Chapter 6

Soil Fertility Management

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Abstract

The inland Pacific Northwest's (PNW) warm, dry climate and deep soils make it ideal for producing high yields of high-quality wheat. Wheat can grow in some of the region's driest areas where other crops cannot. However, drastic topography and precipitation gradients result in variable growing conditions that impact crop yield and complicate nutrient management strategies. Interrelated climate, water, and nutrient dynamics drive wheat development, growth, and associated fertility recommendations; understanding these complex relationships will become increasingly important under changing climate conditions. Concerns related to nitrogen losses, soil erosion and nutrient runoff, and decreasing soil pH can result from improper use of fertilizers and further complicate management strategies. Farm-specific management approaches, regular soil testing, and detailed recordkeeping can help producers improve nutrient use, minimize nutrient losses and environmental degradation, and maintain high yields and quality.

Key Points

- Climate, weather, topography, and soil drive wheat productivity and soil fertility management strategies in the inland PNW.
- Variable landscapes and rainfall gradients affect crop fertilizer accessibility, nutrient use efficiencies, and crop growth. Inland PNW producers can achieve the best growing conditions for wheat by

tailoring management strategies to their specific field and within-field locations.

- Practices that maximize nitrogen use efficiency include fertilizer placement, fertilizer source, timing of application, and rates that match crop species' and varietal nitrogen needs.
- Over-use of fertilizers can result in harmful effects on air, water, and soil quality and negatively affect a producer's bottom line. Appropriate management strategies and regular soil testing can reduce nutrient loss and improve overall farm gains.
- Conserving soil water is imperative in dryland agricultural regions since available soil water directly drives wheat yields and nutrient availability. Increased water stress is likely under predicted climate scenarios. Management strategies that build up soil organic matter and improve soil health can buffer against crop nutrient and water loss.

Introduction

Maintaining soil fertility in wheat-based cropping systems is necessary to achieve satisfactory growth and yields, as well as protein and other quality factors in wheat. Complex interactions among multiple climate, weather, soil, and plant factors in the **inland PNW** can impact crop productivity and affect soil fertility management strategies across locations and within farms. Precipitation and temperature directly influence crop yields, the foundation for all fertilizer application rate recommendations, while the soil itself can affect nutrient availability, retention, and cycling. Plant nutrients are removed from the plant-soil system in the crop at harvest each year (Table 6-1), making it necessary to add many of them back at the beginning of each growing season to ensure marketable wheat yields and protein levels. Typically, wheat producers supply nutrients to their cropping systems by applying commercial fertilizers, and incorporating legumes into their rotations. On occasion, they might supply wheat with nutrients from organic fertilizer sources, although this is a relatively uncommon practice due to the distance of animal production in relation to wheat farms and the large quantities of amendments needed to supply adequate fertility to wheat and other cereal crops. An important concept to understand is that managing soil nutrients is more than simply considering how much fertilizer a crop needs to grow. It is a process that requires controlling a variety of fertility sources over time in complex and dynamic cycles. The challenge is meeting the overall need of the crop and applying nutrients at peak crop demand while continuing to sustain healthy soils and associated natural resources.

The goal of this chapter is to summarize the main factors that impact nutrient requirements and drive associated soil fertility management decisions for wheat-based cropping systems in the inland PNW. A more thorough understanding of how these factors interact and affect wheat yield and quality will help prepare producers and service providers to address regional soil fertility concerns, reduce negative effects to the environment, and achieve high yielding and quality wheat production.

Grower Considerations

Nitrogen Management

Nitrogen (N) is the nutrient that producers supply in the largest quantities each year in wheat-based cropping systems due to the high demand of N

Table 6-1. Nutrient supply and removal in harvested grain* across the main wheat-producing counties of the inland PNW.

Nutrient Source	N	P_2O_5 ton/yr	K_2O
commercial**	143,570	41,439	30,172
recovered manure***	1,377	2,013	6,242
biologically fixed by legumes***	25,322		
total nutrient supply	170,269	43,452	36,414
crop removed***	171,203	63,331	102,602
balance (supply - removed)	–934	–19,879	–66,188
removal ratio (removal/supply)	1.01	1.46	2.82

*Methods described in IPNI (2012). N = nitrogen; P_2O_5 = phosphorus; K_2O = potassium.
**1997, 2002, 2007, 2010-12 County level data interpolated and summarized by International Plant Nutrition Institute (IPNI) from fertilizer sales data collected by the Association of American Plant Food Control Officials (AAPFCO).
***Farm census data from USDA National Agricultural Statistical Service (USDA-NASS) Census of Agriculture, summarized by IPNI.

by cereal crops. Nitrogen is also the most deficient nutrient for all non-legume crops in the inland PNW, and wheat yields respond to additions of N fertilizer in most precipitation zones when N supplied by the soil is low (Rasmussen 1996). Therefore, N is a major focus of nutrient management plans and field recommendations (Pan et al. 1997). Although several forms of N exist in nature, nitrate-N (NO_3-N) and ammonium-N (NH_4-N) are the forms available to plants. The primary determinants of plant-available N are (1) release from soil organic matter by microbes (referred to as **mineralization**), (2) contributions from organic and inorganic N fertilizer sources, and (3) losses from the plant-available N pool (Figure 6-1) (Cassman et al. 2002). Nitrogen, a dynamic nutrient that is altered by biological soil processes as well as exposure to water and air, is particularly complicated to manage compared to nutrients that are less subject to transformations and losses. Nitrogen availability is influenced by precipitation, soil water, and field variability more than most nutrients as a result of its association with

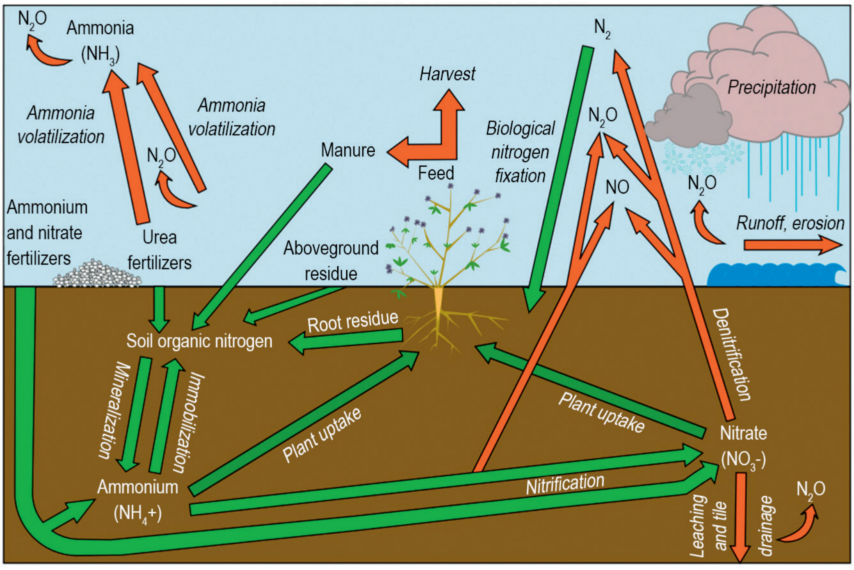

Figure 6-1. Nitrogen cycle diagram. Nitrogen (N) transformations occur as a result of associations with biological organisms, and N cycling processes are greatly impacted by temperature, heat, and other environmental conditions that affect biological metabolic activity. Plant-available N forms, nitrate-N (NO_3-N) and ammonium-N (NH_4-N), can be derived from inorganic fertilizers and organic sources. It is important to consider the complete N cycle to understand plant N uptake abilities as well as potentials for N loss. (Figure created by Nick Kennedy.)

biological organisms. Because climate and topographical factors impact N cycling and crop availability in the inland PNW (Pan et al. 1997), they are presented here with the best options for efficiently using N relative to the region's specific concerns.

Meeting nitrogen use efficiency – matching N availability with crop needs

In general, an efficient system is one that maximizes its outputs relative to its use of inputs, and efficient N use by a wheat crop means that the majority of N available throughout the growing season can be accounted for in the grain at harvest. If N is not taken up by the crop, it remains in the root zone of the soil. **Nitrogen use efficiency** (NUE) of an entire cropping system can be considered as the proportion of all N inputs that are (1) removed in harvested crop biomass, (2) contained in recycled crop residues, and (3) incorporated into residual soil N pools (organic and inorganic sources) (Cassman et al. 2002). All of these components are considered in nutrient management plans (Pan et al. 1997).

Nitrogen use efficiency can be partitioned into soil and plant processes governing **nitrogen uptake efficiency** (how efficiently the plant obtains N from the soil) and **nitrogen utilization efficiency** (how efficiently N is metabolized inside the plant) (Huggins and Pan 1993; Moll et al. 1982). Because NUE is the product of uptake and utilization efficiencies, inefficient use of N can occur because of low uptake of N by the plant, poor utilization by the plant to produce grain, or a combination of both.

Factors that reduce NUE include over-fertilization (too much N supplied for plant needs), sub-optimal yields (too little plant uptake of available N), and N losses (applied N not being used by the plant) (Sowers et al. 1994). Environmental factors that impact these variables can also reduce NUE. For instance, drought conditions can reduce yields, restrict the uptake of N by crops, and shorten the grain-filling period of crops (Maaz et al. 2016; Pan et al. 2007). Dry conditions impair root activity near the surface of the soil, thereby increasing the amount of soil N "stranded" and decreasing the uptake of available N. Nitrogen use efficiency can also be diminished with increasing annual precipitation, as N retention is reduced by denitrification and nitrate-N **leaching** from the root zone, particularly in shallow soils.

The best approach for maximizing NUE at economically optimal yields is to match fertilizer rates based on soil tests, as well as the timing of application with crop uptake needs, which can be difficult. Understanding current practices for applying fertilizers is necessary for knowing how to better meet NUE goals and addressing challenges.

Factors driving current nitrogen management strategies

Field and regional variability impacts on water and nitrogen relationships

Soil and climatic features across the region (e.g., precipitation gradient) as well as within fields (e.g., slope position), greatly impact N cycling dynamics and requirements that affect crop performance and yield potential (Pan et al. 1997). The topography of the inland PNW is quite diverse compared to many other regions (Mulla 1986; Rasumssen 1996), and most of the wheat production acreage is located on steep hillslopes (Busacca et al. 1985) (see Chapter 8: Precision Agriculture). Wheat productivity is determined largely by plant-available water and

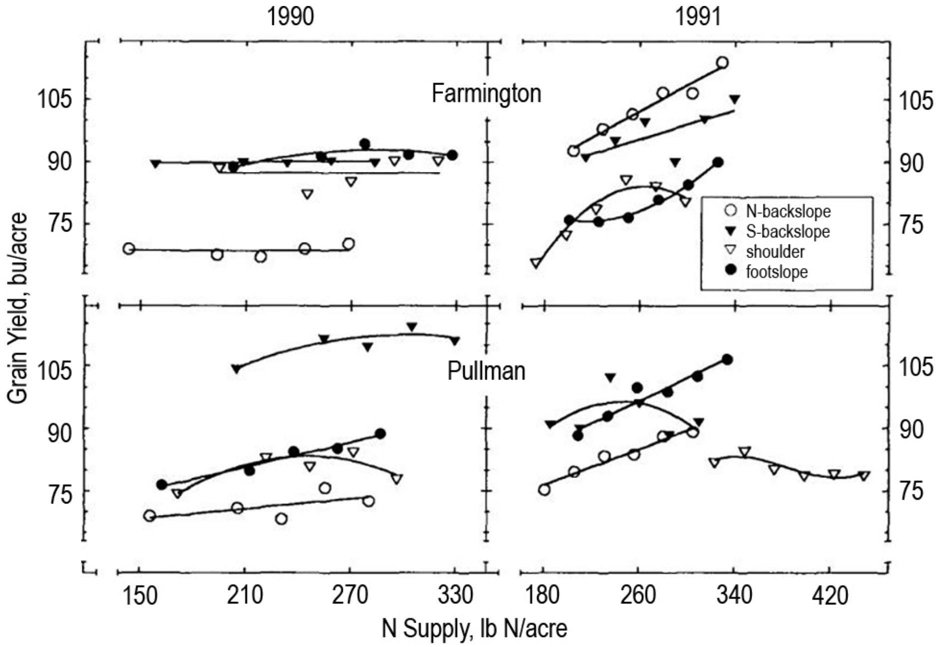

Figure 6-2. Grain yield versus nitrogen (N) supply (residual N plus mineralization plus fertilizer N) at different points along a hillslope at Farmington and Pullman, Washington, in 1990 and 1991. (Used with permission from Fiez et al. 1994b.)

the manner in which water, nutrients, and other crop growth factors are distributed across the landscape (Long et al. 2015). Specifically, water-holding capacity and rooting depth is often limited on eroded hilltops, and N losses and transformations can occur differently depending on field location (Fiez et al. 1994a; Long et al. 2015; Pan et al. 1997).

Especially notable in the hilly Palouse region of the inland PNW, differences in climate and soil productivity at different slope locations contributes to variations in wheat yield and protein levels across fields (Figure 6-2) (Fiez et al. 1994a; Fiez et al. 1995; Mulla 1992; Yang et al. 1998). As a result, there is high annual variability in the amount of N needed to attain optimal yields (Table 6-2) (Pan et al. 1997).

Relationships among precipitation, soils, fertilizers, and wheat yields have been integral to N recommendations since the adoption of commercial N fertilizers in the 1950s (Pan et al. 2007). In fact, quantitative relationships

Table 6-2. Yearly variation in the rate of nitrogen (N) producing the optimum grain yield of winter wheat, in a winter wheat-fallow rotation in Pendleton, Oregon, from 1963 to 1987.

	N Rate (lb/ac)				
Year	0	40	80	120	143
	Grain Yield (bu/ac)				
1963	36	**62**	55	42	37
1965	62	64	**71**	71	68
1967	42	**61**	54	45	39
1969	**54**	55	54	45	43
1971	51	79	**85**	77	67
1973	48	**55**	49	42	42
1975	51	**67**	59	57	57
1977	48	**54**	49	46	45
1979	42	**57**	55	45	49
1981	55	89	100	**104**	100
1983	42	62	86	**97**	92
1985	48	51	**57**	57	57
1987	57	79	**83**	74	71

[1]Grain yields in bold are at the N rate providing optimum yields.
Adapted from Rasmussen (1996).

among water, N, and wheat yield in the inland PNW were determined through extensive field experimentation in the 1950s (Jacquot 1953; Leggett 1959) and have been used ever since to estimate regional wheat yield potentials and soil fertility recommendations. Regional and annual variations increase the challenge for the inland PNW's producers to make appropriate N management decisions on their farms, which can be some of the most important and costly farm management decisions.

Precipitation and soil water

Wheat's responses to nutrients are especially sensitive to the amount of precipitation received during the growing season. Precipitation and soil water accumulated during the growing season influence soil nutrients and plant nutrition directly by (1) increasing crop yield potentials and (2) improving nutrient mobility and transformations in the soil. Wheat yields and total plant-available N are impacted by water availability, making weather-driven N recommendations necessary for dryland wheat production (Pan et al. 2007). Plant-available water also determines wheat protein content (Baker et al. 2004) in dryland environments. Nitrogen management affects the end-use quality of grain (Brown et al. 2005; Miller and Pan n.d.).

Nitrogen recommendations

The amount of N required to achieve wheat yield and protein goals is mainly dependent on the crop's yield potential and the class of wheat being produced. Nitrogen budget-based fertilizer guides are available to help producers estimate these values and develop a specific nutrient management plan for their own dryland wheat production systems in Washington (Koenig 2005), Oregon (Lutcher et al. 2005), and Idaho (Mahler 2007). (Various nutrient management guides exist for producing wheat in Oregon under different precipitation zones. Producers in Southern Idaho should also refer to the Southern Idaho Dryland Winter Wheat Production Guide. All guides are listed under Grower Resources later in this chapter.) Although they have been developed for different states, the basic recommendations and guidelines are similar for all three states. The standard components for calculating annual N fertilizer rates are the N supply needed based on (1) wheat yield potential of a specific site, (2) the amount of N required to achieve yield and protein goals for a desired wheat class, and (3) an inventory of soil N contributions (Figure 6-3).

Step 1: The amount of N fertilizer needed per acre of wheat can be calculated by multiplying the anticipated yield goal by the unit N required (UNR) for soft white winter or club wheat (2.7 lb N/bu) or hard red and white wheat varieties (3.0 lb N/bu). Yield goals and UNRs already account for plant available moisture and grain protein, respectively.

Yield Goal (bu/acre) x UNR (lb N/bu) = N fertilizer required (lb N/ acre)

Step 2: Account for residual soil N contributions in the soil profile to a depth of 4 to 5 feet. Residual N can be measured with soil tests and should be calculated prior to applying fertilizer.

Lbs. N fertilizer required per acre (from Step 1) – Residual Soil N (lb N/acre) = N fertilizer recommendation (lb N/acre)

Figure 6-3. Basic nitrogen (N) fertilizer rate calculation steps. Simplified calculations were developed from nutrient management guides (Koenig 2005; Lutcher et al. 2005; Mahler 2007).

1. *Wheat yield potential*. Wheat yield varies in response to weather, crop rotations, and other management variables. Wheat yields can vary from 25 to over 110 bushels per acre across the region. Correlations between available water and wheat grain yield have been measured extensively throughout the inland PNW and have been used to estimate yield potential in dryland wheat systems (Mahler 2007; Pan et al. 2007; Robertson et al. 2004). Yield goals can be estimated based on a producer's experience, from historical averages, or they can be calculated using pre-plant soil water and expected precipitation during the growing season (Koenig 2005). Estimated **water use efficiencies** (WUEs) for wheat are 7 bushels of soft white winter wheat per acre per inch of available water, and 6 bushels of wheat per acre per inch of available water (for all other wheat classes). Modern semi-dwarf wheat cultivars and improved agronomics have increased yields and therefore the WUE of wheat (Figure 6-4).

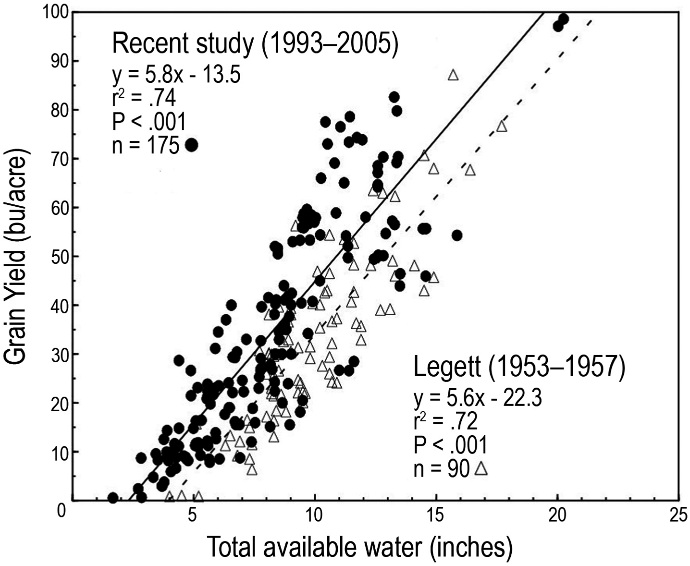

Figure 6-4. The relationship between available water in the soil profile plus spring precipitation and grain yield of dryland wheat in eastern Washington. Data were collected from 1953 to 1957 (dotted line, open triangles) and from 1993 to 2005 (solid line, filled circles). Grain yield data are from a combination of winter and spring wheat. The minimum threshold of available water required for wheat germination has decreased from 5.9 inches in 1953 to 1957 to 2.3 inches in the recent study (1993 to 2005) as a result of improved water use efficiency in newer cultivars of wheat. (From Schillinger et al. 2012.)

2. *Wheat class and protein*. Optimum grain protein levels range from 9% to 10% for soft white wheat and 11% to 14% for hard wheat classes (Brown et al. 2005; Koenig 2005; Lutcher et al. 2005). More specifically, market protein goals for hard wheat classes are 11.5% for hard red winter wheat, 12.5% for hard white wheat, and 14% for hard red spring wheat (Washington Wheat Commission Guides for Hard White Winter, Hard Red Spring, and Hard Red Winter Wheat). Meeting these protein values is critical to produce high-quality wheat and to avoid **dockage** and price reductions for grain at the elevator.
3. *Soil contributions of N*. Residual soil N in the rooting zone can come from both organic and inorganic sources and is one of the most complicated factors to predict and manage (see Chapter 4: Crop Residue Management and Chapter 7: Soil Amendments). Despite similar soil types, climatic conditions, and management

practices, residual soil N varies over time and location since plant-available forms of N are influenced by soil temperature, water content, and management practices. For example, flushes of N mineralization may occur after soil tillage, soil rewetting, or during freeze-thaw cycles.

Practices that promote **soil health** and increase soil organic matter (e.g., incorporating crop residues, manure, or compost) are going to have the greatest influence on supplying N from the soil. The amount of N released from organic sources like crop residues and manure depends on the amount of N they contain and rates of N mineralization. Nitrogen is released from organic compounds over a longer period of time than it is from inorganic sources since mineralization must occur. However, supplies of organic residues not only provide a slow-release source of N, but they also help build **soil structure** and retain water in the rooting zone (see Chapter 2: Soil Health). Improved soil **water holding capacity** can expedite mineralization and nutrient cycling in addition to remediating water stress that crops experience during dry and hot growing conditions.

It is important to consider N released from decomposing legume or other low **carbon-to-nitrogen** (C:N) ratio residues and other sources of soil organic matter. Koenig (2005) estimates that peas can contribute 10 to 20 pounds of N per acre (amounts vary based on pea biomass yield), lentils can contribute 10 pounds of N per acre when biomass is greater than 1,000 pounds per acre, and alfalfa can contribute as high as 50 pounds of N per acre (Table 6-3). These sources of N as well as soil organic matter are considered credits in the N fertilizer calculation (Koenig 2005). It is recommended to credit 20 pounds of N per acre for each 1% of organic matter under conventional tillage and 17 pounds of N per acre for each 1% up to 3% of organic matter under **direct seeding** systems.

Most inorganic N fertilizers enter the plant-available N pool rapidly since they are predominantly composed of simpler, plant-available nitrate-N, ammonium-N, or both. Using plant-available N sources, however, does not guarantee that N will not accumulate in the soil profile. It is possible to have elevated levels of residual N at harvest if inorganic fertilization additions exceed the annual yield requirements for that site. While residual fertilizer N can be recycled in subsequent seasons in inland PNW cropping systems (Maaz and Pan n.d.), over-fertilization can become particularly problematic when fertilizer N rates consistently exceed the amount of N exported in the grain, especially in landscape positions that are vulnerable to N losses.

Residual plant-available soil N, as the sum of nitrate-N and ammonium-N, should be accounted for in soil tests (0 to 5 feet deep or to a restricting layer). When crediting soil N sources, it is important to consider when the soil samples are collected. If soil samples are taken in the spring, up to half of the N released from soil organic matter annually has already occurred. Also, knowledge of crop rotation is important. **Immobilization** or N tie-up can occur when high amounts of cereal straw residues, with wide C:N ratios, are left on the field. Immobilization acts as a debit in fertilizer calculations. No debit is taken after summer **fallow**, but if wheat was the preceding crop, debits of 35 pounds of N per acre (winter wheat), 30 pounds of N per acre (spring wheat), and 25 pounds of N per acre (barley) should be taken.

Despite its complex nature and variability, residual soil N contributions are important to account for when making nutrient management decisions since inorganic N and N mineralization contributed to the majority of grain N at maturity (Sowers et al. 1994). Failing to account for plant-available N in the soil matrix can lead to over-fertilization and nutrient losses.

Factors that impact NUE

Timing application with growth

Crop management, such as residue retention, crop rotation, residual fertilizer from the previous crop, and fertilizer timing, placement, and

Table 6-3. Nitrogen (N) contributions from previous grain and forage legume crops.

Preceding Crop	Preceding Crop Yield (lb/ac)	N Credit (lb N/ac)
Peas	>2500	20
Peas	1500 to 2500	15
Peas	<1500	10
Lentils	>1000	10
Alfalfa	Any	50

Adapted from Koenig (2005).

source all affect NUE (Cassman et al. 2002; Dawson et al. 2008; Lea and Azevedo 2006; Maaz and Pan n.d.; Raun and Johnson 1999). To help producers manage N more effectively in their fields, researchers encourage them to make nutrient management decisions based on the **unit nitrogen requirement** (UNR) and NUE at economically optimal yield for each specific field and crop. Ideally, wheat producers want to identify the lowest UNRs to attain economically optimal yields.

Unit nitrogen requirements

The N requirement or the amount of N needed to produce 1 bushel of wheat is based on a grain protein goal in combination with plant-available soil water and N factors. This amount of N is also referred to as the UNR and is measured in pounds of N needed for each expected bushel of wheat. The UNR is the inverse of NUE (UNR = 1 ÷ NUE) at economically optimal yields (Fiez et al. 1994b). Once the UNR value is identified, it is multiplied by the expected yield (bushels per acre) to provide an N fertilizer application rate recommendation in pounds of N per acre (Step 1 in Figure 6-3). Recommended UNRs are typically 2.7 pounds of N per bushel for soft white winter and club wheat and 3 pounds of N per bushel for hard red or white varieties of wheat (Leggett 1959).

It is important to recognize that these UNR determinations were regionally averaged over different Washington wheat-growing areas (Hergert et al. 1997), and the data was typically produced from experiments conducted on gentle sloped or flat landscape positions for maximizing yield potential and for ease and accessibility for research plot equipment (F.E. Koehler, personal communication). In actuality, agricultural field landscapes exhibit differences in multiple factors that influence N supply, protein-yield relationships, and yield potential (Figure 6-2). Although current guidelines for nutrient management depend on these values, one should recognize that UNRs are variable among years and across landscape positions, ranging from as low as 2 pounds of N per bushel to as high as 3.5 pounds of N per bushel (Koenig 2005; Lutcher et al. 2005; Mahler 2007). Furthermore, these landscape differences do not always repeat their patterns with variable weather, which can result in variable UNRs over landscapes and years. For example, UNR values ranged from 1.8 to 3.9 pounds of N per bushel in a study conducted by Fiez et al. (1994b).

This strongly suggests that site-specific N recommendations cannot be extrapolated from regionally developed recommendation models (Pan et al. 1997).

In the inland PNW, the Extension nutrient management guides mostly take a "Liebig" approach to soft white winter wheat N recommendations (Figure 6-5), which assume that NUE is constant across a large range of yield potentials (Pan et al. 2016). Therefore, the main reason that inefficiencies in N use by wheat occur in the inland PNW is that fertilizer recommendations are calculated based on estimated UNR values as standards as opposed to actual field values. As a result, too little or too much fertilizer gets applied and the wheat plant either experiences N deficiency symptoms (e.g., poor growth and development or inadequate protein levels) or does not use all available N, making it susceptible to volatilization, runoff, or leaching loss. In contrast, a classic "Mitscherlich" approach (Figure 6-5) assumes that the NUE varies greatly across the range of yield potentials observed in the inland PNW, which may or may not be correct for a given crop, region, or farm. An alternative strategy is to integrate effects of yield potential and available water on the response of winter wheat to N, which combines the "Liebig" and "Mitscherlich" approaches. This integrated approach is currently being used to better

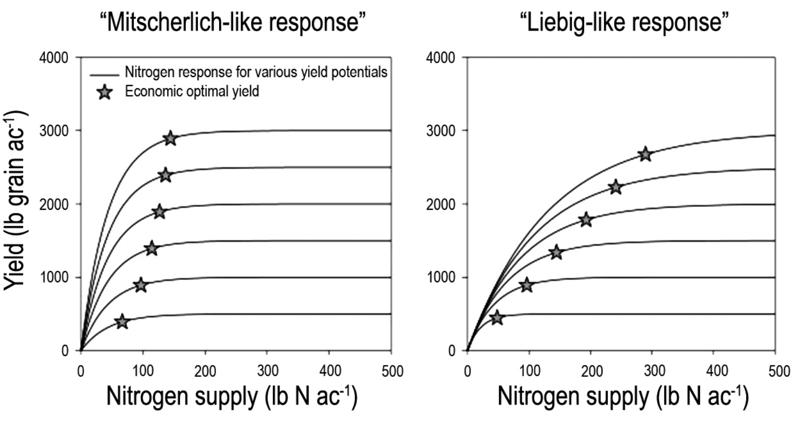

Figure 6-5. A classic Mitscherlich approach to nitrogen (N) recommendations assumes that nitrogen use efficiency (NUE) varies greatly across the range of yield potentials, whereas a Liebig approach assumes NUE is constant across a large range of yield potentials. An integrated approach between the two could improve accuracy in estimating N recommendations. (Adapted from Pan et al. 2016 and Pan 2015.)

understand changes in UNR across the region, and it has indicated that UNR decreased as precipitation increased along the 12 to 20 inch precipitation gradient (Maaz and Pan n.d.). However, additional studies are needed to characterize the potential decrease in NUE as precipitation exceeds 20 inches and the risk of soil N losses increase.

Accurately estimating UNR across fields is an ongoing concern and challenge (Fiez et al. 1994a; 1994b) due to landscape variability as well as an unrealistic requirement to sample a field as intensively as necessary for obtaining actual values. Fortunately, several strategies exist that can help improve N management and NUE, such as split application, **nitrification** inhibitors, and variable rate N applications. Variable N rate practices and technologies have been evolving as computer technologies have been incorporated with agricultural machinery, while remote sensing is a promising tool to delineate management zones based on crop performance indicators (Song et al. 2009). High-tech machines and software packages offer producers more opportunities to increase NUEs on their farms by using site-specific management (see Chapter 8: Precision Agriculture).

However, even without the use of high-tech farming equipment several strategies exist that can help improve N management strategies and NUE. Approaches to increasing NUE should integrate many known components of wheat production into one system (Raun and Johnson 1999). The following strategies can help improve NUE in most cropping systems.

Strategies that improve NUE

Fertilizer placement

Early season N availability is critical for yield and a moderate level of grain protein (Washington Wheat Commission Guide Hard Red Winter Wheat). Nitrogen must be available for plants to take up by the three-leaf stage (Figure 6-6) since the bud for the first tiller forms at this point and N is critical to support tiller formation from the very beginning (Waldren and Flowerday 1979). Most of the N required by wheat is taken up during vegetative growth and used to establish the yield potential (number of heads and kernels per head) (Washington Wheat Commission Guide Hard Red Winter Wheat). Vegetative N is later transported to the kernels to form protein during grain fill in mid to late summer.

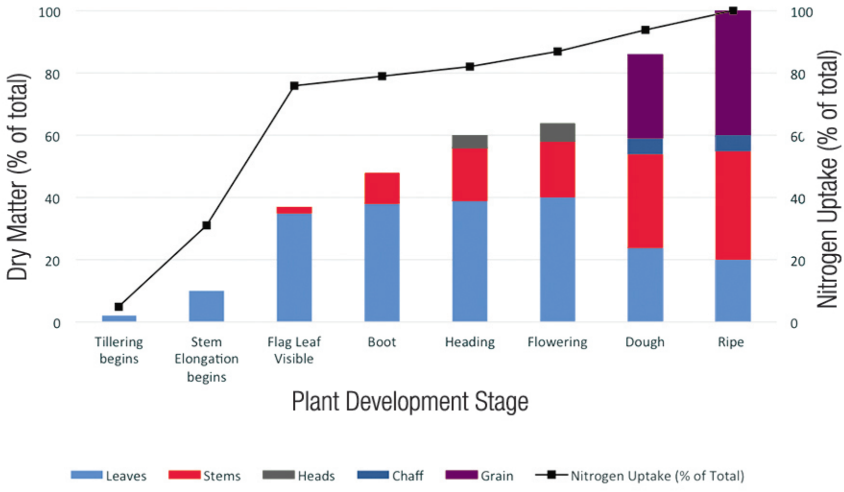

Figure 6-6. Nitrogen uptake by wheat. The total accumulated uptake of nitrogen by wheat estimated by growth stage. Timing of N application should occur earlier in the season when N uptake by the crop is high. As wheat matures, N uptake slows down as the crop metabolizes N to produce grain and protein. (Adapted with permission from Waldren and Flowerday 1979.)

Splitting N fertilizer applications between fall and spring allows producers to conservatively apply smaller amounts of N early in the growing season and then adjust rates and add additional fertilizer in the spring, only if the precipitation outlook is favorable for high wheat yields. Split (fall-spring) applications of N fertilizer are recommended in areas receiving approximately 21 inches of annual precipitation, whereas areas that experience heavy winter precipitation (greater than 24 inches) or have sandy soils might benefit from spring applications only (Mahler 2007). In higher precipitation areas, over 70% of the required fertilizer should be applied in spring (Mahler 2007). Lower NUE associated with all-fall N fertilizer application on winter wheat was associated with N loss, whereas spring-only and split (fall-spring) applications improved NUE as a result of N availability prior to the period of rapid plant uptake of N, which resulted in greater fertilizer recovery (Sowers et al. 1994). The efficient recovery of fertilizer applied in spring during this accelerated phase of N uptake suggests that there was intensive root activity in the surface soil between stem elongation and boot stage (Sowers et al. 1994). Mahler et al. (1994) found both winter wheat grain yield and NUE were greatest when applications were split between fall and spring compared to spring-only or fall-only applications. Under drier growing conditions, it is not necessary to split N applications, and full N rates can be applied in fall for both winter and spring wheat since leaching is less of a concern (Mahler 2007). In dry conditions, NUE is improved by earlier N application that allows fall and winter precipitation to move N lower into the crop root zone and reduces the likelihood of it getting stranded in dry soil.

Grain yield and NUE were not impacted by N source and placement (Mahler et al. 1994). Sowers et al. (1994) also did not see a difference in NUE when spring fertilizers were top-dressed or point-injected. Band application of N fertilizer increased wheat growth, N uptake, and yield in wheat in addition to reducing populations of wild oats (Koehler et al. 1987). Banding of N fertilizer is especially important for spring wheat since there is often not enough precipitation after seeding to move the fertilizer to the root zone (Koehler et al. 1987).

Wheat cultivar yield

Fertilizing with high rates of N to control grain protein is relatively inefficient as NUE decreases with increasing N levels, especially in dry soil conditions (Raun and Johnson 1999). Low crop vigor also decreases NUE. High crop yields help improve NUE because fast growing plants have root systems that more effectively utilize available soil N (Cassman et al. 2002; Pan et al. 2016). Modern wheat cultivars can have increased vigor and increased stress tolerance, as well as improved efficiencies for taking up water and nutrients. Schillinger et al. (2012) found that semi-dwarf varieties of wheat were able to begin grain production with less available water than taller varieties of wheat that were grown prior to 1960 (Figure 6-4). In relation, all aspects that impact crop health, and therefore growth, can also impact NUE, such as insect and weed management, water and temperature regimes, supplies of other nutrients, and use of the best-adapted cultivar (Cassman et al. 2002).

Crop rotations

The sequence and intensity of crops in rotation can influence N supply, NUE, and WUE. More intensive rotations, meaning growing more crops in a given period of time, can improve NUE by increasing WUE and maintaining soil health (Raun and Johnson 1999), especially in dryland systems like those found in the inland PNW. Nitrogen use efficiency can also increase when wheat follows legumes rather than when following fallow or continuous wheat (Baudaruddin and Meyer 1994). For instance, in the inland PNW, the yield potential of winter wheat was greater following spring peas rather than wheat, and winter wheat yields and protein levels were higher for a given amount of fertilizer due to a greater N supply and N uptake efficiency (Maaz and Pan n.d.).

Nitrogen loss and environmental impacts

Leaching

Nitrate-N leaching is a major pathway of N loss in wheat-based cropping systems in the inland PNW. Because it has a negative charge, nitrate-N does not adsorb to negatively charged particles in the same way that positively charged plant nutrients do (Havlin et al. 2005). Nitrate-N is also highly water soluble. As a result, nitrate-N can be lost to leaching when water filters through the soil profile. Wet soils with high residual soil N levels are especially susceptible to leaching losses. In addition, heavy precipitation immediately after urea fertilizer applications will cause substantial amounts of urea leaching loss.

Factors that affect leaching

Both annual and individual precipitation events greatly impact nitrate-N leaching. The risk of leaching from wheat fields in the inland PNW is greatest during winter and early spring when plant uptake of nitrate-N is low and precipitation is high. Leaching is greater when N fertilizer is applied in fall compared to spring (Cameron et al. 2013; Kyveryga et al. 2013). When nitrate-N accumulates in dry soil during the growing season, it can slowly leach down the soil profile following subsequent wet seasons (Cameron et al. 2013). It is therefore important to account for soil N that has been redistributed deep into the rooting zone when determining N fertilizer application rates in order to improve NUE. Leaching risks can also be high on coarse or sandy soils since nitrate-N can easily be lost through large soil pores. Improving soil health by increasing soil organic matter content (see Chapter 2: Soil Health) has the potential to reduce the risk of leaching by improving the soil's water holding capacity, **aggregate**

stability, and nutrient adsorption capacity. Nitrate-N leaching can also be reduced by matching crop N needs with soil type, N supply, and timing of application (e.g., avoiding periods of heavy precipitation).

Environmental impact of leaching

High levels of nitrate-N can be a source of water contamination in surface and groundwater (Schepers et al. 1991). Leaching or surface runoff of nitrate-N from soils to surface water can pollute water bodies through a process called eutrophication. Eutrophication results in high amounts of algal growth and depleted sources of oxygen in the water that can be deadly to fish and other aquatic organisms. Eutrophication is a devastating concern to many salt and fresh water sources across the globe, and these polluted areas or "dead zones" mainly occur downstream from areas that experience heavy agricultural production and overuse of fertilizers. Additionally, leaching or surface runoff of nitrate-N to drinking water sources can cause human and animal health issues. The US Environmental Protection Agency (EPA) has set the maximum contaminant level of nitrate-N at 10 ppm for the safety of drinking water (EPA 2016a). Drinking water exceeding this level has the potential to negatively impact health (Cameron et al. 2013).

Volatilization

Volatilization is the loss of ammonia-N (NH_3-N) gas to the atmosphere from soil. All ammonium and ammonia-based fertilizers, including manure, anhydrous ammonia (AA), aqua ammonia, urea, and urea ammonium nitrate (UAN) have the potential for volatilization (Jones et al. 2013).

Factors that affect volatilization

Water is necessary for transporting N fertilizer into the soil. When fertilizer has been surface- applied and precipitation is minimal, volatilization typically occurs during the first two to three weeks following application (Jones et al. 2007; Turner et al. 2012). High temperatures and high wind can exacerbate volatilization (Havlin et al. 2005; Jones et al. 2013) by drying out surface soils. Typically the risk of volatilization is greater on sandy soils, even with low fertilizer application rates and deep injection.

However, there is little loss from deep-injected fertilizers, particularly AA, to loamy soils (Mullen et al. 2000). Top-dressed urea fertilizers generally have the greatest potential for volatilization (Jones et al. 2007). One half-inch of precipitation or greater within the first 24 hours after surface application of urea or UAN can significantly reduce volatilization (Jones et al. 2013) by moving the fertilizer into the profile and reducing its contact with air.

Volatilization is also greater when N fertilizer is broadcast than when it is banded, and injecting or incorporating N fertilizer immediately after application can reduce volatilization. Shank banding AA fertilizer is the most common N fertilizer application before winter wheat seeding in the inland PNW to minimize volatilization losses (Pan et al. 1997). Because AA is often injected into dry soils, drought-prone field positions may exhibit greater ammonia loss than wetter zones, particularly when soil **compaction** prevents deep shanking (Pan et al. 1997). Other factors that increase the risk of volatilization include high concentrations of soil organic matter and crop residues as well as high soil **pH** and temperatures that increase soil ammonium-N content in dissolved soil water (Jones et al. 2007). Enhanced efficiency fertilizers, controlled-release products, and volatilization inhibitors can also be applied to fields to reduce the loss of ammonia-N (Jones et al. 2013).

Environmental impact of volatilization

Although the gaseous form of ammonia-N is not a greenhouse gas (GHG), it is an environmental concern because the deposition of ammonia-N plays a significant role in the formation of atmospheric particulate matter (PM2.5) that can reduce visibility and lead to atmospheric deposition of N in sensitive ecosystems. In the atmosphere, ammonia-N reacts rapidly with both sulfuric and nitric acids to form fine particles (NOAA 2000; Behera et al. 2013). According to the EPA National Air Pollution Trends Update in 1997, agriculture contributed 85% of US emissions, about 1/3 of which resulted from fertilizer applications.

Denitrification

Denitrification is a process mediated by soil microorganisms that converts nitrate-N to gaseous forms of N. Denitrification is controlled by oxygen concentration and available carbon and is highly variable in space and time (Pan et al. 1997). In particular, nitrous oxide (N_2O) can be lost to the atmosphere and act as a powerful GHG when denitrification converts N present in agricultural soils. Nitrous oxide has approximately 300 times the global warming potential of carbon dioxide (CO_2) for a 100-year timescale, and it accounted for approximately 6% of US GHG emissions (EPA 2016b). Seventy-nine percent of these emissions were from agricultural soil N fertilizer application and other management activities. Denitrification occurs under anaerobic conditions and is more likely to occur when soils high in residual N are saturated, since microbes actively convert nitrate-N to nitrous oxide under these conditions.

Factors that affect denitrification

Denitrification potential is high in anaerobic conditions when soil is saturated. In the inland PNW, the risk of denitrification is particularly high when surface soils remain saturated especially during snowmelt events, in spring or after heavy precipitation (especially on toeslopes), during frequent freeze and thaw events, or when tillage pans impede percolation. Denitrification is negligible when pH is lower than 5 but when pH levels near 6 to 6.5, nitrous oxide presents more than half of the N emissions. Denitrification increases rapidly when temperature is greater than 35°F and is highest at 77 to 95°F (Havlin et al. 2005). The presence of high amounts of residues with low C:N ratios (e.g., legume residues) and other sources of residual soil N can increase nitrous oxide emissions (Baggs et al. 2000) under certain conditions since this material is high in N and serves as a microbial food source.

Nitrate-N leaching, ammonia-N volatilization, and denitrification losses can influence crop N recovery, fertilizer N responses, and NUE. A more thorough overview of N cycling processes and the risk of losses in relation to climate change is available through the Regional Approaches to Climate Change (REACCH) PNW Agriculture and Climate Change Webinar Series available at ***https://www.reacchpna.org/seminars-nitrogen-series***.

Sulfur Management

Sulfur (S) is the second most deficient nutrient in crops after N. Similar to N reactions, biological transformations drive S cycles, which are dominated by organic and microbial soil processes. Due to its relationship with microorganisms, S has reactions that are regulated by soil, precipitation, and temperature. Plant roots absorb S in its oxidized form (SO_4-S) where it is synthesized into an essential component of protein. Although wheat only requires approximately a tenth as much S as it does N (Lutcher et al. 2005), S impacts crop yield and is necessary for producing high-quality baking flour and must be added when soil supplies are insufficient for meeting a crop's nutrient requirements.

Soil tests can help determine if S levels are deficient, but soil tests are less reliable for S than they are for other nutrients (Koenig 2005; Lutcher et al. 2005). In the top foot, Mahler (2007) recommends applying 20 pounds of S per acre for winter wheat when soil tests estimate SO_4-S levels are lower than 10 ppm. Others recommend more conservative application rates for winter wheat ranging from 10 to 15 pounds of SO_4-S per acre for the top foot (Lutcher et al. 2005) or 10 to 20 pounds of SO_4-S per acre for the top two feet (Koenig et al. 2005) when plant-available SO_4-S is between 0 and 8 ppm. For hard red wheat, 1 pound of SO_4-S is applied for each 5 pounds of N applied, up to 25 pounds SO_4-S per acre (Koenig 2005). Lutcher et al. (2005) suggest that producers should also consider adding S if winter wheat is seeded late in the fall, if the last application of S was more than 5 years ago, or if straw exists in greater-than-average quantities in the field.

Factors impacting sulfur requirements

Sulfur is most commonly applied as ammonium thiosulfate (ATS) liquid or ammonium polysulfide during N application. It can also be applied as dry gypsum, ammonium phosphate-sulfate, or ammonium sulfate (Rasmussen 1996). Some forms of S fertilizer (especially ATS) can damage seedlings when applied with the seed, but this problem can be avoided by placing the product adjacent to or below the seed. Wet winter conditions can cause leaching that moves SO_4-S below the root zone, making S deficiencies in winter wheat fairly common in early spring following a wet winter. Deficiency symptoms may disappear later in the season when root growth extends into the deeper layers and can reach S that has migrated. If elemental S fertilizer is used, it is important to know that it is not immediately plant-available. Most elemental S will not be available until 2 or 3 years after application (Lutcher et al. 2005). Higher rates of S may need to be added when a legume crop is following wheat (Koenig 2005). Sulfur fertilizer is also important to supply to canola when it is rotated with wheat in cropping systems (Koenig et al. 2011a).

Phosphorus Management

Phosphorus (P) is important for energy transfer in the plant and is therefore critical for seed formation and grain production in wheat. Plants absorb P as phosphate in the forms $H_2PO_4^-$ or HPO_4^{-2}. Sufficient supplies of P improve overall plant vigor, health, and development. Phosphorus is the third most frequently deficient nutrient in the inland PNW and its application can increase retention of tillers and accelerate crop maturity. Phosphorus deficiency is affected very little by tillage and cropping frequency, but becomes more prevalent when higher crop yields require more P for growth (Rasmussen and Douglas 1992).

Phosphorus recommendations are based on soil test values from the surface one-foot sample. Typically, the Bray or Mehlich method is used for testing acidic soils, and alkaline soils are tested using the Sodium Bicarbonate (Olsen) method. Testing method will impact fertilizer recommendations, and it is important to know which test was used by your lab. Also note that fertilizer P is expressed as P_2O_5. Therefore, P rates are generally expressed in pounds of P_2O_5 per acre. To convert P_2O_5 to elemental P, multiply by 0.44. Because P_2O_5 rates vary widely based on location, it is best to refer to nutrient management guides specific to your region for more detailed information. Specific nutrient management guides provide recommendations for increasing P rates when wheat is produced under reduced tillage (Mahler 2007) or when P fertilizer is broadcast (Koenig 2005).

The amount of P available in the soil solution for plant uptake is often very low due to its low mobility and high likelihood to become fixed to other soil particles. When it is in the form of organic compounds, P can be very stable and slow to mineralize, while in the inorganic form, P can form insoluble calcium, iron, or aluminum compounds. The greatest degree of P fixation occurs at very low and very high soil pH levels. Most P is plant-available when soil pH values are between 6 and 7. When pH values are below 5.5 (acidic soils), P forms compounds with iron and aluminum, and when pH levels are between 7.5 and 8 (alkaline soils), P binds with calcium (Havlin et al. 2005).

Because of its relative immobility in soils, placement of P is critical for reducing its sorption to soil colloids and optimizing its availability to crops. Banding P is recommended over broadcasting because P easily gets tied up by soil minerals and organic compounds, and P should be placed so that it can be easily accessed by the roots. It is best to place P fertilizer below and to the side of the seed since application of P in the seed zone has been associated with early seedling damage and reduced plant densities (Rusan and Pan 1998). Shallow placement of P can also strand it in dry surface soil, whereas deep placement (14 to 18 inches) of P increased its availability and allowed deep roots to access subsoil water later in the season, resulting in increased plant growth and grain yield (Rusan and Pan 1998). If P fertilizer is placed deeper, as recommended by this study, soil samples should be collected 2 feet deep at 1 foot increments to capture all residual soil P before making fertilizer recommendations.

Factors impacting phosphorus requirements

Phosphorus availability is greatly affected by soil pH and it becomes less accessible to crops as it precipitates with soil minerals at both low and high soil pH levels. Lack of soil water can also limit P mobility, especially late in the season in arid and semiarid environments. Crop root growth and activity are directly influenced by P supply and increased root proliferation helps the plant access more water and nutrients deeper in the soil profile. Because of these factors, limited P availability has negatively impacted wheat growth and yield when it was grown in dry soils (Rusan and Pan 1998) or on eroded hilltops (Guettinger and Koehler 1967; Pan and Hopkins 1991a), where water availability and rooting depth are restricted. Performance of wheat on eroded hilltops was improved by using **no-till** management (Pan and Hopkins 1991b) and by inoculating soil with symbiotic mycorrhizal fungi (Mohammad et al. 1995), which helped improve P uptake when supplies were low. In a late-planted, no-till fallow system, Lutcher et al. (2012) found that adding 11 and 33 pounds of P_2O_5 per acre increased overall wheat yields by 4.4% and 7.7%, respectively, compared to a control across sites in north-central Oregon and east-central Washington. Yield improvements were observed following P application when initial Sodium Bicarbonate soil tests were less than 12 ppm (Lutcher et al. 2012).

In many areas of the US, animal manure provides a source of organic P for use on crop fields. However, the geography of the inland PNW often separates animal production from the areas where wheat is grown, and animal manure is not a readily available fertilizer source for most of the wheat or other cereal crops that are produced. South-central Idaho is one exception. This region is dominated by dairy farms in combination with fields on high plateaus and very short growing seasons. Fertilizer costs cannot be recouped by low yield increases at these locations unless producers produce organically certified wheat (organic prices are 2 to 3 times of commodity wheat) and alfalfa hay, which also allows them to utilize locally available manure (Lorent et al. 2016). Research findings from these locations found that in-season application of 5 dry tons of composted dairy manure per acre was optimal to supply adequate P to crops (Hunter et al. 2012).

When applied in excess, P can lead to harmful losses to the environment, and similar to nitrate-N, it can lead to eutrophication. However, in contrast to nitrate-N, which is lost most commonly through leaching, P does not leach and its loss mainly occurs from erosion. Therefore, it is important to minimize erosion in order to reduce loss of P. Field vulnerability to P loss can be estimated based on site characteristics and management strategies using P indexes (field-scale qualitative assessment tools). Land managers concerned with P loss can access P indexes for agricultural phosphorus management using the Oregon/Washington Phosphorus Indexes (Sullivan et al. 2003) specific to sites east and west of the Cascade Mountain Range.

Potassium, Chloride, and Micronutrient Management

Although equally as important as N, S, and P for supporting healthy wheat growth and development, other nutrients are rarely added as fertilizers since their levels in the soil are generally sufficient for meeting the nutrient requirements of wheat in the inland PNW. Important aspects are mentioned below. However, due to low crop requirements for these nutrients, little information is available about them.

Potassium

Potassium (K) is an important macronutrient influencing plant-water relations and is supplied to them in its ionic form, K. Potassium is expressed as K_2O in fertilizers. To convert K_2O to K, multiply by 0.83. Silt loam textured soils that make up most of the inland PNW are rich in K-bearing minerals and generally test high or very high for available K. In general, soil K supplies are adequate across the region (Lutcher et al. 2005). Additions of K are typically not recommended for wheat; however, Mahler (2007) suggests incorporating K fertilizer into the soil during planting on eroded hilltops and knobs when soil tests indicate low levels. Applications of 50 to 100 pounds of K_2O per acre can be beneficial if soil test reports show less than 75 ppm K (sodium acetate test) or 90 ppm K (bicarbonate extract test) in the surface foot of soil (Koenig 2005). Responses to K fertilizers on eroded hilltops may only be obtainable when P deficiency is also addressed (Guettinger and Koehler 1967). Potassium is mostly contained in the straw and crop residue of wheat. In cropping systems where straw is baled and removed, K removal can be as much as 100 pounds of K_2O per ton of residue. Producers should carefully evaluate soil test levels of K on sandy textured soils or where straw or forage crops are being removed.

Chloride

Chloride (Cl) is important for biochemical processes in plants, and although wheat requires minimal amounts of this nutrient, dryland winter wheat responds when Cl is applied. On occasion, Cl may increase grain yield, test weight, and kernel size (Lutcher et al. 2005). Supplying wheat with Cl has also been noted to reduce the incidence of physiological leaf spot (PLS) and "take-all" root rot (see Chapter 10: Disease Management for Wheat and Barley) in winter wheat (Engle et al. 1997; Karow and Smiley 1997; Smiley et al. 1993). Some cultivars of winter wheat are more susceptible to PLS; however, if these diseases are a concern and if soil tests are low, 10 to 30 pounds of Cl per acre can be supplied to wheat, but should not be applied with the seed. Benefits from adding Cl at these rates can last for several years (Lutcher et al. 2005). Potassium chloride (KCl) is the most available form of Cl.

Micronutrients

Other micronutrients including Copper (Cu), Iron (Fe), Manganese (Mn), Molybdenum (Mo) and Boron (B) have not been found to cause responses to wheat in the inland PNW. Zinc (Zn) deficiencies can be found on severely eroded hillslopes, but Mahler (2007) and Lutcher et al. (2005) have not found additions of Zn to be economical for wheat. However, micronutrient status has not been widely investigated throughout the inland PNW, and it is likely that micronutrients may be limiting in some situations. If producers are applying any of these nutrients, leave untreated test strips to evaluate the application.

Soil pH and Liming

Decreasing soil pH (soil acidification) is a growing concern in eastern Washington and northern Idaho (Mahler 1985; McFarland and Huggins 2015; McFarland et al. 2015) and has serious implications for inland PNW cropping systems. Increasing soil acidity is becoming a crop production limitation in northern Idaho and other inland PNW cropland areas (Veseth 1987). Soil pH values have been measured below 5.2 throughout the Palouse region (Table 6-4). Aluminum becomes more soluble as soil pH declines below 5.2, causing the potential for aluminum toxicity in wheat. Acidic soils can also negatively impact wheat indirectly by interacting with wheat root diseases (Paulitz and Schroeder 2016) or herbicides (Raeder et al. 2016). However, wheat cultivars respond differently to acidic soils (Froese et al. 2015).

Table 6-4. Percentage of fields at different soil pH ranges in 1985 (Mahler 1985) collected in the eastern Washington and north Idaho region. Mahler's data is compared to a 2014 soil survey in Columbia County, Washington, Washington State University variety testing program sites, and other random sample sites from the eastern Washington region.

1985 Mahler survey of soil pH values surface 12 inches		2014 Columbia County survey of soil pH values surface 12 inches	
Soil pH	% of fields	Soil pH	% of fields
>6.0	9	>6.0	3
5.6–5.9	38	5.6–5.9	8
5.2–5.4	32	5.2–5.4	66
<5.2	21	<5.2	23

Soil acidity is a major limitation to soil productivity in much of the world and is considered the master variable by soil chemists (McBride 1994). Soil pH has a direct impact on many of the chemical and biological processes in the soil, causing yield reductions in many crops (Koenig et al. 2011b). Soil pH (concentration of hydrogen in solution) is the measure of hydrogen (H^+) ions (acid soils) or hydroxide (OH^-) ions (alkaline soils) in the soil solution (Horneck et al. 2007). Regionally, soil pH values are declining (becoming more acidic) because of applications of N fertilizers, plant nutrient uptake, and precipitation (Mahler 1985; McFarland and Huggins 2015; McFarland et al. 2015) with N being the largest contributor. The presence of ammonia-N or ammonium-N in the soil contributes to the presence of hydrogen ions that result from the conversion (nitrification) to nitrate by soil bacteria (Carter 2016). This process releases hydrogen ions into the soil. The hydrogen ions replace base cations (e.g., K^+, Mg^{+2}, Ca^{+2}) from the soil **cation exchange capacity** and lower the soil solution pH. An application of N placed on or in the soil normally is within the top 6 inches of the soil profile and often creates a stratified layer of acidity (Carter 2016).

Standard soil sampling methodologies (one foot samples) tend to overlook the problem of stratified acid soil layers that have developed in once neutral pH soils. Reduced tillage may intensify or narrow the thickness of layers of stratification compared to inversion tillage systems where more soil mixing occurs, diluting the acidity somewhat. Inversion tillage systems experience the same rate of acidification, but the soil is mixed in a larger volume and may not be as noticeable. Soil sampling procedures that collect the top foot of soil in increments of 3 inches or less have been adopted to try to identify stratification of acidity and nutrients that may have developed (Carter 2016). Soil pH meters have also been found to have good results for monitoring soil in the field (Carter 2016).

Liming of acid soils is a common practice on agriculture soils of the world that have low pH. Liming is the application of amendments containing calcium carbonate ($CaCO_3$) to react with the hydrogen ions to reduce the acidic conditions (Thompson et al. 2016a; 2016b; 2016c). Soil pH is the controlling factor in the availability of primary (Table 6-5) and secondary (not shown) soil nutrients. Other impacts of soil acidity include poor plant root development, herbicide persistence, reduced (or intensified)

Table 6-5. Fertilizer efficiency and availability at different soil pH levels.

Soil pH	% Fertilizer Efficiency			% Fertilizer Unavailable
	N	P	K	
7.0	100	100	100	0
6.0	89	52	100	20
5.5	77	48	77	33
5.0	53	34	52	54
4.5	30	23	33	71

Modified and used with permission from The Mosaic Crop Nutrition Fertilizer Use Guide (2016).

herbicide activity, reduced crop yield, increased drought stress, aluminum toxicity, reduced soil structure, and reduced water **infiltration**.

Liming applications should be considered whenever soil pH levels drop below critical levels, which varies depending on the crop type (Froese et al. 2015) and many soil-applied herbicides (Raeder et al. 2016). Some soil-applied herbicides require a minimum pH, which can be found listed on many herbicide labels.

As the soil pH continues to decline, larger application rates of lime should be applied. The soil pH scale is not a linear relationship; it is logarithmic, meaning a change from pH 7 to 6 is a 10× change in acidity, but a change from pH 7 to 5 is a 100× change in acidity. The application rate of liming products should be considered in the same manner because it will take a much larger application rate and more time to correct the lower pH (Thompson et al. 2016a; 2016b; 2016c).

Liming application rates and lime activity depend on the fineness of the ground limestone, purity of the product, and the availability of water. Finer particles react faster than coarse materials, which will require weathering to reach soil solution and neutralize hydrogen ions. Lime effectiveness is measured by purity, particle size, and chemical composition relative to calcium carbonate equivalency. The Oregon Lime Score is one such rating system, and the Calcium Carbonate Equivalent (CCE) scoring method is an expression of the acid-neutralizing capacity of a carbonate rock relative to that of pure calcium carbonate, expressed as a percentage. These scoring systems may not adequately rate some of the newer ultra-fine limestone products that are available. The finer particles are more mobile in the soil and react faster than typical agricultural liming products.

Soil testing labs will provide lime recommendations relative to the soil sample properties. These recommendations indicate the amount of CCE needed to raise the soil pH to a certain specified level (6.5) in the plow layer or top six inches of soil. Recommendation methods may not be standard between labs. If recommendations are large, split applications should be considered over multiple years. There are several lime recommendation procedures. Since declining pH is a relatively recent concern (e.g., last 30 years) (Mahler 1985) in the inland PNW, the most reliable procedures have yet to be tested or determined.

As a producer and/or landowner, it is important to monitor soil pH levels and make lime applications before pH levels get dangerously low in the top 6 inches of soil. Below 5.5 is certainly approaching a level of concern and should be considered for a corrective lime application. A recommendation might be as high as 4,000 pounds per acre of CCE lime to raise the pH to 6.5, but a split application would probably be in order.

It is more economical and more sustainable to maintain a soil pH of 6.5, which will allow more efficient use of fertilizer and soil-applied chemicals, healthier plants, better weed control, and optimized crop yields, leading to a more sustainable agriculture production system.

Soil pH can be highly variable across the landscape due to topographic and soil conditions. It is likely that most fields in wheat production in the inland PNW have variable liming rates to address variable soil pH conditions. Additional information about soil acidification in the inland PNW can be found at ***www.smallgrains.wsu.edu***, including several factsheets and videos also listed in Grower Resources below.

Soil Sampling and Tests

Routine soil testing is an important practice for guiding producers to make appropriate soil fertility management decisions. Soil tests can accurately estimate factors such as nutrient deficiencies or excesses, nutrient holding capacity, soil pH, and organic matter content. Using actual values of available soil nutrients to determine fertilizer rates is one of the most important factors for improving nutrient use efficiencies, particularly in non-uniform environments like those found throughout much of the inland PNW.

Soil samples can be collected using composite sampling, grid sampling, or management zone sampling. Detailed explanations of these sampling procedures can be found in Collins (2012). Composite sampling is the least intensive sampling method and likely the most appropriate procedure for wheat producers sampling large-scale fields. Soil samples should be collected prior to planting and fertilizing the crop. Soil samples can be collected in spring or fall. An advantage of collecting soil in fall is that fall samples can determine how well the previous crop used the fertilizer it was supplied. If substantial nutrients are remaining in the soil after harvest, the plant did not use what was available and fertilizer rates should be adjusted. Errors of this type could occur if yield potential was estimated too high, residual soil contributions were not accurately accounted for, or other factors reduced yield and negatively impacted nutrient use (Koenig 2005). Post-harvest assessment of crop yield and protein performance is also encouraged in relation to N supply to help identify site-specific UNRs and improve NUE (Pan et al. 2007).

Soil test recommendations have been developed based on testing the top foot of soil with the exception of N and S. Because N and S are mobile nutrients, it is recommended to sample 0 to 5 feet, or to a restricting layer, for N and 0 to 2 feet for S, in one-foot increments. If practices that involve deeper placement of fertilizer are used for any nutrient, for example P, soil samples should be collected in one-foot increments up to that depth to improve accuracy of fertilizer recommendations. When sampling for pH, it is advisable to sample the top foot of soil in 3 or 4 inch increments to determine the degree of pH stratification, especially in long-term direct-seed fields.

Soil tests also help evaluate the long-term effectiveness of nutrient management strategies on a farm and detailed recordkeeping is encouraged. Carefully track annual fertilizer rates, additions of lime or other soil amendments, crop rotations and yields, and soil test data in a notebook, spreadsheet, or database. Multi-year records can provide a better understanding of nutrient dynamics within fields and can help indicate whether application rates and decision drivers, such as yield potentials, are accurate or need to be adapted. More in-depth details about appropriate soil sampling methods and test evaluations are provided in Soil Sampling (Mahler and Tindall 1997) and Soil Testing: A Diverse Guide for Farms with Diverse Vegetable Crops (Collins 2012). Fertilizer recommendations based on soil tests are specific to each nutrient, and producers should reference nutrient management guides for more specific information.

Conclusions

Interactions among climate, water, and nutrient dynamics impact wheat development, growth, and associated soil fertility management strategies in the inland PNW. Variability among these factors across the region is common, and diverse landscapes and local weather conditions complicate the choices that producers have to make regarding timing and application of nutrients. Environmental concerns associated with N losses, soil erosion, nutrient runoff, and soil acidification can result from improper use of fertilizers and make inland PNW wheat production systems less sustainable over the long-term. Because nutrient cycling is impacted by temperature, precipitation, and available soil water, understanding the importance of these variables in relation to current nutrient management decisions will help prepare producers to adapt to changes associated with future climate-related stresses. Practices that improve resource use efficiencies (e.g., fertilizers and water), build soil, and reduce pollution have the ability to decrease the negative environmental impacts associated with over-use of fertilizers while improving the resiliency of the soil and wheat production in the inland PNW.

Grower Resources

Nitrogen Management Webinar Series

https://www.reacchpna.org/seminars-nitrogen-series

A series of three, one-hour-long recorded video webinars addressing issues related to agricultural N and the environment.

- Nitrogen Cycling and Losses in Agricultural Systems
- Nitrous Oxide Emissions in Inland Pacific Northwest Cropping Systems

- Nitrogen Management and Climate Change Mitigation in Pacific Northwest Cropping Systems

Nitrogen and Post-Harvest Calculators

http://smallgrains.wsu.edu/soil-and-water-resources/

Dynamic tools based on the Dryland Winter Wheat Nutrient Management Guide that help calculate N supply.

Soil pH Video Series

http://smallgrains.wsu.edu/soil-and-water-resources/soil-acidification-in-the-inland-northwest/

A series of three, 6 to 10 minute videos discussing associated concerns and treatment of low soil pH.

- Soil pH – What it Looks Like
- Soil pH – How it Happens
- Soil pH – Managing it on the Farm

Extension Management Guides

Regionally specific Extension guides that provide recommendations and calculations for determining appropriate soil fertility management strategies in wheat-based cropping systems.

Nutrient Management

Dryland Winter Wheat Eastern Washington Nutrient Management Guide. 2005. Washington State University Extension Publication EB1987.

Nitrogen Management for Hard Wheat Protein Enhancement. 2005. Pacific Northwest Extension Publication PNW 578.

Northern Idaho Fertilizer Guide Winter Wheat. 2007. University of Idaho Extension Publication CIS 453.

Phosphorus Fertilization of Late-Planted Winter Wheat in No-till Fallow. 2012. Pacific Northwest Extension Publication PNW631.

Phosphorus Increases Wheat Yields. 1967. Washington State Cooperative Extension Service Publication EM 2940.

Southern Idaho Dryland Winter Wheat Production Guide. 2004. University of Idaho Extension Publication BUL0827.

Winter Wheat in Continuous Cropping Systems (high precipitation zone). 2007. Oregon State University Extension Service FG 84-E.

Winter Wheat in Continuous Cropping Systems (Intermediate precipitation zone). 2006. Oregon State University Extension Service FG 83-E.

Winter Wheat and Spring Grains in Continuous Cropping Systems (Low precipitation zone). 2006. Oregon State University Extension Service FG 81-E.

Winter Wheat in Summer-Fallow Systems (Intermediate precipitation zone). 2006. Oregon State University Extension Service FG 82-E.

Winter Wheat in Summer-Fallow Systems (Low precipitation zone). 2005. Oregon State University Extension Service FG 80-E.

Water Availability

Predicting Wheat Grain Yields Based on Available Water. 2012. Washington State University Extension Publication EM049E.

Nutrient Losses

Agricultural Phosphorus Management using the Oregon/Washington Phosphorus Indexes. 2003. Oregon State University Extension Service EM 8848-E.

Factors Affecting Nitrogen Fertilizer Volatilization. 2013. Montana State University Extension Publication EB0208.

Management of Urea Fertilizer to Minimize Volatilization. 2007. Montana State University and Washington State University Extension Publication EB173.

Soil pH and Liming

Acid Soils: How Do They Interact with Root Diseases? 2016. Washington State University Extension Publication FS195E.

Acidifying Soil for Crop Production: Inland Pacific Northwest. 2007. Pacific Northwest Extension Publication PNW599.

Agricultural Lime and Liming, Part 1: Introduction Agricultural Lime and Liming. 2016. Soil Acidification Series. Washington State University Extension Publication FS212E.

Agricultural Lime and Liming, Part 2: Laboratory Testing to Determine Lime Requirements. 2016. Soil Acidification Series. Washington State University Extension Publication FS217E.

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