in western Nebraska. J. Environ. Sci. Health. A26(3), 335-345.

Saint-Fort, R., R.M. Raina, and B. Prescott. 1995. Subsurface environmental quality under a cattle feedlot and adjacent cropfield. J. Environ. Sci. Health. A30(3), 637-650.

Sawyer, J. E., M.A. Schmitt, R.G. Hoeft, J.C. Siemens and D.H. Vanderholm. 1991. Corn production associated with liquid beef manure application methods. J. Prod. Agric. 3:335-344.

Scheppers, J.S., and R.H.Fox. 1989. Estimation of N Budgets for Crops. p. 221-246. In: R.F. Follett (ed.) Nitrogen Management and Ground Water Protection. Elsevier Science Publishers, Inc. Amsterdam.

Schipper, Louis A., J.C. Williamson, H.A. Kettles, and T.W. Speir. 1996. Impact of land-applied tertiary-treated effluent on soil biochemical properties. Journal of Environmental Quality. 25: 1073-1077.

Schroder, J.J., L. ten Holte, H. van Keulen, and J.H.A.M. Steenvoorden. 1993. Effects of nitrification inhibitors and time and rate of slurry and fertilizer N application on silage maize yield and losses to the environment. Fertlizer Research. 34: 267-277.

Schroder, J.J., W.J.M. de Groot, and W. van Dijk. 1992. Nitrogen losses from continuous maize as affected by cover crops. In: J.R. Archer et al. (eds.) Nitrate and Farming Systems, Aspects of Applied Biology. 30:317-326.

Sidle, R.C. and L.T. Kardos. 1979. Nitrate leaching in a sludge-treated forest soil. Soil Sci. Soc. Am. J. 43:278-282.

Sieling, K., O. Gunther-Borstel, and H. Hanus. 1996. Effect of slurry application and mineral nitrogen fertilization on N leaching in different crop combinations. Journal of Agricultural Science, Cambridge (1997). 128,79-87. Cambridge University Press.

Sims, J. Thomas, Bruce L. Vasilas, Karen L. Gartley, Bill Milliken, and V. Green. 1995. Evaluation of soil and plant nitrogen tests for maize on manured soils of the Atlantic coastal plain. Agron. J. 87:213-222.

Sims, J. Thomas. 1987. Agronomic evaluation of poultry manure as a nitrogen source for conventional and no-tillage corn. Agron. J. 79:563-570.

Smith, J.H. 1976. Treatment of Potato Processing Waste Water on Agricultural Land. J. Environ. Qual. 5:113-116.

Smith. S. J., A.N. Sharpley, J.W. Naney, W.A. Berg, and O.R. Jones. 1991. Water quality impacts associated with wheat culture in the southern plains. J. Environ. Qual. 20:244-249.

Staricka, J.A. G.R. Benoit, A.E. Olness, J.A. Daniel,and D.R. Huggins. 1994. Movement of fall-applied nitrogen during winter in western Minnesota. p. 105-112. In: Environmentally Sound Agriculture. Proc. 2nd conference. Am. Soc. Of Agric. Engineers.

Taylor, H. and H. Vroomen. 1989. Timing of Fertilizer Applications. p. 40-45 In: Agricultural Resources Inputs: Situation and Outlook. U.S. Dept. of Agric. Economic Research Service. AR-15. August 1989.

Thompson, R.B. and B.F. Pain. 1989. Denitrification from Cattle Slurry Applied to Grassland. p.247-260. In: J. A. Hansen and K. Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press Inc., San Diego, CA.

Tindall, James A., Robin L. Petrusak, and Peter B. McMahon. 1995. Nitrate transport and transformation processes in unsaturated porous media. Journal of Hydrology. 169: 51-94.

Van Den Abbeel, R. A. Claes, and K. Vlassak. 1989. Gaseous Nitrogen Losses from Slurry-Manured Land. p.213-224. In: J. A. Hansen and K. Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press Inc., San Diego, CA.

Vetter, H., and G. Steffens. 1981. Surface Runoff. p. 84-86. In: J.C. Brogan (ed.) Nitrogen Losses and Surface Runoff from Landspreading of Manures. Martinus Nijhoff/Dr. Junk Publishers. The Hague.

Williams, J.R., and D.E. Kissel. 1991. Water Percolation: An Indicator of Nitrogen-Leaching Potential. p. 59-83. In: R. F. Follett, D. R. Keeney, and R. M. Cruse (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Science Society of America, Inc., Madison, WI.

Section 6

Addiscott, T. M. and D.S. Powlson. 1992. Partitioning losses of nitrogen fertilizer between leaching and denitrification. Journal of Agricultural Science, Cambridge (1992), 118:101-107.

Adriano, D.C., P.F. Pratt, and F.H. Takatori. 1972. Nitrate in unsaturated zone of an alluvial soil in relation to fertilizer nitrogen rate and irrigation level. J. Environ. Qual. 1:418-422.

Alcoz, Mercedes M., Frank M. Hons, and Vincent A. Haby. 1993. Nitrogen Fertilizer Timing Effect on Wheat Production, Nitrogen Uptake Efficiency, and Residual Soil Nitrogen. Agron. J. 85:1198-1203.

Bartholomew, W.V. 1965. Mineralization and immobilization of nitrogen in the decomposition of plant and animal residues. In: W.V. Bartholomew and F.E. Clark (eds.) Soil nitrogen. Agronomy. 10:285-306. Amer. Soc. of Agron., Madison, WI.

Boawn, L.C., J.L. Nelson, and C.L. Crawford. 1963. Residual nitrogen from NH4NO3 fertilizer and from alfalfa plowed under. Agron. J. 55:231-235.

Bristow, A.W., J.C. Ryden, and D.C.Whitehead. 1987. The fate at several time intervals of 15N-labelled ammonimum nitrate applied to an established grass sward. Journal of Soil Science. 38:245-254.

Bundy, L.G., and E.S. Malone. 1988. Effect of residual profile nitrate on corn response to applied nitrogen. Soil Sci. Soc. Am. J. 52:1377-1383.

Chaney, K. 1989. Effect of nitrogen fertilizer rate on soil nitrate nitrogen content after harvesting winter wheat. Journal of Agricultural Science, Cambridge (1990), 114:171-176.

Chang, C. and T. Entz. 1996. Nitrogen leaching losses under repeated cattle feedlot manure applications in southern Alberta. J. Environ. Qual. 25:145-153.

Chichester, F.W. 1977. Effects of increased fertilizer rates on nitrogen content of runoff and percolate from monolith lysimeters. J. Environ. Qual. 6:211-217.

Cook, K.V. 1996. Review of six potato processing facilities in the Columbia Basin, Washington. Washington State Department of Ecology, Water Quality Program, Watershed Management Section Publication WQ-R-95-90.

Davies, D.B., and R. Sylvester-Bradley. 1995. The contribution of fertiliser nitrogen to leachable nitrogen in the UK: a review. J. Sci. food Agric. 68: m399-406.

Egginton, Gwen M. and K.A. Smith. 1986. Losses of nitrogen by denitrification from a grassland soil fertilized with cattle slurry and calcium nitrate. Journal of Soil Science. 37:69-80.

Francis, G.S., R.J. Haynes, and P.H. Williams. 1994. Nitrogen mineralization, nitrate leaching and crop growth after ploughing-in leguminous and non-leguminous grain crop residues. Journal of Agricultural Science, Cambridge (1994). 123, 81-87. Cambridge University Press.

Gast, R.G., W.W. Nelson, and J.M. MacGregor. 1974. Nitrate and chloride accumulation and distribution in fertilized tile-drained soils. J. Environ. Qual. 3(3): 209-213.

Goss, M.J., P. Colbourn, G.L. Harris, and K.R. Howse. 1988. Leaching of Nitrogen under Autumn-Sown Crops and Effects of Tillage. p. 269-282. In: D.S. Jenkinson and K.A. Smith (eds.) Nitrogen Efficency in Agricultural Soils. Chichester: Elsevier.

Hahne, H.C.H., W. Kroontje, and J.A. Lutz, Jr. 1977. Nitrogen fertilization: I. Nitrate accumulation and losses under continuous corn cropping. Soil Sci. Soc. Am. J. 41:562-567.

Harris, G.L., M.J. Goss, R.J. Dowdell, K.R. Howse, and P. Morgan. 1984. A study of mole drainage on a clay soil. Journal of Agricultural Science (Cambridge). 102:561-581.

Hergert, G.W. 1986. Nitrate leaching through sandy soil as affected by sprinkler irrigation management. J. Environ. Qual. 15:272-278.

Hermanson, R.E., A.C.S. Rao, W.L. Pan, K.F. Duncan, and M.A. Wright. 1995. MNB: Manure nutrient balancer, version 1.0. Washington State University Cooperative Extension: MCP0026.

Herron, G.M., G.L. Terman, A.F. Dreier, and R.A. Olson. 1968. Residual nitrate nitrogen in fertilized deep loess-derived soils. Agron. J. 60:477-482.

Hubbard, R. K., L.E. Asmussen, and H.D. Allison. 1984. Shallow groundwater quality beneath an intensive multiple-cropping system using center pivot irrigation. J. Environ. Qual. 13:156-161.

Isfan D., J. Zizka, A.D'Avignon, and M. Deschenes. 1995. Relations between nitrogen rate, plant nitrogen concentration, yield and residual soil nitrate-nitrogen in silage corn. Commun. Soil Sci. Plant Anal. 26 (15 & 16), 2531-2557.

James, D.W. 1975. Nitrogen fertilizer use efficiency. p. 75-84. In: Proc. 26th Annu. Fertilizer Conf. Northwest Plant Food Assoc., Salt Lake city, Utah.

Jarvis, S. C., M. Sherwood. and J.H.A.M. Steenvoorden. 1987. Nitrogen Losses from Animal Manures: from Grazed Pastures and from Applied Slurry. p.195-212. In: H. G. v.d. Meer, et al. (eds) Animal Manure on Grasslad and Fodder Crops. Martinus Nijhoff Publishers, Dodrecht, Netherlands.

Jemison, John M. Jr., and Richard H. Fox. 1994. Nitrate leaching from nitrogen-fertilized and manured corn measured with zero-tension pan lysimeters. J. Environ. Qual. 23:337-343.

Johnson, G.V. and W.R.Raun. 1995. Nitrate leaching in continuous winter wheat: use of a soil-plant buffering concept to account for fertilizer nitrogen. J. Prod. Agric. 8: 486-491.

Johnston, A.E., S.P. McGrath, P.R. Poulton, and P.W. Lane. 1989. Accumulation and Loss of Nitrogen from Manure, Sludge, and Compost: Long-term Experiments at Rothamsted and Woburn. p.126-139. In: Jens AA. Hansen and Kaj Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press., London.

Jokela, W.E. and G.W. Randall. 1989. Corn yield and residual soil nitrate as affected by time and rate of nitrogen application. Agron. J. 81:720-726.

Jolley, V.D., and W.H. Pierre. 1977. Profile accumulations of fertilizer-dreived nitrate and total nitrogen recovery in two long-term nitrogen rate experiments with corn. Soil Sci. Soc. Am. J. 41: 373-378.

Keeney, D. R. 1986. Nitrate in Ground Water - Agricultural Contribution and Control. pp.329-351. In: Proceedings - Conference on Agricultural Impacts on Ground Water. Omaha, NE. 11-13 Aug. National Water Well Assoc., Dublin, OH.

Lerch, R.N., K.A. Barbarick, D.G. Westfall, R.H. Follett, T.M. McBride, and M.F. Owen. 1990. J. Prod. Agric. 3:66-71.

Liang, B.C., M. Remillard, and A.F. MacKenzie. 1991. Influence of fertilizer, irrigation, and non-growing season precipitation on soil nitrate-nitrogen under corn. J. Environ. Quality. 20:123-128.

Linville, K.W. and G.E. Smith. 1971. Nitrate content of soil cores from corn plots after repeated nitrogen fertilization. Soil Sci. 112:249-255.

MacGregor, J.M., G.R. Blake, and S.D. Evans. 1974. Mineral nitrogen movement into subsoils following continued annual fertilization for corn. Soil Sci. Soc. Am. Proc. 38:110-113.

Martin, D.L., D.G. Watts, L.N. Mielke, K.D. Frank, and D.E. Eisenhauer. 1982. Evaluation of nitrogen and irrigation management for maize production using water high in nitrate. Soil Sci. Soc. Am. J. 46: 1056-1062.

Meisinger, J. J., T.H. Carski, M.A. Nys, and V.A. Bandel. 1982. Residual nitrae nitrogen in Maryland. p. 215. In: Agronomy Abstracts. ASA, Madison, WI.

Nelson, W.W., and J.M. MacGregor. 1973. Twelve years of continuous corn fertilization with ammonium nitrate or urea nitrogen. Soil Sci Sco. Am. Proc. 37:583-586.

Olsen, R.J., R.F. Hensler, O.J. Attoe, S.A. Witzel, and L.A. Peterson. 1970. Fertilizer nitrogen and crop rotation in relation to movement of nitrate nitrogen through soil profiles. Soil Sci. Soc Amer. Proc., Vol. 34: 448-452.

Olson. R.V. 1980. Fate of Tagged Nitrogen Fertilizer Applied to Irrigated Corn. Soil Sci. Soc. Am. J. 44: 514-517.

Power, J. F. and F. E. Broadbent. 1989. Proper Accounting for N in Cropping Systems. p.159-181. In: R. F. Follett (ed.) Nitrogen Management and Ground Water Protection. Elsevier Science Publishing Co. Inc., New York, NY.

Powlson, D.S., P.R. Poulton, T.M. Addiscott, and D.S.McCann. 1989. Leaching of Nitrate from Soils Receiving Organic or Inorganic Fertilizers Continuously for 135 Years. p. 334-345. In: Jens Aa. Hansen and Kaj Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press, London.

Pratt, P.F. 1984. Nitrogen use and nitrate leaching in irrigated agriculture. p. 319-333. In: R.D. Hauck (ed.) Nitrogen in Crop Production. Am. Soc. Agron., Madison, WI.

Randall, G. 1985. Nitrogen movement. p. 139-152. In: Summarized Proceedings of the Plant Nutrient Use and the Environment Symp., Oct. 1985, Kansas city, MO. The Fertilizer Institute, Washington, D.C.

Raun, W.R., and G.V. Johnson. 1995. Soil-plant buffering of inorganic nitrogen in continuous winter wheat. Agron. J. 87:827-834.

Robbins, C.W. and D.L. Carter. 1980. Nitrate-nitrogen leached below the root zone during and following alfalfa. J. Environ. Qual. 9(3):447-450.

Roth, G.W. and R.H. Fox. 1990. Soil nitrate accumulation following nitrogen-fertilized corn in Pennsylvania. J. Environ. Qual. 19:243-248.

Ryker, S.J. and J.L. Jones. 1995. Nitrate concentrations in ground water of the Central Columbia Plateau. U.S. Geological Survey Open-File Report 95-445.

Schepers, J.S., and A.R. Mosier. 1991. Accounting for Nitrogen in Nonequilibrium Soil-Crop systems. p. 125-138. In: R.F. Follett et al. (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Science Society of America, Inc., Madison, WI.

Schroder, J.J., L. ten Holte, H. van Keulen, and J.H.A.M. Steenvoorden. 1993. Effects of nitrification inhibitors and time and rate of slurry and fertilizer N application on silage maize yield and losses to the environment. Fertlizer Research. 34: 267-277.

Shipley, P.R., J.J. Meisinger, and A. M. Decker. 1992. Conserving residual corn fertilizer nitrogen with winter cover crops. Agron, J. 84: 869-876.

Smith, J.H., C.W. Robbins, and C.W. Hayden. 1975. Plant nutrients in potato processing wastewater used for irrigation. In: Proc. 26th Ann. Pacific Northwest Fertilizer Conf., 15-17 July 1975, Salt Lake City, Utah. P. 159-165.

Smith, J.H. and J.R. Peterson. 1982. Recycling of nitrogen through land application of agricultural, food processing, and municipal wastes. In F.J. Stevenson (ed.) Nitrogen in agricultural soils. Agronomy 22: 791-831. American Society of Agronomy.

Spallacci, P. 1979. Effects of land spreading of large amounts of livestock excreta on crop yield and crop and water quality. Report EC-Meeting, Oldenburg, Bad Zwischenahn.

Spalding, R.F., M.E. Exner, G.E. Martin, D.D. Snow. 1993. Effects of sludge disposal on groundwater nitrate concentrations. Journal of Hydrology. 142:213-228.

Stanford, G. 1973. Rationale for optimum nitrogen fertilization in corn production. J. Environ. Qual. 2:159-166.

Timm, H., N.B. Akesson, M.O. O'Brien, W.J. Flocker, and G. York. 1976. Soil and crop response to variable loading of canning wastes. Technical Paper, American Soc. Of Agric. Engineers, 1976 Annual Meeting, Davis, CA.

Timmons, D.R. and A.S. Dylla. 1981. Nitrogen leaching as influenced by nitrogen management and supplemental irrigation level. J. Environ. Qual. 10: 421-426.

Van Der Ploeg, R.R., H. Ringe, and Galina Machulla. 1995. Late fall site-specific soil nitrate upper limits for groundwater protection purposes. J. Environ. Qual. 24:725-733.

Vetter, H., and G. Steffens. 1981. Surface Runoff. p. 84-86. In: J.C. Brogan (ed.) Nitrogen Losses and Surface Runoff from Landspreading of Manures. Martinus Nijhoff/Dr. Junk Publishers. The Hague.

Vinten, A.J.A., B.J. Vivian, F. Wright, and R.S. Howard. 1994. A comparative study of nitrate leaching from soils of differing textures under similar climatic and cropping conditions. Journal of Hydrology. 159: 197-213.

Walters, D.T., and G.L. Malzer. 1990. Nitrogen management and nitrification inhibitor effects on nitrogen-15 urea: II. Nitrogen leaching and balance. Soil Sci. Soc. Am. J. 54: 122-130.

Watts, D.G. 1977. Nitrogen loss for the soil and its relationship to irrigation management. In: PE Fischbach (ed.) Protection of a unique ecological area through improved water and fertility. Tech. Comp. Tep. B-024-NEB. Nebraska Water Resour. Center, Lincoln, NE.

Watts, Darrell G., and Derrel L. Martin. 1981. Effects of water and nitrogen management on nitrate leaching loss from sands. Transactions of the ASAE. p. 911-916.

Watts, D.G., G.W. Hergert, and J.T. Nichols. 1991. Nitrogen leaching losses from irrigated orchardgrass on sandy soils. J. Environ. Qual. 20:355-362.

Westfall, D.G., J.L. Havlin, G.W. Hergert, and W.R. Raun. 1996. Nitrogen management in dryland cropping systems. J. Prod. Agric. 9: 192-199.

Section 7

Baker, J.L. and H.P. Johnson. 1981. Nitrate-nitrogen in tile drainage as affected by fertilization. J. Environ. Qual. 10:519-522.

Baker, J.L., K.K. Campbell, H.P. Johnson, and J.J. Hanway. 1975. Nitrate, phosphorus, and sulfate in subsurface drainage water. J. Environ. Qual. 4:406-412.

Bouwer, Herman. 1989. Linkages with Ground Water. p. 363-372. In: R.F. Follett (ed.) Nitrogen Management and Ground Water Protection. Elsevier Science Publishers, Amsterdam.

Brown, L.C., J.L.Nelson, C.L. Crawford. 1963. Residual nitrogen from NH4NO3 fertilizer and from alfalfa plowed under. Agron. J. 55: 231-235.

Daliparthy, Jayaram, Stephen J. Herbert, and Peter L.M. Veneman. 1994. Dairy manure applications to alfalfa: crop response, soil nitrate, and nitrate in soil water. Agron. J. 86:927-933.

Drury, C.F., D.J. McKenney, W.I. Findlay, and J.D.Gaynor. 1993. Influence of tillage on nitrate loss in subsurface runoff and tile drainage. Soil Sci. Soc. Am. J. 57:797-802.

Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Englewood Cliffs, N.J.

Kladivko, E.J., G.E. Van Scoyoc, E.J. Monke, K.M. Oates, and W. Pask. 1991. Pseticide and nutrient movement into subsurface tile drains on a silt loam soil in Indiana. J. Environ. Qual. 20:264-270.

Lowrance, R.R. and H.B. Pionke. 1989. Transformation and Movement of Nitrate in Aquifer Systems. p. 374-392. In: R.F. Follett (ed.) Nitrogen Management and Ground Water Protection. Elsevier Science Publishers, Amsterdam.

Madison, R.J. and J.O. Brunett. 1985. Overview of the occurrence of nitrate in ground water of the United States. p. 93-105. In: U.S.G.S. National Water Summary. U.S. Geol. Surv. Water-Supply Paper 2275.

Magette, W.L., J.D. Wood, and T.H. Ifft. 1990. Nitrate in shallow ground water. ASAE. Pap. 90-2502. A. Soc. of Agric. Engr., St. Joseph, MI.

Mathers, A.C., B.A. Stewart, and B. Blair. 1975. Nitrate nitrogen removal from soil profiles by alfalfa. J. Environ. Qual. 4:403-405.

Olsen, R.J., R.F. Hensler, O.J. Attoe, S.A. Witzel, and L.A. Peterson. 1970. Fertilizer nitrogen and crop rotation in relation to movement of nitrate nitrogen through soil profiles. p.448-452. In: Soil Sci. Soc Amer. Proc., Vol. 34.

Pionke, H.B. and R.R. Lowrance. 1991. Fate of Nitrogen in Subsurface Drainage Waters. p. 237-258. In: R. F. Follett, D. R. Keeney, and R. M. Cruse (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Science Society of America, Inc., Madison, WI.

Pratt, P.F., G.H. Cannell, M.J. Garber, and F.L. Blair. 1967. Effects of three nitrogen fertilizers on gains, losses, and distribution of various elements in irrigated lysimeters. Hilgardia 38:265-283.

Saint-Fort, R., J.S. Schepers, and R.F Spaulding. 1991. Potentially mineralizable nitrogen and nitrate leaching under different land-use conditions in western Nebraska. J. Environ. Sci. Health. A26(3), 335-345.

Schertz, D.L. and D.A. Miller. 1972. Nitrate N. accumulation in the soil profile under alfalfa. Agron. J. 64:660-664.

Schuman, G.E. and L. F. Elliott. 1978. Cropping an abandoned feedlot to prevent deep percolation of nitrate-nitrogen. Soil Sci. 126:237-243.

Schuman, G.E., T.M. McCalla, K.E. Saxton, and H.T. Knox. 1975. Nitrate movement and its distribution in the soil profile of differentially fertilized corn watersheds. Soil Sci. Soc. Am. Proc. 39:1192-1197.

Sims. J.T. 1987. Agronomic evaluation of poultry manure as a nitrogen source for conventional and no-tillage corn. Agron. J. 79:397-401.

Southwick, L.M., G.H. Willis, D.C. Johnson, and H.M. Selim. 1995. Leaching of nitrate, atrazine, and metribuzin from sugarcane in southern Louisiana. J. Environ. Qual. 24:684-690.

Stewart, B.A., F.G. Viets, and L. Hutchinson. 1968. Agriculture's effect on nitrate pollution of ground water. J. of Soil and Water conservation. 21:13-15.

W. Walther. 1989. The Nitrate Leaching Out of Soils and their Significance for Groundwater, Results of Long-term Tests. p. 346-358. In: J. A. Hansen and K. Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press Inc., San Diego, CA.

Section 8

Baker, J.L. and H.P. Johnson. 1981. Nitrate-nitrogen in tile drainage as affected by fertilization. J. Environ. Qual. 10:519-522.

Baker, J.L., K.K. Campbell, H.P. Johnson, and J.J. Hanway. 1975. Nitrate, phosphorus, and sulfate in subsurface drainage water. J. Environ. Qual. 4:406-412.

Bottercher, J., O. Strebel, and W.H.M. Duynisveld. 1985. Vertikale stoffkonzentrationsprofile in grundwasser eines lockergesteins-aquifers und dern deren interpretation (Beispiel Furhberg Feld). Z. dt. Geol. Ges. (Hannover). 136:543-552.

Burwell, R.E., G.E. Schuman, K.E. Saxton, and H.G. Heinemann. 1976. Nitrogen in subsurface discharge from agricultural watersheds. J. Environ. Qual. 5:325-329.

Chichester, F.W., and S.J. Smith. 1978. Disposition of N-labeled fertilizer nitrate applied during corn culture in field lysimeters. J. Environ. Qual. 7:227-233.

Chichester, F.W. 1977. Effects of increased fertilizer rates on nitrogen content of runoff and percolate from monolith lysimeters. J. Environ. Qual. 6:211-217.

Daliparthy, Jayaram, Stephen J. Herbert, and Peter L.M. Veneman. 1994. Dairy manure applications to alfalfa: crop response, soil nitrate, and nitrate in soil water. Agron. J. 86:927-933.

Endelman, F.J., D.R. Keeney, J.T.Gilmore, and P.G. Safigna. 1974. Nitrate and chloride movement in the Plainfield loamy sand under intensive irrigation. J. Environ. Qual. 3:295-298.

Englund, J.O. and S. Haldorsen. 1986. Profiles of nitrogen species in a sand-silt aquifer at Haslemoen, Solor, south Norway. Nordic Hydrol. 17:295-304.

Firestone, M. K. 1982. Biological Denitrification. p.289-326, In: F. J. Stevenson (ed.) Nitrogen in Agricultural Soils. American Society of Agronomy, Madison, WI.

Gambrell, R., J. Gilliam, and S. Weed. 1975. Denitrification in subsoils of the North Carolina coastal plain as afected by soil drainage. J. Environ. Qual. 4:311-316.

Gast, R.G., W.W. Nelson, and J.M. MacGregor. 1974. Nitrate and chloride accumulation and distribution in fertilized tile-drained soils. J. Environ. Qual. 3(3): 209-213.

Gast, R.G., W.W. Nelson, and G.W. Randall. 1978. Nitrate accumulation in soils and loss in tile drainage following nitrogen applications in continuous corn.. J. Environ. Qual. 7(2): 258-261.

Gerwing, J.R., A.C. Caldwell, and L.L. Goodroad. 1979. Fertilizer nitrogen distribution under irrigation between soil, plant, and aquifer. J. Environ. Qual. 8:281-284.

Gillham, R.W. 1991. Nitrate Contamination of Groundwater in Southern Ontario and the Evidence for Denitrification. In: I. Bogardi and R.D. Kuzelka (eds.) Nitrate Contamination: Exposure springer-Verlag, Berlin. Consequence and Control. NATO ASI series, Series G: Ecological Sciences. 30: 181-198.

Hallberg, G.R. 1989. Nitrate in Groundwater in the United States. p. 35-74. In: R.F. Follett (ed.) Nitrogen Management and Ground Water Protection. Elsevier Science Publishers, Amsterdam.

Hubbard, R. K., L.E. Asmussen, and H.D. Allison. 1984. Shallow groundwater quality beneath an intensive multiple-cropping system using center pivot irrigation. J. Environ. Qual. 13:156-161.

Jackson, W.A., S.R. Wilkinson, and R.A. Leonard. 1977. Land disposal of broiler litter: changes in concentration of chloride, nitrate nitrogen, total nitrogen, and organic matter in a Cecil sandy loam. J. Environ. Qual. 6(1): 58-62.

Jacobs, T.C. and J.W. Gilliam. 1985. Riparian losses of nitrate from agricultural drainage waters. J. Environ. Qual. 14:472-478.

Jones, M.B., J.E.Street, and W.A. Williams. 1974. Leaching and uptake of nitrogen applied to annual grass and clover-grass mixtures in lysimeters. Agronomy Journal. 66: March/April 1974, 256-258.

Keeney, D. R. 1986. Nitrate in Ground Water - Agricultural Contribution and Control. pp.329-351. In: Proceedings - Conference on Agricultural Impacts on Ground Water. Omaha, NE. 11-13 Aug. National Water Well Assoc., Dublin, OH.

Keeney, D.R. 1981. Soil Nitrogen Chemistry and Biochemistry. p. 259-276. In: I.K. Iskander (ed.) Modeling Wastewater Renovation; Land Treatment. Wiley, New. York.

Kissel, D.E., J.T. Ritchie, and Earl Burnett. 1974. Nitrate and chloride leaching in a swelling clay soil. J. Environ. Qual. 3:401-404.

Krajenbrink, G.J.W., L.J.M. Boumans, and C.R. Meinardi. Hyrochemical Processes in the Top Layer of Groundwater Under Pasture Land. p. 317-333. In: J. A. Hansen and K. Henriksen (eds.) Nitrogen in Organic Wastes Applied to Soils. Academic Press Inc., San Diego, CA.

Logan, T.J., G.W. Randall, and D.R. Timmons. 1980. Nutrient content of the tile drainage from cropland in the North Central Region. NC Regional Publ. 268. Res. Bull. 1119. OARDC, Wooster, OH.

Lowrance, R.R., R.T. Todd, and I.E. Asmussen. 1984. Nutrient cycling in an agricultural watershed: I. Phreatic movement. J. Environ. Qual. 13:22-27.

MacGregor, J.M., G.R. Blake, and S.D. Evans. 1974. Mineral nitrogen movement into subsoils following continued annual fertilization for corn. Soil Sci. Soc. Am. Proc. 38:110-113.

Mariotti, A., A. Landreau, and B. Simon. 1988. 15N isotope biogeochemistry and natural denitrification process in groundwater: application to the chalk aquifer of northern France. Geochim. Cosmochim. Acta. 52:1869-1878.

Miller, M.H. 1979. Contribution of nitrogen and phosphorus to subsurface drainage water from intensively cropped mineral and organic soils in Ontario. J. Environ. Qual. 8:42-48.

Owens, L.B. 1990. Nitrate-nitrogen concentrations in percolate from lysimeters planted to a legume-grass mixture. J. Environ. Qual. 19:131-135.

Owens, L.B. 1987. Nitrate leaching losses from monolith lysimeters as influenced by nitrapyrin. J. Environ. Qual. 19:131-135.

Owens, L. B. 1960. Nitrogen movement and transformations in soils as evaluated by a lysimeter study utilizing isotropic nitrogen. Soil Sci. Soc. Am. Proc. 24:372-376.

Parkin, T.B., and J.J. Meisinger. 1989. Denitrification below the crop rooting zone as influence by surface tillage. J. Environ. Qual. 18:12-16.

Payne, W.J. 1981. Denitrification. Wiley and Sons, New York. 214 pp.

Pionke, H.B. and R.R. Lowrance. 1991. Fate of Nitrogen in Subsurface Drainage Waters. p. 237-258. In: R. F. Follett, D. R. Keeney, and R. M. Cruse (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. Soil Science Society of America, Inc., Madison, WI.

Ronen, Daniel, and Mordeckai Magaritz. 1985. High concentration of solutes at the upper part of the saturated zone (water table) of a deep aquifer under sewage-irrigated land. Journal of Hydrology. 80: 311-323.

Smith, J.H. and J.R. Peterson. 1982. Recycling of Nitrogen Through Land Application of Agricultural, Food Processiong, and Municipal Wastes. In F. J. Stevenson (ed.) Nitrogen in Agricultural Soils. Agronomy 22:791-832.

Smith, R.L., B.L. Howes, and J.H. Duff. 1991. Denitrification in nitrate-contaminated groundwater: occurrence in steep vertical geochemical gradients. Geochim. Cosmochim. Acta. 55:1815-1825.

Spalding, R.F., M.E. Exner, G.E. Martin, D.D. Snow. 1993. Effects of sludge disposal on groundwater nitrate concentrations. Journal of Hydrology. 142:213-228.

Timmons, D.R. and A.S. Dylla. 1981. Nitrogen leaching as influenced by nitrogen management and supplemental irrigation level. J. Environ. Qual. 10: 421-426.

Timmons, D.R. 1984. Nitrogen leaching as influenced by water application level and nitrification inhibitors. J. Environ. Qual. 13: 305-309.

Trudell, M.R., R.W. Gillham, and J.A. Cherry. 1986. An in-situ study of the occurrence and rate of denitrification in a shallow unconfined sand aquifer. J. Hydrol. 83: 251-268.

Tyler, D.D. and G.W. Thomas. 1977. Lysimeter measurements of nitrate and chloride losses from siol under conventional and no-tillage corn. J. Environ. Qual. 6:63-66.

Vogel, J.C., A.S. Talma, and T.H.E. Heaton. 1981. Gaseous nitrogen as evidence for denitrification in groundwater. J. Hydrol. 50:191-200.

Weil, R.R., R.A. Weismuller, and R.S. Turner. 1990. Nitrate contamination of groundwater under irrigated coastal plain soils. J. Environ. Qual. 19:441-448.

Zwerman, P.J., T. Greweling, S.D. Klausner, and D.J. Lathwell. 1972. Nitrogen and phosphorus content of water from tile drains at two levels of management and fertilization. Soil Sci. Soc. Am. Proc. 36:134-137.

Section 9

Badini, O., Stockle, C.O., and E.H. Franz. 1997. Application of crop simulation modeling and GIS to agroclimatic assessment in Burkina Faso. Agriculture Ecosystems and Environment (in press).

Castellvi, F., Perez, P.J., Stockle, C.O., and M. Ibanez. 1997. Methods for estimating vapor pressure deficit at a regional scale depending on data availability. Agriculture and Forest Meteorology (in press).

Donatelli, M., C.O. Stockle, E. Ceotto, and M. Rinaldi. 1996. CropSyst validation for cropping systems at two locations of Northern and Southern Italy. European Journal of Agronomy (in press).

Ferrer, F. and C.O. Stockle. 1995. A model for assessing crop response and water management in saline conditions. In ICID/FAO Workshop on Irrigation Scheduling: From Theory to Practice. Sept. 1995, Rome, Italy.

Ndlovu, L. 1994. Weather data generation and its use in estimating evapotranspiration. Ph.D. dissertation. Washington State University, Pullman, WA. 143pp.

Pala, M., C.O. Stockle, and H.C. Harris. 1996. Simulation of durum wheat (triticum durum) growth under differential water and nitrogen regimes in a mediterranean type of environment using CropSyst. Agricultural Systems 51:147-163.

Pannkuk, C.D., C.O. Stockle, and R.I. Papendick. 1998. Evaluating CropSyst simulations of wheat growth under different tillage and residue management practices in a wheat-fallow region of the US Pacific Northwest. Agricultural Systems (In press).

Peralta, J.M., C.O. Stockle, K.E. Saxton, and L.G. King. 1997. Nitrogen form an irrigated crop rotation available for contaminating ground water: A long-term simulation study. Proceedings of the Conference on Best Management Practices for Irrigated Agriculture and the Environment. U.S. Committee on Irrigation and Drainage and Bureau of Reclamation. Fargo, North Dakota, July 16-19, 1997.

Stockle, C. O., S. Martin and G. S. Campbell. 1994. CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. Agricultural Systems 46:335-359.

Stockle, C.O. 1996. GIS and simulation technologies for assessing cropping systems management in dry environments. American Journal of Alternative Agriculture 11:115-120.

Stockle, C.O. and M. Donatelli, 1996. The CropSyst Model: A brief description. In: Plentinger, M.C. and F.W.T. Penning de Vries (Ed.), Rotation models for ecological farming. CAMASE/PE workshop report. Quantitative Approaches in Systems Analysis No. 10. AB-DLO, Wageningen, The Netherlands. 138 pp.

Stockle, C.O. and R. Nelson. 1997. CropSyst User's manual. Dept. of Biological Systems Engineering, Washington State University, Pullman, WA.

Stockle, C.O., M. Cabelguenne, and P. Debaeke. 1997. Validation of CropSyst for water management at a site in southern France using submodels of different complexity. European Journal of Agronomy (accepted).

Stockle, C.O. and P. Debaeke. 1997. Modelling crop nitrogen requirements: a critical analysis. European Journal of Agronomy (accepted).