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POTATO NUTRIENT MANAGEMENT FOR CENTRAL WASHINGTON

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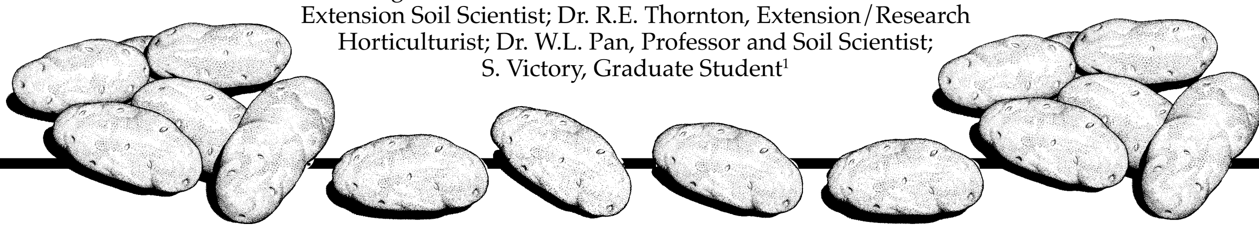

This management guide summarizes nutrient management concepts for maintaining high yields, while minimizing environmental impact. It was written to provide management details and background to understand and support the reasoning behind the recommendations. The goal of all nutrient management should be to follow good farming practices (Best Management Practices, BMPs) which avoid applying nutrients in excess of plant needs. Research-based recommendations in this guide are designed to optimize potato tuber yield and quality in the Columbia Basin and other major Northwest production areas. Observations and recommendations commonly made by crop consultants in central Washington (Lang and Stevens, 1997) are included as a statement of current practices. Additional production factors (e.g., irrigation management, soil and tissue sampling) are discussed in relation to nutrient management, but for more comprehensive recommendations, additional extension publications or a county extension agent should be consulted.

Nutrient application should be made on the basis of plant demand. Plant demand is a function of growth rate, growth stage (Table 1), climatic conditions, and cultivar. The amount of nutrients required by a potato crop are also related to a realistic yield potential for the selected cultivar and land farmed. Thus, the amount of fertilizer applied to a potato crop should depend on the supplying power of the soil, the potential for nutrient loss, and the growth potential of the cultivar (Dean, 1994). For the purposes of this guide, fertilizer recommendations will be made based on the "sufficiency concept." That is, based on a soil test value, the amount of fertilizer recommended is the amount needed to produce optimum yield of the current crop. The recommendation does not contain any specific provision for the amount of a nutrient removed with the crop or any additional amount of nutrient to build up the soil's ability to supply the nutrient for future crops.

Recommendations in this guide represent current research based understanding of nutrient management needed to provide optimum yield and quality of irrigated potatoes in central Washington, while insuring maximum protection of environmental quality. These recommendations will need to be modified and fine-tuned to fit each potato management unit to optimize yield, quality, and environmental protection at each location.

POTATO GROWTH STAGES & NUTRIENT DEMAND

Potato growth can be divided into four distinct stages (Table 1). Coordination of nutrient availability with the nutrient requirement of each growth stage has a profound influence on yield, specific gravity, and other quality characteristics. Russet Burbank has been selected as the model cultivar due to the amount of research information available and the acreage planted to Russet Burbank. Information concerning nutrient management for other long season (indeterminate) and short season (determinate) cultivars is included when available.

The rate of potato shoot emergence during growth stage I depends on soil temperature. Under

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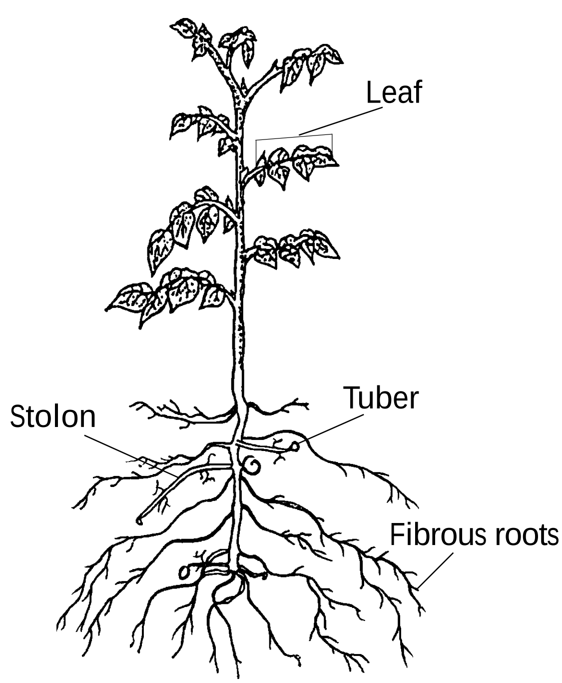
Table 1. Plant growth stages of Russet Burbank potato.

Stage I	Plant development after planting and until tuber initiation.
Stage II	Begins with initiation of tubers at the tips of stolons (tuberization) approximately 10 to 14 days prior to flowering.[z] Tuberization is defined as an enlargement which is double the normal stolon diameter. Little or no enlargement of initiated tubers (bulking) occurs during this stage.
Stage III	Enlargement of initiated tubers (bulking); tuber growth is linear if all growth conditions are optimum; tuber dry weight increases due to translocation of plant nutrients and food reserves from the shoots and roots into the tubers.
Stage IV	Tuber maturation occurs as vines start to yellow, leaf loss is evident.

Adapted from Kleinkopf and Westermann, 1981

[z]Growers should monitor tuber initiation and flowering to determine tuber initiation under their growing conditions due to interactions of soil temperature, water, and fertility modifying the initiation of this growth stage each season. Plant stress promotes tuberization when plants are small.

favorable growing temperatures (typically 55 to 65˚F during early spring), shoots emerge within 21 days after planting (DAP). By emergence, primary roots have elongated 4 to 6 inches from the seedpiece (Fig. 1). Promoting rapid root development under the furrow improves water and nutrient efficiency during subsequent fertigation (applying liquid fertilizers through the irrigation system). Root



elongation is most rapid during stage I, reaching 2 feet below the hill and into the furrow zone as early as 30–40 DAP under optimum soil physical conditions (Pan et al., 1994). Although stolons can be initiated throughout most of the growing season, during early growth (stage I) the majority of stolons are produced for tuber set. During emergence and initial growth, plant nutrients are supplied primarily from reserves in the seed piece until the plant establishes a leaf area of approximately 31–62 $inch^2$ or when plants have covered approximately 50% of the ground surface (using a 34-inch by 9-inch plant spacing) (Dean, 1994). Optimizing earliest tuber set should be a goal of the management system.

Early-season nutrient management is critical for development of a healthy root system and preventing excessive vine growth during stages I and II. For short season (determinate) cultivars, tuber initiation begins when plants reach a genetically regulated shoot to root ratio. In the subsequent developmental stage (stage III), maximum tuber bulking occurs until plant senescence or environmental conditions end the growing season (Kleinkopf and Dwelle, 1978). High nutrient availability early in the growing season does not influence tuber initiation in short season (determinate) cultivars as strongly as in long season (indeterminate) cultivars. Short season cultivars generally have a greater early-season bulking rate which must be supported by greater early-season nutrient availability than for indeterminate cultivars (Ojala et al., 1989). However, excess fertilizer application should be avoided at all growth stages for both short and long season cultivars to increase fertilizer efficiency and minimize potential leaching or erosion losses of nutrients.

SOIL AND PLANT SAMPLING

Maintaining nutrient levels to optimize growth is critical for sustaining plant health and tuber growth rates. Best nutrient management practices include the use of soil and tissue (petiole) analysis. Proper sample collection and selection of a testing laboratory which maintains high analytical standards increases the potential for obtaining reliable values for coordinating fertilizer management.

Soil Sampling

Pre-season soil tests provide critical information to determine the amount of residual nutrients available. In-season soil analysis is an additional tool to monitor nutrient availability and complement petiole analysis. Crop consultants in central Washington have found in-season soil tests can predict potentially limiting soil nutrients (primarily nitrogen) which can be adjusted prior to significant drop in petiole concentrations (Lang and Stevens, 1997).

The following factors should be considered when collecting soil samples:

- The sampling site or sites should be representative of the major soil type in the field

- Consistency in sampling from the same field site provides better comparisons of nutrient availability from week to week

- Pre-season samples should be from the tillage root zone (generally the upper 12 inches)

- In-season samples should be taken in the area of most active nutrient uptake by roots; a bed position and sampling protocol should be established and maintained throughout the growing season

- Deep samples (> 12 inches) should be collected periodically to monitor nutrient availability in the root zone; deep soil samples are important when sampling mobile nutrients such as nitrate and sulfate

- Sampling intensity (number of samples) depends on field variability and size of management unit within a field

- High intensity sampling using a systematic approach such as grid sampling or intense sampling based on knowledge of soil properties or yield potential will be useful if site specific management can be used to differentially treat delineated management areas

- Soil sampling to 3 or 4 feet should be used following cropping to determine effectiveness of in-season nitrogen management.

Tissue sampling

Petiole sampling (Fig. 2) has been used to assess and predict in-season potato nutrient status. Petiole analysis may include all essential nutrients, but often only nitrate levels are reported throughout the season. Petiole analysis should be interpreted based on **trends** over the season and **not** on values from a **single sampling date**. Results from a single petiole analysis may be affected by time of day samples are collected, climatic conditions preceding sample collection, and cultural practices, such as plant stress, age, or disease, that are not directly related to fertility status. Nutrient concentrations are not uniform throughout the plant and may change as

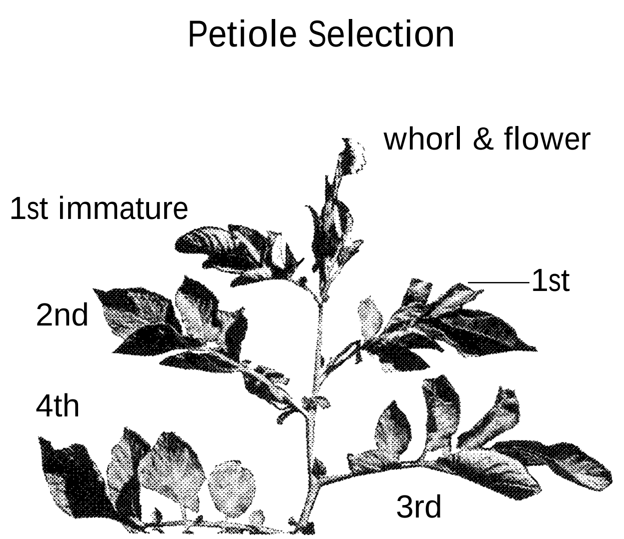


Figure 2. The leaf arrangement on a potato stem (Holland, 1996).

the tissue matures. For example, nitrogen, phosphorus, potassium, copper, zinc, and sulfur levels decrease with increasing leaf age. In contrast, calcium, magnesium, boron, iron, and manganese levels generally increase. Thus, a consistent method for selecting a petiole of the same age (fourth or fifth node, Fig. 2) must be used to avoid differences in nutrient concentrations between sampling dates. Also, trends in petiole analysis values should be evaluated based on cultivar, length of growing season, yield and quality goals, plant part selected for analysis, and research data. If nutrient concentrations are significantly different for a single sampling date, as compared to previous values, additional sampling prior to adjusting in-season fertilizer application rates is recommended. Tissue samples improperly collected, handled, and analyzed result in inaccurate results. Improperly interpreted tissue analysis values and trends can result in improper fertilization.

The following factors should be considered when collecting petiole samples:

- Plants should be sampled every 7 to 10 days beginning about 4 weeks after emergence and ending about 3 weeks before vine-kill

- Petioles should be collected from plants in the same location as soil sample collection to allow comparisons of soil nutrient availability with petiole tissue nutrient status

- Each field should be sampled at the same time of day throughout the season

- Petioles should be collected from the first fully expanded leaf (fourth or fifth petiole from the growing tip); select one leaf position and use it consistently throughout the season for comparison with critical values based on the same plant part (Fig. 2)

- 30 to 40 petioles should be included in the sample to increase accuracy and provide enough sample weight for a complete analysis; 15–20 petioles may be sufficient if only nitrate is to be determined (verify amount of tissue needed with your testing laboratory)

- All leaflets should be stripped off the petiole at the time of sampling

- Petioles should be washed to remove any surface contamination due to fertilizer or water residue*

- Refrigerate at < 50˚F or air dry petiole samples which are not submitted for analysis immediately*

- Do not compare tissue nutrient analysis results which are derived from—a single season's analysis, different sampling methods, plant parts, handling techniques, or laboratory analysis methods.

**Contact your testing laboratory to determine their preferred method for handling petioles between sampling and analysis.*

NITROGEN

An effective nitrogen fertilization program coordinates amount and timing of fertilizer application with plant demand and soil nitrogen supply. Poor nitrogen fertility management can lead to inefficient nitrogen utilization, which can reduce crop yield (total yield and percentage of #1's), tuber quality, and pose significant environmental risk.

Potato Nitrogen Needs

Nitrogen is required in large amounts to maintain optimum shoot and tuber growth. Nitrogen may be supplied by residual soil nitrogen reserves, mineralized soil nitrogen, nitrogen in irrigation water, and fertilizer application. Uptake of nitrogen (crop requirement) is determined by the amount a cultivar requires to produce a given yield. The amount of nitrogen required in the plant/soil environment to meet this need is determined by the cultivar's nitrogen use efficiency and length of growing season. The amount of nitrogen available to meet a crop's requirement depends upon the efficiency of the management system. The potato plant's nitrogen uptake efficiency under current best management practices is approximately 65% (Roberts et al., 1991), an efficiency which is comparable to that of corn and wheat.

. . .Under optimum growing conditions, a 30 to 35 ton/acre crop of Russet Burbank potatoes can be produced with a season total of 300-350 lb N/acre *(Kleinkopf and Westermann, 1986; Lauer, 1985; Lauer, 1984; Roberts and Cheng, 1986; Roberts et al., 1991).*

Nitrogen supply should be adjusted approximately ± 10 lb N/acre for each ton which varies from the 30–35 ton/acre range (Table 2). The total nitrogen accumulation at a given yield is independent of soil type. Whether soils are silt loam or sand has little influence on the total nitrogen taken up by the potato plant to produce a 30–35 ton potato crop. Therefore, although timing and placement may differ, total nitrogen available for uptake should be the same on different soil types and irrigation systems. For example, silt loam soils which are furrow irrigated are often thought to require higher pre-plant nitrogen than sandy soils with sprinkler irrigation, due to limitations in mid-season applications. To promote tuber initiation on silt loam soils, lower pre-plant application rates in conjunction with mid-season sidedress or foliar (aerial spray) applications may be a better alternative than high pre-plant application. Alternately, sandy soil (especially coarse sands in the black sands region of Washington) has low moisture and nutrient holding capacities and require modified irrigation frequency and rates to limit movement of nutrients below the root zone. For these soils both pre-season and in-season nitrogen applications may be required in small increments to limit the concentration of nitrogen subject to leaching at any given time.

Current pre-season management is based on nitrogen found in the top 12 inches of soil. Residual soil nitrogen, remaining from the previous crop or from organic matter release (present in the top 12 inches of the soil profile prior to planting) is a portion of the seasonal nitrogen available for uptake and should be subtracted from total nitrogen applied. Unlike other soil test values, nitrogen is reported in "lbs/acre" and can be considered equivalent to lbs/acre of fertilizer nitrogen. Additional study of pre-season sampling is needed to develop an understanding of the potential importance to potato production of nitrate in the 12–24 inch zone. Early-season irrigation management is critical to limit the potential loss of residual and preplant applied nitrogen due to leaching. An estimate of total season nitrogen application needed in combination with residual soil nitrogen concentrations is provided in Table 2.

Mineralization (the microbial conversion of organic nitrogen to ammonium), is a factor to be considered in predicting total nitrogen fertilizer application. Nitrogen is made available for uptake throughout the growing season due to mineralization of soil organic matter. The amount released depends on soil organic matter present, soil texture, climate, and crop residues. Under most central

Table 2. Nitrogen fertilizer rates[z] for total season application based on residual soil concentrations (0 to 12 inch depth) and potential yield of Russet Burbank produced in the Columbia Basin.

Soil test N ($NO_3 + NH_4$)	Potential yield (tons/acre)			
	20	25	30	35
(ppm)	N Application Rate (lb/acre)			
0	200	250	300	350
10	160	210	260	310
20	120	170	220	270
30	80	130	180	230

[z]Does not include N needed for microbial decomposition of previous crop residue or from mineralized soil organic matter. Assumes ppm x 4.0 = lbs/acre; may be adjusted for different bulk densities.

Washington conditions (especially sandy soils), mineralized nitrogen may represent a small percentage of the total nitrogen available. However, if an estimate of mineralizable nitrogen is available from soil analysis, it should be considered available for uptake and subtracted from the nitrogen to be applied. Estimates of released nitrogen range from 20–50 lbs N/acre for each percent soil organic matter.

Organic residues from previous crops in the rotation or from cover crops planted prior to potatoes influence the availability of nitrogen during the growing season. Organic residues high in carbon remove available soil nitrogen from the soil solution as the organic residues are broken down by soil microorganisms. Possible microbial tie-up of nitrogen must be accounted for in early-season nitrogen management. Approximately 10 lb N/ton of high carbon to nitrogen ratio straw residue, such as from field corn or wheat, may be needed to supply adequate nitrogen for microbial breakdown of these crop residues and thus may be temporarily unavailable to the potato crop. A portion of this nitrogen will be released to the crop during the season and can be managed with reduced in-season nitrogen applications. Much of the nitrogen required for microbial breakdown of high carbon residues may be available as residual soil nitrate following harvest. Soil sampling can be used to determine nitrogen availability.

Cover crops commonly grown for nematode control (rape and immature sudan grass) or soil stabilization may have very low carbon to nitrogen ratios and high nitrogen concentration, which allow for rapid residue breakdown, making the nitrogen from these sources available for plant uptake early in the growing season. Breakdown of succulent cover crops in the early spring may occur prior to significant plant growth, thus exposing released nitrate to possible leaching with inefficient irrigation management. Increases in soil nitrogen availability have been found as early as 2–5 weeks after incorporation of the green vegetative crops (Weinert, 1996). Well established winter cover crops such as wheat, rye, and brassicas which are incorporated into the soil in the spring, can reduce over-winter nitrate leaching and reduce total nitrogen fertilizer application required by 75 to 150 lb N/acre, as nitrogen is released through microbial breakdown (Weinert et al., 1995). Nitrogen released from crop residues will be observed as elevated or maintained soil and petiole nitrate levels, thus reducing in-season nitrogen application. Frost-killed cover crops such as sudan grass begin to release inorganic nitrogen in the fall and early spring, so careful irrigation management is required to retain this nitrogen in the root zone. Optimum utilization of this nitrogen released from cover crops requires the use of in-season soil sampling. Increased soil nitrate levels may not be detected by changes in petiole nitrate levels in time to adjust in-season nitrogen application rates to prevent over application of nitrogen.

In some production areas, irrigation waters may contain a significant amount of nitrate. Highest concentrations of nitrate may be found in well waters. The amount of nitrogen being applied with irrigation water should be calculated and subtracted from fertilizer applications needed to meet total nitrogen requirement.

A survey of crop consultants (Lang and Stevens, 1997) indicates total nitrogen application rates for a 30–35 ton/acre crop sometime exceed 300–350 lb N/acre due to management and environmental problems which include: (1) suboptimal irrigation timing and quantity; (2) suboptimal timing of nitrogen fertilizer application, based on potato growth stage; (3) disease and or pest pressures; and (4) periods of early season high precipitation. Inappropriate management practices can lead to inefficient nitrogen utilization, which has the potential to reduce tuber yield and quality. This negative effect cannot be overcome with increased nitrogen rate or application frequency, especially late in the growing season. Using nitrogen to overcome inappropriate management practices increases the potential for nitrogen leaching, ultimately leading to an increase in the potential for groundwater contamination.

Timing Nitrogen Applications

Nitrogen applications which are split between pre-plant and in-season provide opportunities to increase nitrogen use efficiency and minimize leaching by preventing excess availability. Excessive amounts of nitrogen at planting can elevate salt levels, adversely influencing moisture availability in the zone of new root growth (Kunkel et al., 1977). Avoiding excess nitrogen availability during growth stages I and II also favors a balanced proportion of roots and shoots, resulting in enhanced tuber set (Kleinkopf and Dwelle, 1978; Kleinkopf and Ohms, 1977; Lauer, 1984; Lauer, 1985; Ojala et al. 1989). Maximizing early tuber initiation and set increases the potential **duration** of tuber bulking phase of development. Delaying tuber initiation and the onset of tuber bulking due to excess nitrogen availability increases the potential of decreased yield and quality because there is less time for tuber bulking to occur. Additionally, surplus nitrogen availability during the early growth stages can delay the transition from shoot accumulation to shoot translocation of nitrogen to the tubers until early August. Delay of tuberization by two weeks can decrease yields by 5 tons/acre (Kleinkopf and Dwelle, 1978). The addition of a set daily or weekly nitrogen application rate throughout the growing season is not an effective nitrogen management strategy, due to differences in shoot and tuber growth rates which have different nitrogen demands. This type of routine nitrogen application does not account for variation in uptake rate due to growth stage or growing conditions.

Based on developmental growth stages (Table 1), early vegetative growth (stage I) uses between 10 to 15% of the total season nitrogen required for maximum yields in Russet Burbank (Ojala et al., 1989; Westermann and Kleinkopf, 1981).

. . . For split nitrogen applications no more than 1/3 of the expected total seasonal nitrogen (including residual soil nitrogen) should be applied preplant or at planting *(Lauer, 1984)*

Maximum early tuber production can be achieved with pre-plant application rates of 60 to 120 lb N/acre, when adjusted proportionally for residual soil nitrogen.

The first in-season application should occur prior to the end of stage II (tuberization). By the end of tuber initiation (early stage II), between 30 to 40% of the total nitrogen uptake has occurred (Ojala et al., 1989; Westermann and Kleinkopf, 1981). The most rapid nitrogen uptake corresponds to the beginning of tuber bulking, which occurs at the beginning of stage III, normally in early July. Thus, the crucial time for maintaining adequate nitrogen fertility is during mid-season (stage III, Table 1) when nitrogen uptake is largely determined by tuber growth rate. For indeterminate cultivars, the majority of nutrient uptake occurs between 40–100 DAP (Pan et al., 1994, Roberts et al., 1991).

To anticipate this demand, in-season nitrogen application should be managed by monitoring nitrogen availability through soil (NO_3 + NH_4) and plant tissue (petiole NO_3) analysis. Following pre-plant applications, the balance of total nitrogen applications should take place as fertigation through sprinkler systems, as a sidedress under furrow irrigation systems, or as foliar application (using aerial sprays). Monitoring soil nitrogen availability and petiole nitrate trends aids in preventing deficiency levels during stage III, and insures maximum tuber bulking rates (Ojala et al., 1989). Application of in-season nitrogen using petiole analysis trends should be restricted to the amount of nitrogen which can be taken up and utilized by the potato plant prior to the next application. Typical uptake rates of 3–4 lb N/acre each day for stage III can be supported by applications of 5 to 7 lbs N/acre each day (factoring in the 65% efficiency rate). Petiole NO_3 levels should be used to determine when lower rates of application should be used. Many crop consultants in central Washington have found with appropriate seasonal management, a nitrogen application rate of approximately 35 lb N/acre each week is adequate to support potato nitrogen uptake rates during tuber bulking (Lang and Stevens, 1997).

Generally, the total period of in-season (split) application will be from row closure to 100 DAP for a 120- to 130-day crop (Lauer, 1984) because approximately 95% of the total nitrogen uptake is completed by the end of stage III (Westermann and Kleinkopf, 1981). Additional fertilization beyond 100 DAP should be carefully evaluated because of two separate factors. First, the majority of shoot and tuber nutrient accumulation has been completed (Pan and Hiller, 1992). Secondly, a significant decline in root length occurs during bulking thereby reducing nutrient uptake capacity (Pan et al., 1994). With the reduced uptake capacity of roots during the end of stage III and stage IV growth, substantial amounts of nitrogen may be subject to leaching after harvest if high fertilizer application rates are maintained (McNeal, 1975). Additionally, late-season applications adversely affect tuber quality and yield by stimulating re-growth of deteriorating vines, which results in a reduction in dry matter accumulation in the tuber (Lauer, 1984) and internal defects observed as heat necrosis. Any late season applications of nitrogen should use low rates and high frequency applications to maximize nitrogen uptake potential. Late-season soil sampling can be used to determine when soil nitrate levels begin to increase while petiole nitrate levels continue to decline, indicating soil nitrate availability is not limiting plant nitrate supply. Termination of in-season fertilizer application at the beginning of stage IV allows for normal senescence of foliage and maturation of tubers (Lauer, 1984). Thus, in-season (split) nitrogen application should be completed prior to the onset of significant vine senescence. As plants begin to die back during stage IV, irrigation rates must also be modified to reflect decreasing demand for water.

Modifications in management strategies recommended by crop consultants (Lang and Stevens, 1997) for determinate cultivars include:

- reduce or increase pre-plant nitrogen applications as compared to standard management for indeterminate cultivars
- begin in-season nutrient applications at an earlier developmental stage, at higher rates than indeterminate cultivars due to higher nitrogen requirement for early season tuber bulking
- use the same fertilizer program as indeterminate cultivars with an earlier termination date

Nitrogen Petiole Values

Seasonal optimum petiole nitrogen values are normally at the highest concentration during early stages of growth and decrease through the season, with greatest declines occurring during tuber bulking (Table 3). Although optimal values recom-

Table 3. Recommended optimal petiole nitrate concentrations, based on survey of industry consultants[z] and research[y], for the developmental growth stages of Russet Burbank potato produced in the Columbia Basin.

	Petiole NO_3-N Concentration (ppm)		
Developmental Stage	Consultant Ranges	Research Plot Ranges	Recommended Ranges
Stage I	– – – –	– – – –	– – – –
Stage II	20,000 to 30,000	15,000 to 22,000	15,000 to 26,000
Stage III	12,000 to 30,000	12,000 to 15,000	12,000 to 20,000
Stage IV	8,000 to 15,000	6,000 to 10,000	6,000 to 10,000

[z]Lang and Stevens, 1997.
[y]Jones, 1975; Painter, 1978; Westermann and Kleinkopf, 1982.

mended by crop consultants in Washington vary widely (Lang and Stevens, 1997), research places optimal values in lower ranges (Jones, 1975; Painter, 1978; Westermann and Kleinkopf, 1982).

Optimal nitrate petiole values have been developed by researchers using highly controlled areas where measured petiole nitrate concentrations are representative of the entire area. Therefore, these optimal values may have a fairly narrow range due to intensive management of limited production area. When interpretation of petiole nitrate concentrations are expanded to large production fields, field variability must be considered in management decisions. In many fields, soil and/or growing conditions may differ significantly. Therefore, petiole sampling areas should be selected to represent the **major** conditions found in the field. The recommended petiole nitrate levels shown in Table 3 reflect field variation. Overall nitrogen field management must optimize nitrogen utilization and crop production for the majority of field conditions. Areas with extreme production problems can be adequately managed only with site specific management techniques. Under some production conditions, petiole nitrate concentrations may be below published critical levels even under optimum nitrogen fertilizer application rates. Under these conditions, only small increases in yield may occur with additional nitrogen application (Rykbost et al., 1993); thus, factors which may limit petiole nitrate concentrations should be considered.

Decreases in petiole nitrate concentrations can indicate a decreased nitrogen supply or a reduced ability for nitrogen uptake by the plant; thus, in-season nitrogen application must take both possibilities into consideration. Consider that potato shoots accumulate nitrogen up to approximately 80 DAP, beyond which time nitrogen is translocated to tubers (stage III) (Pan et al., 1994), because tuber growth requirements exceed nitrogen supplied from root uptake (Kunkel et. al, 1977). This transition from nitrogen accumulation in the shoots to translocation of nitrogen to tubers can occur as early as mid-July (Kleinkopf and Westermann, 1980), coinciding with the high nitrogen demand associated with tuber bulking.

Average Russet Burbank petiole NO_3-nitrogen can be maintained with soil nitrogen (NO_3+ NH_4) concentrations of 10 to 15 ppm in the top 18 inches of soil (Westermann and Kleinkopf, 1981). Under abnormally cool spring conditions, measurement of total petiole nitrogen should be considered when unusually low petiole nitrate levels are found. Nitrate availability may be limited under cool soil conditions, resulting in low petiole nitrate which may not accurately reflect the nitrogen status of the plant, because of ammonium uptake.

In-season soil samples need to be taken from the area of greatest nutrient uptake. This area will depend upon soil texture, bed shape, growth stage, and irrigation management. Therefore, a specific sampling protocol should be developed for each cropping system. It is important to be consistent with the sampling protocol throughout the growing season and over successive rotations of potatoes on the same land. Based on growth stages, adequate seasonal soil nitrogen in the top 18 inches should be within the following values (Westermann and Kleinkopf, 1982):

Developmental Stage	Soil NO_3-N+ NH_4-N Concentration
	(18-inch depth)
Stage I	15 ppm
Stage II	> 10 to 15 ppm
Stage III	10 ppm
Stage IV	< 10 ppm

As discussed previously, in-season sampling will be critical in detecting nitrogen release from crop residues and late-season build-up of nitrogen as plants begin the process of maturing/senescing and become less efficient in nitrogen uptake.

Nitrogen management has been related to several plant health problems. Optimum nitrogen availability produces a healthy plant which is more resistant to plant diseases. Nitrogen deficiency in potato tissue has been associated with the severity of *Verticillium* wilt in Russet Burbank potato (Davis et al., 1990). However, it is important to remember excessive nitrogen can lead to excessive canopy growth, which may be more susceptible to leaf diseases; thus, nitrogen management which balances plant growth (canopy and tuber) optimizes disease resistance.

Nitrogen Sources

Common forms of nitrogen fertilizer include urea, anhydrous ammonia, liquid (aqua) ammonia, ammonium sulfate, ammonium nitrate, calcium nitrate, and nitrogen solutions. Research in central Washington indicates that under best management practices nitrogen source has practically no effect on potato yield, quality, or nitrogen uptake rate (Davis et al., 1984; Kunkel et al., 1977). Specifically, total yield, percentage of #1's, specific gravity, blackspot index, and chip color are the same regardless of the form of nitrogen applied (Loescher, 1981). However, ammonium in mixed sources may be less likely to be lost to early season leaching and may be important to consider in reducing leaching when spring rainfall may increase the risk of nutrient movement beyond the root zone. Alternatively, for soils which have low residual nitrate levels, nitrate fertilizers may be preferable (Davis et al., 1984). Additional factors which impact nitrogen source selection include:

- cost
- other nutrient sources applied with nitrogen
- possible soil acidifying effect of the nitrogen source
- source available
- salt index

Environmental Risk

For maximum protection of groundwater from contamination, nitrogen should be managed throughout the cropping system. Best management practices for water and nitrogen applications during the potato production season are necessary to maximize nitrogen use efficiency and minimize the potential for nitrate loss below the rooting zone. Remember that nitrate leaching is possible throughout the potato cropping system. Nitrate can be lost not only during potato production, but also during the non-cropping period. Encouraging deep root growth of other crops during the rotation, to recover nitrogen which moved beyond the potato root zone can significantly reduce nitrogen leaching.

Irrigation Management

Careful water management is essential to avoid water (drought) stress which could result in yield and quality losses. However, excessive irrigation also causes significant yield and quality losses and increases the potential for leaching nitrogen below the root zone. Early and late season over-application of water represents the greatest potential for leaching of nitrate below the rooting depth. To manage irrigation effectively scheduling must be adjusted during the season to equal crop water use. Scheduling irrigation frequency and rate such that irrigation is within 0 to 6 inches of the potato crop's seasonal evapo-transpiration rate maximizes yield and specific gravity potential (J. Stark,1996[2]). Exceeding the optimal irrigation level can reduce yield up to 1.5 tons/acre and cannot be overcome by increasing nitrogen application rates (J. Stark, 1996[2]).

Effective irrigation management requires maximum uniformity of the irrigation system. Irrigation water should be analyzed to determine nutrient content (especially NO_3), so that significant

[2]Effects of irrigation and nitrogen management on potato quality. Washington Potato Information Exchange. Pasco. May 29, 1997.

concentrations are considered in the nutrient management plan. Additionally, irrigation water supplies should be analyzed for chemical properties such as pH, soluble salts, sodium, and bicarbonate concentration. These factors can affect nutrient availability, directly impacting yield, quality, and long-term soil conditions. More comprehensive irrigation management information is available in the WSU Cooperative Extension publication, *Irrigation Management Practices to Protect Groundwater and Surface Water Quality; State of Washington* (EM4885).

PHOSPHORUS

The need for phosphorus fertilization in Pacific Northwest potato production is well documented (Stevens, 1989; Westermann et al., 1986; Westermann and Davis, 1992). The soil solution concentration of phosphorus is low; therefore, there is little risk of leaching phosphorus under central Washington conditions. However, excessively high phosphorus application does increase the risk of phosphorus moving off fields into surface water, with potential negative environmental impact. Best management practices which reduce runoff and erosion significantly reduce the potential loss of phosphorus to surface waters.

Phosphorus plays a critical role in root development and overall plant health, which is directly related to yield. However, once phosphorus levels are at concentrations which adequately support plant health, large increases in phosphorus application rate to support increased yields are unnecessary. For maximum tuber yields, phosphorus should be mixed into the seed bed prior to planting to support: early shoot and root growth (stage I), tuber initiation (stage II), and tuber bulking (stage III). Plant phosphorus levels in mid- and late-season (stages III and IV) may be raised by applications of phosphorus using foliar sprays, application through irrigation water, or soil applied phosphorus followed by irrigation. However, due to the small distances phosphorus moves in the soil, feeder roots must be near the soil surface to make in-season application effective.

Phosphorus fertilizer application rate should be based on soil analysis results (reported in ppm). Research has established a relationship between soil test phosphorus and a soil's ability to supply phosphorus to the plant. This relationship is used to relate soil test phosphorus to the amount of phosphorus fertilizer which must be added to adequately supply the crop (Table 4). If a soil test is erroneously thought to represent lbs of phosphorus available for uptake, it will lead to errors in determining the needed application rate.

Table 4. Phosphorus fertilizer rates[z] for total season application based on pre-plant soil test concentrations (0 to 12 inch depth) for Russet Burbank potato produced in the Columbia Basin.

Soil test P (sodium bicarbonate)	Application Rate (lb/acre)[z]	
(ppm)	P	P_2O_5[y]
3	130	295
6	90	204
9	70	159
12	50	114
12 to 20	30	68
Above 20	0	0

[z]Recommended application rates are for average conditions; conditions such as high soil pH, high free lime, or high bicarbonate irrigation water will restrict phosphorus availability and therefore, application rates should be increased to supply crop needs.

[y]To convert P_2O_5 to P, multiply by 0.44.

A pre-plant soil test phosphorus value of 20 ppm (sodium bicarbonate extraction) was determined to be adequate for optimum production without additional phosphorus application on non-calcareous to slightly calcareous soils (Dow et al., 1974). Although potato yields have increased significantly since the late 1970s, little research on phosphorus requirements has been conducted in Washington. However, the adequacy of this soil test level was supported by research in Idaho during the 1980s (Westermann and Kleinkopf, 1984; Westermann et al., 1985), which indicated recommended phosphorus rates (Table 4) are sufficient to reach current yield goals. It should be noted that soil and water conditions may occur which require phosphorus application rates significantly higher than those listed in Table 4. Elevated soil pH, in association with free lime (calcium carbonate), decreases phosphorus availability to the plant. Under these conditions, higher rates or banding should be considered in order to increase phosphorus availability. Also, irrigation water high in bicarbonate will decrease phosphorus availability, requiring increases in application rate. Under conditions in which phosphorus availability is difficult to maintain, in-season applications should be considered. Consult with your county extension agent to determine appropriate increases in phosphorus application rate under these cultural conditions.

Some growers apply pre-plant phosphorus even when soil analysis concentrations exceed 20 ppm based on the belief that a positive growth response might be possible and a portion of the additional phosphorus will be utilized by other rotation crops (Stevens, 1989). Pre-plant application rates recommended by crop consultants vary from no additional phosphorus application (with soil concentrations of 30 to 40 ppm) to applying between 50 to 350 lb P_2O_5/acre regardless of soil tests results (Lang and Stevens, 1997). Recommendations by crop consultants for total season phosphorus application rates vary from 0 to 420 lb P_2O_5/acre (Lang and Stevens, 1997). Whereas some crop consultants recommend split applications, the majority report under standard procedures more than 80% of the total season phosphorus is applied prior to planting. Although limited data exists, a potential early-season benefit for placement of phosphorus at mark-out and/or planting exists. Placement at planting varies with the producer, but a common location is 4 inches out to each side and 2 inches above the seed piece. Placement of phosphorus in the area of early-root-zone growth appears to increase root growth, thus maximizing plant establishment and early tuber set. Adequate phosphorus availability in the furrow will promote root development in this region, thereby reducing the potential for water and nutrient losses. In soils with low phosphorus fixation capacity and low phosphorus availability, broadcast and incorporation of phosphorus fertilizer may be recommended.

Although some crop consultants recommend lower rates of phosphorus for early season (determinate) cultivars (Lang and Stevens, 1997), there appears to be little data which indicate a difference in phosphorus requirements for early (determinate) and long (indeterminate) season cultivars. Confirmation of an upper phosphorus soil test value, which maintains the soil's ability to reach yield goals for both determinate and indeterminate cultivars remains to be established. High phosphorus soil concentrations do not appear to negatively impact yield. High concentrations have been suggested to reduce zinc availability; however, this is not documented.

Crop consultants usually do not alter recommendations in application rate due to soil texture or irrigation system (Lang and Stevens, 1997). However, phosphorus application rates may need to be increased on soils which contain a significant fraction of $CaCO_3$ or "free lime" (>1-2%). Elevated levels of free lime in the soil cause phosphate fertilizers to be rapidly precipitated to form slowly available calcium phosphate. Work in Idaho indicates increasing application rates by as much as 120 lb P_2O_5/acre to an upper limit of 400 lbs P_2O_5/acre may be needed to supply adequate plant available phosphorus in soils with 5-15% free lime. Banding of acidifying nitrogen and phosphorus mixed fertilizers will increase phosphorus availability in these soils. Free lime generally occurs in isolated areas of fields in Washington. Therefore, intensive soil sampling and variable rate application may be of value to economically increase plant available phosphorus.

Commercial phosphorus sources are equivalent in phosphorus availability when used properly. Source and application method in central Washington is often determined by grower preference and compatibility with application equipment.

Trends in petiole phosphorus concentration should be used to monitor and evaluate in-season timing and rate of application, when an adjustment appears necessary. Research indicates adequate phosphorus petiole values should be > 1000 ppm soluble P (0.22% total P) until plant maturation or approximately 20 days prior to vine kill (Roberts and Dow, 1982: Westermann et al., 1986). Total phosphorus concentration (%) in the petiole may be converted to soluble phosphorus concentration (ppm) by the following equation (Roberts and Dow, 1982; Westermann, 1984):

$$P_{\text{soluble (ppm)}} = 5600\,(P_{\text{total (\%)}})^2 + 3620\,(P_{\text{total (\%)}}) - 10$$

However, the testing laboratory used by each producer should be contacted to determine what petiole phosphorus concentrations are reported (total and/or soluble phosphorus concentrations). Some central Washington plant and soil testing laboratories recommend maintaining 4th petiole phosphorus at 0.6 to 0.8 % total phosphorus, with in-season applications if petiole levels drop to approximately 0.4% (Lang and Stevens, 1997). In-season phosphorus applications of foliar sprays (aerial applications), fertigation, or as dry material followed by irrigation are recommended to help maintain petiole phosphorus levels when poor root function, disease, or environmental stress have a negative effect on phosphorus uptake. By plotting petiole phosphorus concentration, producers can predict if phosphorus may become limiting in the future (Westermann et al., 1986). If petiole levels are predicted to fall below the critical concentration, an in-season application should be made prior to a drop in phosphorus petiole concentration below the critical level.

Early root growth and optimum nutrition which maintains healthy plant growth can help plants resist disease infection. Although phosphorus has not been directly linked to specific quality factors or plant diseases, some research (Davis et al., 1994) suggests when less than optimum phosphorus uptake (due to inadequate availability) occurs, the incidence of *Verticillium* wilt in potato increases.

POTASSIUM

Potatoes require high levels of potassium in concentrations which are comparable to or greater than nitrogen (Tindall, 1992; Tindall and Westermann, 1994; Tindall et al., 1993; Westermann et al., 1994a). Potassium is taken up from the soil solution as the potassium ion (K^+) which is replenished predominately from the exchange sites on soil colloids. Therefore, soil extracted K^+ (reported in ppm) provides an index of soil potassium supplying ability (Table 5). Caution should be used because an assumption that soil analysis values represent pounds of potassium available for uptake will lead to errors in determining the needed application rate.

Potassium application rates should be based on soil analysis (Table 5). Although potato yields have increased significantly since the late 1970s, little research on potassium requirements has been conducted in central Washington. It should be noted that large amounts of potassium are removed by crops commonly included in the potato rotation. Therefore, marginally fertilized soil may, over time, require increased rates of potassium fertilizer application.

Table 5. Potassium fertilizer rates for total season application based on pre-plant soil test concentrations (0 to 12 inch depth) for Russet Burbank potato produced in the Columbia Basin.

Soil test K (sodium bicarbonate)	Application Rate (lb/acre)	
(ppm)	K	K_2O^z
60	400	480
120	300	360
180	200	240
240	100	120
>240	0	0

[z]To convert K_2O to K multiply by 0.83.

At recommended potassium soil levels, yield does not appear to be directly related to increased application rates or source of potassium (KCl, K_2SO_4, or thiosulfate). In fact, applications in excess of recommended rates may be detrimental to potato quality (Tindall and Westermann, 1994; Westermann et al., 1994b). High rates of potassium fertilizers may cause slight decreases in tuber specific gravity, which is especially important to potato used in processed products. This effect is seen more often with fertilizers containing potassium chloride than with formulations which contain potassium sulfate, although research suggests (Westermann et al., 1994b) that both potassium sources decrease specific gravity to a similar degree, even when nitrogen application rates were equal. Thus, producers with tuber specific gravity problems may want to consider altering the potassium fertilizer source and/or application rate. However, there are reports of increased disease resistance with the use of potassium chloride. Crop consultants have not consistently seen significant differences in disease incidence related to potassium source. However, high rates of potassium chloride have been related to significant reductions in potato tuber quality (Lang and Stevens, 1997).

Applying a major portion of total season potassium fertilizer prior to planting has been found effective in obtaining maximum yields (Tindall et al., 1993). Westermann and Tindall (1995) found under their production system that pre-season potassium application at adequate rates was more effective than split application, including fertigation. Presently, data is not available to determine if banding is as effective as applying potassium as a broadcast incorporation in central Washington. The practice of applying potassium in multiple split applications does provide the advantage of reducing the amount of potassium at planting, thereby reducing the potential for salt concentrations becoming a problem. However, banding potassium fertilizer materials beside the seed piece at planting has the potential to elevate salt levels in the area in which sprouting of the seed piece occurs, causing detrimental results in root development. Due to limited uptake by foliage, in-season aerial application of potassium does not appear to meet plant (tuber) demands. Fertigation could be used when potassium levels are found to be within adequate concentrations during the growing season. Although data is limited, potassium fertigation is potentially an effective means of helping match the 3–7 lb K/acre each day potassium uptake rate which takes place during bulking (Tindall, 1992). Collectively, although in-season split potassium applications hold some potential advantages, research has yet to determine the effectiveness of in-season potassium fertigation. Thus, it should only be considered a supplement to an optimum pre-plant program.

Recommended application rates can be used on most soil types. On extremely sandy soils, where potassium holding capacity is extremely low, application timing may need to be modified and split applications may be advantageous. Petiole analysis may be used to monitor the seasonal trends of potassium uptake. Although adequate values recommended by crop consultants in Washington vary somewhat (11.7% early-season, 10.1% mid-season, 8.5% late- season or >10% maintained throughout the season), research has defined sufficient potassium petiole concentrations in the following ranges:

Developmental Stage	Sufficient Petiole K Concentration (%)
Stage I	– – – –
Stage II	8 to 11
Stage III	6 to 9
Stage IV	4 to 6

SULFUR

Although sulfur deficiencies are not common in central Washington, sulfur is an essential element in potato growth and production. For this reason, soil test values are commonly provided for sulfur to aid in potato crop management. However, research data to verify critical soil test levels for sulfate-sulfur or a relationship between application rate and yield response is limited.

Sulfate (SO_4^{-2}) is a mobile ion and may be subject to leaching. Thus, early season sulfur deficiency may occur where leaching has moved sulfate below the root zone. For this reason, soil samples should be taken to a depth of 24 inches to verify sulfate availability to the potato crop. Depending on source, preplant broadcast and incorporation of sulfur applications (in the available sulfate form) may occur along with application of some N-P-K fertilizer formulations.

The concentration of sulfate in irrigation supplies will vary depending upon the source of the water. Irrigation water should be analyzed for sulfate to determine irrigation's contribution to the annual sulfur supply.

The majority of sulfur fertilizer is applied in the sulfate form, although elemental sulfur may be applied as a plant nutrient and/or as a means to lower soil pH. It should be recognized that when elemental sulfur is applied, a significant lag in sulfate availability occurs due to limited microbial activity. This occurs particularly under cold, wet soil conditions, which are common early in the growing season. Ultimately the source of sulfur fertilizer applied is influenced by grower preference, availability from the fertilizer supplier, and need to reduce soil pH (Lang and Stevens, 1997).

The standard recommendation has been to apply sulfur fertilizer at a rate of 40 lb S/acre, if sulfur is known to be deficient (Dow et al., 1974). Crop consultant recommendations vary from application rates of approximately 40 to 250 lb S/acre for production of a 30 to 35 ton potato crop (Lang and Stevens, 1997). Soil test information may be useful in determining sulfur availability (Table 6). Sulfur deficiency can occur with soil test levels < 2 ppm SO_4^{-2}-S (Marx et al., 1996).

Table 6. Sulfate-sulfur soil test ranges and interpretation for east of the Cascades.

	SO_4^{2-}-S (ppm)
low	< 2
medium	2 to 10
high	>10

Adapted from Marx et al., 1996.

In-season monitoring of soil and petiole concentrations are an aid in preventing sulfur deficiencies. Sulfur petiole concentrations should be maintained within a range of 0.15 to 0.20 % to support tuber growth (stage III) (Westermann and Davis 1992). Testing laboratories in central Washington place sufficient sulfate petiole concentrations in the following ranges (Lang and Stevens, 1997):

Developmental Stage	Petiole SO_4^{-2}-S Concentration (%)
Stage I	– – – –
Stage II	0.22 to 0.25
Stage III	0.20 to 0.22
Stage IV	0.18 to 0.20

As with all petiole analysis information, trends over the season and between different seasons should determine changes in sulfate application rates.

ADDITIONAL NUTRIENTS

Calcium is sometimes erroneously considered a micronutrient. It is actually an essential macronutrient required for plant growth and has been implicated as a factor influencing tuber quality. Although the relationship between calcium and tuber quality has received significant interest, research has not established a direct relationship. A possible link between low calcium availability to tubers and the severity of internal brown spot (IBS) has been suggested (Clough, 1994; Olsen et al., 1995). Under some field conditions IBS has been decreased by calcium fertilization.

Although calcium and magnesium are essential plant nutrients for plant growth they are seldom limiting in central Washington soils. Calcium is immobile in plant tissues. To be translocated to the tubers during bulking, calcium must be taken up by the stolons and/or stolon roots. Therefore, any calcium fertilization program must be designed to increase the calcium concentration in the zone of tuber formation. To maintain calcium availability in the zone of tuber formation, the solubility and potential leaching of calcium fertilizers must be considered (Pan and Hiller, 1992). Clough (1994) raised calcium levels in sandy soils using gypsum and calcium nitrate. Additional research is needed to determine the parameters that must be considered in the use of calcium fertilizers.

Presently there is limited data to support an economic response to the application of boron (B), iron (Fe), manganese (Mn) or copper (Cu), although the idea of applying complete fertilizer mixes which contain these nutrients is attractive to many producers. These nutrients are needed in only small quantities, but are essential to plant growth. Application of individual plant nutrients should be based on soil test or petiole analysis (Tables 7 and 8). Low, marginal, and adequate petiole concentrations have been reported for some micronutrients (Table 8).

Micronutrient deficiencies under central Washington production conditions are uncommon. However, availability of zinc can become growth limiting under high pH, high free lime, or very high phosphorus soil conditions. Zinc soil concentrations above 1.0 ppm (DTPA extraction) are considered sufficient, while soil concentrations < 0.8 ppm can cause deficiency symptoms. Applications of 10 lb Zn equivalent/acre are recommended to supply adequate zinc for optimum crop production. Grower experience should be considered in adjusting zinc application rates when chelated materials are applied.

Economic responses to boron application are not common because relatively low levels of boron are required for optimum growth. Excess levels of boron can have a negative impact on growth due to plant toxicity and should be avoided. Application rates recommended by crop consultants vary from 0 to 5 lb B/acre (Lang and Stevens, 1997). Boron should be applied in a broadcast-incorporated application and not banded.

Iron application on alkaline soils is inefficient unless a chelated formulation is applied, and then, response may be minimal. Lowering soil pH using soil amendments can increase the availability of iron for plant uptake. Manganese availability may also be improved by formation of an acid fertilizer band in the root zone. Foliar applications of micronutrients may be useful in correcting deficiencies.

Table 7. Critical soil test levels for micronutrient (0 to 12 in depth) for Russet Burbank potato produced in the Columbia Basin.

Nutrient	B^z	Cu^y	Fe^y	Mn^y	Zn^x
			ppm		
Critical concentration	0.5	—	—	—	0.8 to 1.0

[z]Extracted with hot water.
[y]Insufficient research data to determine critical soil test levels Cu, Fe, Mn.
[x]Extracted with DTPA.

Table 8. Suggested nutrient ranges (ppm)[z] for the most recently matured petiole (fourth) for Russet Burbank potatoes produced in the Columbia Basin.

		ppm	
Nutrient	Low	Marginal	Adequate
Boron	< 10	10 to 20	> 20
Copper	< 2	2 to 4	> 4
Iron	< 20	20 to 50	> 50
Manganese	< 20	20 to 30	> 30
Zinc	< 10	10 to 20	> 20

Adapted from Hiller, 1993.
[z]Micronutrient levels will vary with growth stage; current research data is insufficient to give specific ranges based on growth stage.

SUMMARY

The recommendations provided in this management guide are meant to be just that, recommendations. They will have to be modified and fine tuned to meet the needs of each management unit. However, before significant changes in these recommendations are made, a producer must understand the effect such changes will have on yield and quality of tubers and the potential threat of loss of nutrients to the environment. Minimizing leaching of nitrate and other nutrients from the root zone must become a primary management objective.

These recommendations are based on research; therefore, they should be expected to be modified as additional knowledge and understanding of nutrient management is obtained. Best nutrient management requires that all management steps be optimized. Soil preparation, planting, irrigation and disease control must be performed according to best management practices if nutrient management for optimum production is to be obtained.

REFERENCES

Clough, G.H. 1994. Potato tuber yield, mineral concentration, and quality after calcium fertilization. J. Amer. Soc. Hort. Sci. 119:175–179.

Davis, J.M., W.H. Loescher, M.W. Hammond, and R.E. Thornton. 1984. The effects of soil fumigation on the nitrogen nutrition of potatoes. Proc. Wash. State Potato Conf. pages 51–55.

Davis, J.R., L.H. Sorensen, J.C. Stark, and D.T. Westermann. 1990. Fertility and management practices to control Verticillium wilt of the Russet Burbank potato. Amer. Potato J. 67:55–65.

Davis, J.R., J.C. Stark, L.H. Sorensen, and A.T. Schneider. 1994. Interactive effects of nitrogen and phosphorus of Verticillium wilt of Russet Burbank potato. Amer. Potato J. 71:467–481.

Dean, B.B. 1994. Cultivation, fertilization, and irrigation. In: Managing the potato production system. Haworth Press, Inc. New York. pages 69–83.

Dow, A.I., A.R. Halvorson, R.E. Thornton, and S. Roberts. 1974 Fertilizer guide: irrigated potatoes for central Washington. Washington State Univ. Extension Service (FG–7).

Hiller, L.K. 1993. Role of micronutrients in potato fertilization. Proc. Univ. Idaho Winter Commodity School. 25:186–193.

Jones, J.P. 1975. Petiole analysis as a guide to nitrogen fertilization application. Proc. Idaho Potato School. pages 75–76.

Kleinkopf, G.E. and R.B. Dwelle. 1978. Effect of nitrogen fertilization on tuber set and tuber size. Proc. Idaho Potato School. pages 26–28.

Kleinkopf, G.E. and R.E. Ohms. 1977. Nitrogen and time of application in potato yield and quality. Proc. Idaho Potato School. pages 15–17.

Kleinkopf, G.E. and D.T. Westermann. 1980. Effects of N and cultural practices on potato growth and quality. Proc. Idaho Potato School. pages 12–18.

Kleinkopf, G.E. and D.T. Westermann. 1981. Predicting nitrogen requirements for optimum potato growth. Proc. Univ. Idaho Winter Commodity School. pages 81–84.

Kleinkopf, G.E. and D.T. Westermann. 1986. Petiole testing for efficient nitrogen management. Proc. Univ. Idaho Winter Commodity Schools 18:163–165.

Kunkel, R. N.M. Holstad, and B.L. McNeal. 1977. Comparison of some nitrogen sources for potato. Proc. Wash. State Potato Conf. pages 31–37.

Lang, N.S. and R.G. Stevens. 1997. Survey of central Washington fertilizer recommendations. Proc. Wash. State Potato Conf. (In press)

Lauer, D.A. 1985. Russet Burbank yield response to sprinkler-applied nitrogen fertilizer. Amer. Potato J. 63:61–69.

Lauer, D.A. 1984. Response of RB potatoes to sprinkler-applied N fertilizer on sandy soils. Proc. Wash. State Potato Conf. pages 39–49.

Loescher, W.H. 1981. Nitrogen source as it affects potato growth. Proc. Wash. State Potato Conf. pages 89–92.

Marx, E.S., J. Hart, and R.G. Stevens. 1996. Soil test interpretation guide. Oregon State University Extension Service (EC 1478).

McNeal, B.L. 1975. Nitrogen, minimum tillage, and the Columbia Basin. Proc. Wash. State Potato Conf. pages 75–79.

Ojala, J.C., J.C. Stark, and G.E. Kleinkopf. 1989. Influence of irrigation and N management on potato yield and quality. Amer. Potato J. 67:29–42.

Olsen, N.L., L.K. Hiller, L.J. Mikitzel, R.E. Thornton, and W.L. Pan. 1995. Internal brown spot (IBS) development in greenhouse grown 'Russet Burbank' tubers. Proc. Wash. State Potato Conf. pages 29–35.

Painter, C.G. 1978, NO_3-N in potato petioles in relation to yield and quality of tubers. Proc. Idaho Potato School. pages 23–25.

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. pages 105–111.

Pan, W.L., L.K. Hiller, E. Lundquist, and R. Bolton. 1994. Potato root development. Proc. Farrow. 1991. Potato uptake and recovery of N-15 enriched NH4/NO3 from periodic applications. Agro. J. 83:378–381.

Roberts, S. and A.I. Dow. 1982. Critical nutrient ranges for petiole phosphorus levels of sprinkler-irrigated Russet Burbank potatoes. Agro. J. 74:583–585.

Roberts, S. and H.H. Cheng. 1986. Potato response to rate, time, and method of nitrogen application. Proc. Wash. State Potato Conf. pages 69–80.

Roberts, S., H.H. Cheng, and F.O. Farrow. 1991. Potato uptake and recovery of N^{-15} enriched NH_4/NO_3 from periodic applications. Agro J. 83:378–381.

Rykbost, K.A., N.W. Christensen, and J. Maxwell. 1993. Fertilization of Russet Burbank in short-season environment. Amer. Potato J. 70:699–710.

Stevens, R.G. 1989. Phosphorus relationships in potato production. Proc. Wash. State Potato Conf. pages 63–67.

Tindall, T.A. 1992. Potassium in potatoes. Proc. Univ. Idaho Winter Commodity Schools 24:123–124.

Tindall, T.A. and D.T. Westermann. 1994. Potassium fertility management of potatoes. Proc. Univ. Idaho Winter Commodity Schools 26:239–242.

Tindall, T.A., D.T. Westermann, and J.C. Stark. 1993. Potassium management in irrigated potato systems of Southern Idaho. Proc. Univ. Idaho Winter Commodity Schools 25:149–154.

Weinert, T. 1996. Cover crops and the N cycle in a potato-based rotation. M.S. Thesis, Washington State Univ., Pullman, Wash.

Weinert, T., W. Pan, M. Moneymaker, G. Santo, and R. Stevens. 1995. Green-manured winter cover crops in irrigated potato rotations. Proc. Wash. State Potato Conf. pages 23–35.

Westermann, D.T. 1984. Mid-season P fertilization effects on potatoes. Proc. 35th Ann. Fertilizer Conf. pages 73–81.

Westermann, D.T. and J.R. Davis. 1992. Potato nutritional management changes and challenges into the next century. Amer. Potato J. 69:753–767.

Westermann, D.T. and G.E. Kleinkopf. 1981. Potato growth and nitrogen requirements. Proc. Wash. State Potato Conf. pages 121–128.

Westermann, D.T. and G.E. Kleinkopf. 1982. Potato management for optimum yield and quality. Proc. Univ. Idaho Winter Commodity Schools 14:102–104.

Westermann, D.T. and G.E. Kleinkopf. 1984. Phosphorus nutrition of potatoes. Proc. Univ. Idaho Winter Commodity Schools 16:215–219.

Westermann, D.T., G.E. Kleinkopf, and G.D. Kleinschmidt. 1985. Phosphorus fertilization of potatoes—a review. Proc. Univ. Idaho Winter Commodity Schools 17:147–151.

Westermann, D.T., G.E. Kleinkopf, and G.D. Kleinschmidt. 1986. Phosphorus fertilization of potatoes—a review. Proc. Wash. State Potato Conf. pages 15–20.

Westermann, D.T. and T.A. Tindall. 1995. Managing potassium in potato production systems of Idaho. Proc. Idaho Potato School. pages 201–242.

Westermann, D.T., T.A. Tindall, D.W. James, and R.L. Hurst. 1994a. Nitrogen and potassium fertilization of potatoes: yield and specific gravity. Amer. Potato J. 71:417–431.

Westermann, D.T., T.A. Tindall, D.W. James, and R.L. Hurst. 1994b. Nitrogen and potassium fertilization of potatoes: sugars and starch. Amer. Potato J. 71:433–453

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