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Lack of growing season precipitation and the temperate climate in north central Oregon pose challenges to growing spring wheat crops. Phosphate and sulfate fertilization can improve early growth of spring wheat in this region and soil testing aids in determining rates of fertilization. In this study, anion exchange membranes (AEM) were used to assess phosphorus and sulfur supply rates in four, minimally-tilled, annually cropped spring wheat fields in north central Oregon. To determine the validity of AEM in this region, uptake of P and S by hard red spring (HRS) wheat was correlated with soil supply of P and S as predicted by AEM. I found that in low soil water content and cool soil temperature conditions, AEM did not accurately measure plant available P and S. Unlike plants, AEM are static instruments that cannot measure plant available nutrients when soil conditions limit mineralization and diffusion of plant nutrients. I also found that three consecutive years of drought across the study sites has led to P and S quantities

sufficient for maximum yield potential of HRS wheat without fertilization. These results suggest that growers in north central Oregon may not necessarily need to fertilize wheat crops following a drought and that AEM may provide inaccurate information regarding soil nutrient status.

Environmental Constraints on the use of Anion Exchange Membranes in Dryland Wheat

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I understand that my thesis will become part of the permanent collection of the Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Andrea Elizabeth Redman, Author

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CHAPTER 1.
INTRODUCTION

In north central (NC) Oregon, growing hard red spring wheat as a direct seeded, annual crop (DS-AC) is an alternate production system from the traditional conventionally tilled, soft white winter wheat-fallow system. The DS-AC system alters nutrient release in the soil from that of a conventional system (Koehler, 1979; Smith and Elliot, 1990). Therefore, growers producing hard red spring (HRS) wheat in a DS-AC system must change the soil fertility management from that of a conventional system. However, little information exists on HRS wheat production in a DS-AC system in NC Oregon. Without knowledge of nutrient uptake by hard red spring wheat from a DS-AC system, yields will continue to be less than from conventionally tilled, winter wheat after fallow. The soil and water conservation realized from the DS-AC system will not prevail throughout the dryland agriculture region of North Central Oregon without satisfactory yield.

Among the macronutrients for plant growth, phosphorus (P) and sulfur (S) are particularly influenced by changes to the soil brought about by direct seeding and annual cropping. Soil testing has long aided in optimizing yields by allowing growers to apply fertilizers in precise quantities. However, soil tests conducted by chemically extracting soil nutrients may not provide an accurate measure of the amount of plant available nutrients (Havlin et al., 1999). Rather, chemical soil tests measure only the potential availability of a nutrient.

An alternate method of soil testing that warrants research is an ion exchange resin. Ion exchange resins, inserted into the soil, not only provide data on nutrients available to the plant, but can also supply information on the availability of a nutrient throughout the growing season. Ion exchange resins have the potential to allow growers to optimize fertilizer use in DS-AC systems by aiding in the understanding of how the soil in such a system supplies nutrients to a crop.

This review will address direct seeding and annual cropping in the dryland agriculture region of NC Oregon. The purpose of the review is to set the stage for the importance of research on phosphorus and sulfur fertility in DS-AC hard red spring wheat. The review will also examine the relevance of ion exchange resins as a means of detailing soil nutrient dynamics in DS-AC wheat.

1.1 Literature Review:
Dryland Spring Wheat Production In A Direct Seeded, Annually Cropped System

1.1.1 North central Oregon climate

The Mediterranean-type climate of North Central (NC) Oregon is adapted to the production of cool-season crops, such as wheat, which produce most of their biomass prior to the high summer temperatures, thus using water more efficiently than warm-season crops (Rasmussen, 1989). NC Oregon experiences cool, moist winters and warm to hot, dry summers. Mean annual precipitation across the region ranges from less than 203 mm to approximately 762 mm. The precipitation pattern in the Pacific Northwest has a large influence on wheat production in NC Oregon. In this region, approximately 70% of the precipitation falls between October and April, outside the growing season (OCS, 2002). Mean annual temperature in NC Oregon varies with elevation: Heppner, Oregon, at 574 meters (m) has a mean annual temperature of 10.4 °C while The Dalles, Oregon, at 31 m, has a mean annual temperature of 12.8 °C (OCS, 2002).

Wind also affects wheat production in NC Oregon. High seasonal winds are common in NC Oregon causing wind erosion of productive topsoil from fallow fields. Windspeed measured in Hermiston, Oregon, for example, averaged greater than 15 miles/hour 30% of the time between March and June; however, such conditions were recorded between July and October only 13% of the time. Variation in windspeed is also observed diurnally, with the highest windspeed generally occuring in the afternoon and the lowest windspeed in the morning (Papendick, 1998).

1.1.2 North central Oregon soils

The soils of NC Oregon are formed in loess parent material deposited approximately 13,000 to 18,000 years ago (Busacca and Montgomery, 1992). The Walla Walla soil series is common to the four sites of this research project all located in Oregon: The Dalles, Heppner, Moro, Pendleton. The series is classified as a coarse-silty, mixed, mesic Typic Haploxeroll. Additionally, it is a deep, well-drained silt loam. A typical pedon consists of the following: Ap horizon (0-15 cm) of very dark grayish brown (10YR 3/2) moist, BA horizon (15-48 cm) of dark brown (10YR 3/3) moist, Bw horizon (48-112 cm) of brown (10YR4/3) moist, BCk horizon of very pale brown (10YR 5/3) moist with disseminated lime present (SCS, 1988). Typically, the mollic epipedon of the Walla Walla series is 25 to 48 cm thick and depth to secondary carbonates ranges from 109 to more than 152 cm (SCS, 1988). The depth of loess in the Walla Walla series of NC Oregon ranges from about 1 meter to approximately 15 meters (Busacca, 1991; Busacca and Montgomery, 1992). The entire depth of the Walla Walla soil series profile depends on several factors. These include original loess deposition, location, and field-landscape position.

The nutrient rich, loess topsoil accounts for the productivity of NC Oregon. The present topsoil has buried older loess deposits called paleosols. Paleosols can limit wheat yield because they have higher clay and lime content making them less nutrient-rich, less permeable, and denser than the present surface soil. If erosion has removed a substantial amount of the topsoil, growers may be planting directly into the unproductive paleosol. Busacca et al.. (1984) noted wheat producers planting on eastern Washington hillslopes may be seeding directly into the less productive paleosol because soil erosion either exposed the paleosol completely or caused it to be located within the seeding zone.

1.1.3 Contrasting cropping systems

Wheat grown in NC Oregon receiving less than 480 mm of annual precipitation is traditionally farmed as a conventionally tilled, wheat-fallow system (Jennings et al., 1990). This two-year rotation ensures crop stability and has produced favorable winter wheat yields. In a 15-year (1972 –1987) study at Columbia Basin Agriculture Research Station in Pendleton, Oregon, wheat yields from a winter wheat-fallow rotation were 21% and 31% higher than yields from a wheat-pea rotation and a wheat-wheat rotation, respectively (Rasmussen, 1989). However, direct seeding has been shown to decrease soil erosion and has the potential to store sufficient water for wheat to be grown annually. This has led to the alternate cropping system of direct seeding in conjunction with annual cropping. Direct seeding and intensified cropping, as with annual crop production, have a large influence on soil biological, chemical and physical properties. The mechanics of each system follows.

Conventional tillage in a wheat-fallow rotation. In the winter wheat-fallow rotation, winter wheat is sown in October of every other year and harvested in July of the following year. The ground is fallowed for 14 to 15 months to complete the two-year rotation. The main purpose of the fallow period is to allow the soil to accumulate sufficient water to produce a subsequent wheat crop (PNW, 1999; Jennings et al., 1990).

One way soil water storage is achieved is by tilling to disrupt the continuity of macropores in the soil creating a “dust mulch”. The powdery soil structure of the 10 to 12 cm dust mulch dries quickly and allows less soil water to evaporate from the zone below the dust mulch (Schillinger, 1992). Macropores are the major pathway for soil water movement. Lack of continuity between macropores in the subsoil and topsoil causes water to be "trapped" in the subsoil thereby decreasing evaporation (Schillinger, 1992). Soil water also is stored because moisture is not exhausted by crop plants nor by weeds in the fallow field. Weeds are controlled by a combination of disking and chiseling in the fall after winter wheat harvest to control weeds. Weed control can also be achieved with the use of field cultivators and sweeps in areas that receive less than 480 mm of precipitation because lower amounts of residue are produced. The fallow field is rod weeded two to five times to control weeds and to maintain a 10 to 13 cm soil mulch. In some cases, the grower uses nonselective herbicides to delay initial tillage operations (USDA-ARS, 1995).

Despite historical yield stability, four factors cause the wheat-fallow rotation to be inefficient. First, the fallow period is only about 30% efficient in storing precipitation (PNW, 1999). Second, income is limited to every other year for a given acre in a two year wheat-fallow rotation. This means growers practicing wheat-fallow cropping are not as economically competitive with growers in other parts of the world that produce a crop in every field every year (PNW, 1999).

Third, increased soil disturbance caused by intensive tillage negatively impacts soil physical, chemical, and biological properties (Bezdicek et al., 1998). During the fallow period, the soil may be tilled up to 9 times (Janosky, Young, and Schillinger, 2002). Each tillage operation disrupts the soil organism community adversely affecting the organisms' population and diversity. Soil organisms are not only necessary for nutrient cycling, they also play a role in the physical properties of soil. For example, soil microorganisms, such as fungi and bacteria, secrete polysaccharides that bind soil aggregates together creating stable soil structure conducive to high hydraulic conductivity. Likewise, the burrowing action of earthworms creates channels from the soil surface to the subsoil through which water flows (Brady and Weil, 1999). Bezdicek et al.. (1998) assessed soil quality in farmers' fields using no-till (NT) for 10 to 25 years compared to adjacent conventionally tilled (CT) fields. The researchers found infiltration rates in NT were 20% to 40% higher than infiltration rates in CT. The higher infiltration rates in NT were attributed to the continuity of root channels and macropores created by insects and earthworms (Bezdicek et al., 1989).

Fourth, tillage and fallowing both have been cited as causes of soil erosion. Tillage causes erosion in two ways. Tilling soil results in low soil aggregate strength caused by disturbance of soil organism communities. Soil organisms secrete substances that bind soil particles into aggregates (Brady and Weil, 1999). Soils that slake easily or disperse readily upon raindrop impact do not maintain effective pathways for the transport of water. Precipitation ponds, and on hillslopes, runs off carrying soil away

(Brady and Weil, 1999). A fallow field, in combination with a low water infiltration rate, is of particular concern in late winter and throughout spring when NC Oregon receives the majority of its precipitation. Because the fallow field does not have plant cover to hold soil in place, the precipitation of winter and spring easily wash soil downslope. Busacca et al.. (1984) measured the rate of average annual soil loss by water erosion in Walla Walla soils in the Palouse region of Washington to be as great as 36 tons/hectare on conventionally tilled slopes. Slopes under minimal tillage systems had annual erosion rates of 35 to 52% of the conventionally tilled slopes. The second cause of tillage related erosion is due to mechanical undercutting of the soil causing the soil to slide downslope. This mechanically caused erosion is called tillage erosion. Busacca et al. (1984) measured 29 tons/hectare of eroded soil after a single plowing on a 5.7 degree slope in the Palouse.

Direct seeding in an annual cropping system. Research and education on direct seeding in Pacific Northwest cropland began in the 1970's (PNW Extension, 1999). Direct seeding (DS) is one method of crop residue management. The United States Department of Agriculture (USDA) defines crop residue management as follows: *Any tillage and planting system that uses no-till, ridge tillage, mulch tillage, or another system designed to retain all or a portion of the previous crop's residue on the soil surface. The portion required depends on other conservation practices that may be included in the farmer's total conservation plan* (USDA – ARS, 1995). When, 30% or more residue cover is left on the soil surface, the crop residue management system is called no till (NT) (USDA – ARS, 1995). Direct seeding was implemented as a preventative measure to soil erosion and as a way to increase soil moisture. Increased soil water storage has the potential to allow growers to intensify crop systems as well as diversify the types of crops grown.

In a direct seeded system, the soil is undisturbed and the crop is planted directly into the residue of the previous crop. Seeds are planted into narrow slots in the seedbed created by coulters, row cleaners, disk openers, in-row chisels, or roto-tillers (ERS/USDA, 1997). If seed is planted at the same time fertilizer is applied, only one pass over the field is required; if planting is separate from fertilizer application, two passes must be made. Weeds are controlled with chemicals rather than tillage. Increased water storage and water use efficiency in direct seeded crops has allowed growers in 30.5 – 40.5 cm precipitation zones more flexibility in crop rotations (PNW, 1999). Water storage in direct seeded soils can be sufficient for growers to produce a crop every year, thereby eliminating the need for fallow (PNW, 1999).

The major benefits from direct seeding and annual cropping result from an increase in surface residue and soil organic matter (SOM). Surface residue and soil organic matter affect soil physical, chemical, and biological properties often enhancing soil quality (Smith and Elliot, 1990; Aase and Pikul, 1995; Bezdicek, 1998; Brady and Weil, 1999). Numerous studies in the United States and Canada have assessed the effects of direct seeding on soil properties (Carter, 1987; Dick et al., 1989; Pikul and Aase, 1995; Bezdicek et al., 1999).

Soil organic matter influences the biology of soil because it is the energy source for heterotrophic organisms in the soil (Brady and Weil, 1999). The cycling of nutrients in the soil is mediated by the soil organism response to the quantity (Smith and Elliot,

1990) and quality (Douglas et al., 1980) of soil organic matter as well as to soil moisture and temperature (Brady and Weil, 1999).

The more organic matter in soil, the more abundant the soil organism community and the greater the potential for nutrient cycling. The quantity of organic matter in cultivated soil is related to the amount of crop residue returned to the soil. In wheat-fallow rotations, there is a lower return of residue over time because a crop is produced every other year as opposed to an annual rotation that returns residue every year (Pikul and Aase, 1995).

The quantity of SOM is also related to tillage. The absence of tillage in a direct seed system leaves organic matter on the soil surface rather than burying it. Because the residue is not incorporated into the soil, soil organism access to the residue is limited and decomposition is slower (Douglas et al., 1980). Decomposition of residue is more rapid when buried because temperature and moisture remain more stable; stable conditions are conducive to sustaining microorganism activity (Smith and Elliot, 1990; Rasmussen, 1996, Bezdicek, 2001). Thus, higher levels of SOM remain in a direct seeded system with the potential to supply a greater population of soil organisms for an extended length of time.

Soil moisture is a soil physical property affected by SOM in a DS-AC system. Soil moisture is a major factor influencing soil microorganism activity (Smith and Elliot, 1990). Earthworms and fungi are most active in moist environments; nematodes and bacteria are "swimmers" that require water to move (Brady and Weil, 1999). In a controlled study of wheat straw decomposition on the soil surface, Stott et al. (1986) demonstrated decomposition rates slowed as soil water potential increased from –33 kPa to –5.0 MPa. Three factors related to SOM cause soil water content to be higher in a DS-AC system than in a conventional system.

First, SOM can hold up to 90% of its weight as water (Smith and Elliot, 1990). Thus, a soil containing more organic matter will have a higher water holding capacity than a soil from which organic matter has been depleted.

Second, cumulative water storage is greater in residue covered soil than in soil into which residue is tilled (Pannkuk et al., 1997; Jones and Popham, 1997). Residue reflects solar radiation and serves as a barrier to water vapor loss from the soil. Pannkuk et al. (1997) measured an increase of 15 mm in total water stored in winter fallow soil covered with residue than in winter fallow soil without residue. In a study conducted by Ramig and Ekin (1987) in eastern Oregon, snow trapped by standing stubble in a no till field increased water storage sufficiently such that its wheat yield surpassed that from a fall-tilled field from which the snow was blown.

Third, an abundance of macropores in a direct seeded system cause the rate of water infiltration, and therefore soil water content, in direct seeded soil to be greater than that of tilled soil (Dick et al., 1989; Bezdicek et al., 1998). Macropores are the main pathway of air and water movement through the soil. Macropores exist in well-structured soil between soil aggregates. Humus, or decomposed organic matter, combines with clay particles to form cohesive, stable aggregates (Smith and Elliot, 1990; Alexander, 1999). Polysaccharides secreted by soil organisms also form stable aggregates (Brady and Weil, 1999). Because stable soil aggregates do not slake as water moves through the soil, soil pores remain unobstructed and are able to efficiently transport water from the surface into the soil. Macropores are also created by root growth through the soil and by the activity of soil microorganisms (Brady and Weil, 1999). Tillage breaks and collapses these macropores reducing the hydraulic conductivity and subsequent infiltration rate of the soil.

Just as soil moisture is important to soil organism activity and nutrient cycling, so is soil temperature. Soil organism activity is maximal at temperatures between 20 and 40 °C (Brady and Weil, 1999; Goh, 1988). Consequently, mineralization is accelerated between 20 and 40 °C. Stott et al. (1986) measured a steady decrease in decomposition rates of wheat straw residue on the soil surface as soil temperature decreased from 20 to 0 °C.

Spring wheat seeded in a DS-AC field may be planted into soil temperatures below 20C, the lower limit for mesophilic soil microorganism activity, so nutrients from fertilizers may not be released when the growing wheat plant requires the nutrient (Klepper et al., 1983). Consequently, lower yields in direct seeded wheat are associated with delayed growth and low tiller numbers in the early growth stage (Klepper et al., 1983; Rasmussen 1996).

Soil is often cooler under residue cover than in bare soil because: 1) residue reflects solar radiation, and 2) the lighter color of residue does not absorb as much solar radiation as dark, clean-tilled soil (AAFRD, 1999). Researchers in Canada found the soil temperature in a sampling period from March 15 through March 30 to be 0.29 °C warmer in direct seeded soils (measured at 2 cm depth) than in conventionally tilled soil (measured at 5 cm depth). Later in the spring, the difference in soil temperatures between the two systems reversed. Throughout the period of April 1 through May 10, soil temperatures were 0.89 °C cooler, and from May 11 through June 15, temperatures were 0.78 °C cooler in direct seeded soil. Temperature differences result from the insulating properties of the residue layer and reflection of sunlight by the residue (AAFRD, 1999).

Many studies have been conducted on winter wheat response to P and S in a conventionally tilled, wheat - fallow system while few studies have assessed P and S management in HRS wheat nor in direct seeded, annually cropped systems. For example, Rasmussen (1992) studied the differences in P and S responses in different winter wheat cropping systems. He found that P and S affected a winter wheat crop differently in direct seeded, annually cropped winter wheat than in a conventionally tilled, winter wheat–fallow system. Sulfur advanced the growth stage of direct seeded winter wheat, but not conventionally tilled winter wheat.

The effect of P on growth stage was just the opposite; P advanced growth stage in conventionally tilled, but not direct seeded wheat. Phosphorus increased dry matter production and grain yield in all cropping systems while S increased dry matter and grain yield only in annually cropped wheat. Yield was highest in the conventionally tilled, wheat-fallow system and lowest in the direct seeded, annually cropped system. Thus, Rasmussen concluded winter wheat response to P was influenced by higher yields and not by frequency of cropping or tillage because it responded to P in all cropping systems. On the other hand, he concluded winter wheat response to S was affected by frequency of cropping and tillage because the wheat did not respond to S in all cropping systems. As is evident from these results, P and S fertility must be managed distinctly in DS-AC systems, but the exact effect of the DS-AC system on HRS wheat warrants research.

Although, this data applies to winter wheat, varying response to P and S also can be expected in HRS wheat. Hard red spring wheat is planted into cool, moist soil in the spring and has a shorter growing season than winter wheat. The growing conditions HRS wheat encounters have the potential to alter P and S response in direct seeded, annually cropped systems to an even greater extent.

1.1.4 Phosphate for hard red spring wheat

Phosphorus, a macronutrient essential to plant growth, has been shown to increase wheat yields (Boatwright and Viets, 1966; Black and Reitz, 1972), a fact made evident by increased use of superphosphate in the 1880's followed much later by a boom in the manufacture of triple superphosphate in the mid-1940's through the early 1970's (Beaton, 2003). Because of the essential role of P in wheat production and its abundant use in agriculture, it is important to assess how direct seeding may influence the relationship of P to soil, as well as its role in wheat production.

Phosphorus is used by plants in a number of fundamental life processes. It is part of adenosine triphosphate (ATP), a compound that drives energy synthesis in cells. The genetic proteins, deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), contain P as does the lipid bi-layer in cellular membranes (Brady and Weil, 1990). Specifically, ample P nutrition in cereal crops, such as hard red spring (HRS) wheat, is important because it helps prevent lodging by strengthening structural tissues in straw. Sufficient P also speeds maturity of cereals causing grain to ripen earlier (Havlin et al., 1999).

It is critical that phosphorus be available to spring wheat from germination to heading in order to maximize biomass and grain yield (Boatwright and Haas, 1961; Boatwright and Viets, 1966). When P was available from germination to heading, Boatwright and Viets (1966) found spring wheat grown in a nutrient solution produced a maximum number of tillers, maximum total plant biomass, and highest yield. Grain yield was adversely affected if the wheat did not receive P soon after emergence. Boatwright and Viets (1966) reported grain yield was 42% of the yield of the control when P was withheld from the nutrient solution for two weeks and 19% of the yield when P was withheld for three weeks.

Phosphorus is absorbed by plants from the soil in an inorganic form, nevertheless, both organic and inorganic forms of P have the potential to supply plants with P. Plants absorb P as HPO_4^{-2} and $H_2PO_4^-$. Maximum absorption of P occurs at pH 6.5 when the precipitation of P with aluminum or calcium is minimal. At pH below 7.2, HPO_4^- is more abundant in the soil solution; conversely, at pH higher than 7.2, HPO_4^{-2} dominates the solution (Havlin et al., 1999; Mullen, 1999). P generally exists as three forms in the soil: organic P, calcium-bound P, and iron- or aluminum-bound P.

The rise in organic matter in DS-AC systems (Bezdicek, 2001) increases the soil supply of P over time. Organic matter in the soil increases the availability of P by several methods. First, SOM supports soil microorganism populations and the decomposition of the microorganism biomass releases H_2PO_4 (Mullen, 1999). Second, large humic molecules bond to clay and aluminum- and iron hydrous oxides occupying the sites where P may have been retained. Third, similar to the competition of humic molecules for binding sites, organic acids, such as citrate, malate, oxalate, and tartate, as well as CO_2, compete with P for binding sites. Organic acids and CO_2 are released by plant roots and soil microorganisms (Brady and Weil, 1999; Mullen, 1999). Nitrifying bacteria and sulfur-oxidizing bacteria produce acids that enhance the release of $H_2PO_4^-$ from phosphate salts (Mullen, 1999). Some of the organic acids chelate with Al and Fe decreasing their ability to bind with P (Brady and Weil, 1999). Fourth, SOM increases organic P in the soil providing more P for mineralization (Fuller et al., 1956). Fuller (1956) found the more wheat straw residue added to the soil, the more P the test plant, ryegrass, absorbed. Futhermore, additional P was absorbed from residue with higher concentrations of P and from residue that had decomposed for an extended amount of time.

On the contrary, wheat straw has also been implicated in immobilization of P when added to soil (Black and Reitz, 1972). Black and Reitz (1972) found that increasing amounts of wheat straw added to four soils, decreased the amount of soluble P recovered by $NaHCO_3$ extraction over a 60-day period. The decrease in P occurred because wheat straw has high C:N and C:P ratios and when it is added to the soil, it boosts the carbon content in the soil disproportionately to N and P. The excess of C relative to N and P cause microorganisms to incorporate all N and P into their biomass leaving little N and P free in the soil for mineralization. As decomposition continues, though, the C:N:P ratio decreases (Black and Reitz, 1972) eventually allowing mineralization of P.

The C:N:P ratio of organic matter can therefore be said to govern whether P is mineralized or immobilized. Because soil microorganisms require certain ratios of C:N:P, they must assimilate C, N, and P in amounts relative to that ratio. If the amount of C or N in organic matter is large relative to the amount of P, the P will be immobilized (Myrold, 1999). The following C:P ratios determine whether P is mineralized or immobilized: net mineralization of organic P occurs when the C:P ratio is less than 200, net immobilization of inorganic P occurs when the C:P ratio is greater than 300, and no gain or loss of inorganic P occurs between values of 200 to 300 (Havlin et al., 1999; Mullen, 1999).

The N:P ratio is more variable than the C:P ratio because it varies with soil type, but when the ratio of N:P is large, P is immobilized (Havlin et al., 1999). P is immobilized at high N:P ratios for the same reason high C:P ratios immobilize P; microorganisms require a set ratio of C:N:P to live. If P limits the assimilation of N, soil microorganisms will use all P from the soil solution which could leave little P available for plants.

Nitrogen is also important to the P cycle in soil because it promotes wheat root growth. Greater root length increases the surface area for absorption of P from the soil solution. Boatwright and Viets (1966) demonstrated a relationship between N and P. Spring wheat grown in nutrient solution containing both N and P produced the maximum amount of dry matter at an earlier plant stage than spring wheat grown in solution with either N or P alone. Tissue analyses of the plants showed the N and P fertilized plants absorbed 9 kg more N per hectare than plants fertilized with N only.

The ratio of C:N:P is not the only determinant of P mineralization; soil type and chemistry also influence P mineralization (Sander et al., 1991). The interaction between soil and P is independent of cropping system, but deserves attention because it plays a role in soil fertility management. High levels of iron and aluminum on the surface of mineral particles adsorb P sequestering it from the soil solution and plant uptake (Havlin et al., 1999). The amount and type of clay in a soil also affect the availability of the nutrient. Clay particles have a high surface area to which P adheres. Therefore, higher P levels are required in clayey soils to meet the demands of a crop for P (Havlin et al., 1999; Black and Reitz, 1972).

Soil chemistry influences the availability of inorganic P. In acidic soils, inorganic P precipitates with iron or aluminum to form secondary P minerals such as aluminum- or iron-hyrdroxy phosphate compounds. Inorganic P also adsorbs to the surface of iron or aluminum oxides and clay minerals. In neutral or basic soils, inorganic P precipitates as calcium-P secondary minerals or it is adsorbed to surfaces of calcium carbonate ($CaCO_3$) and clay minerals (Brady and Weil, 1999; Havlin et al., 1999).

The subsoil in NC Oregon is calcareous which poses a challenge to P management because high pH soils retain P. Akinremi and Cho (1991) found the major mechanism of P fixation in a calcareous soil was the precipitation of P with exchangeable Ca^{2+} rather than precipitation with Ca in the $CaCO_3$ compound. In the study, cation exchange resins were used to manipulate the cation exchange capacity (CEC) and exchangeable Ca^{2+} of the various soil treatments. One treatment consisted of carbonated sand mixed with a cation exchange resin saturated with Ca^{2+}; this created a sand mixture with a CEC of 21.5 cmolc/kg mixture. The second treatment, the control, consisted of carbonated sand without a resin creating a mixture with a CEC of 0 cmolc/kg. Diffusion of the phosphate anion down the sand column was inhibited by the precipitation of P with Ca^{2+} from the $CaCO_3$, however the precipitation occurred only at the surface where the P had been applied. Phosphorus diffusion was more severely limited and inhibited down the entire length of the sand column by P precipitating with exchangeable Ca^{2+} from the resins. Akinremi and Cho (1991) concluded the CEC of a soil with exchangeable Ca^{2+} may determine the extent of P fixation moreso than the presence of $CaCO_3$.

In order to ensure an adequate supply of P to wheat plants, the DS-AC grower must take soil moisture into account. Soil moisture is important to biological and chemical transformations of P in the soil, as well as, mass flow and diffusion of P to the root zone. Power et al. (1961) demonstrated yield increases from dryland spring wheat in eastern Montana were influenced by a combination of available soil P, soil moisture, and growing season precipitation. In the study, 50% of the variation in spring wheat response to fertilizer on soils in the middle range of P (25- to 45 lb P_2O_5/ acre) was accounted for by soil moisture.

Soil temperature, like soil water content, influences P cycling in DS-AC soil. In NC Oregon, spring wheat is planted in March when soil is cool. Cool soil temperatures decrease the availability of P at a time critical for developing wheat plants (Power et al., 1961). Power et al. (1964) found plant growth at soil temperatures above 15 °C were more dependent on available P in the soil solution than plant growth below 15 °C. Below a soil temperature of 15 °C, plant growth increased with increasing P rates up to 16 ppm whereupon growth leveled off. P availability declines in cool soil because soil organism activity diminishes to such an extent that organic P and P in fertilizer is not mineralized. Furthermore, plant roots rely on diffusion of soil P to the surface of the root and cool soil slows diffusion rates. P mineralized from fertilizer diffuses short distances; Khasawneh et al.. (1974) recorded phosphorus diffusion of only three to five centimeters. Cool soil can slow diffusion to an extent that wheat cannot obtain sufficient quantities of P (Havlin et al., 1999).

The restriction of cool soil temperature on P availability places an importance on placing P near developing wheat roots (Koehler, 1959; Klepper et al., 1983). Banding P at seeding results in greater fertilizer P efficiency and higher yields than broadcast application of P (Sanders et al., 1991). Less soil-fertilizer contact occurs when P is applied in a band than when broadcast over the soil surface. Less contact between the soil and fertilizer decreases the surface area in contact with soil and allows less P to be adsorbed by the faces of minerals and more P to remain in solution for plant uptake.

The concentration of high P in the soil solution also is influenced by the type of fertilizer (Judel et al., 1985). For example, water soluble P fertilizers, such as monoammonium phosphate (MAP) and diammonium phosphate, are 90% to 100% water soluble. The high water solubility of MAP and DAP creates a rapid and effective increase in soil solution P. The speed and magnitude of the increase in phosphorus in the soil solution is important for maximum absorption of the nutrient before it is adsorbed to soil minerals (Lindsay, 1959; Havlin et al., 1999).

Khasawneh et al. (1974) studied the difference in the mobility of three types of phosphorus fertilizers in a fine sandy loam; the orthophosphate, diammonium orthophosphate (DAP) and the polyphosphates, triammonium pyrophosphate (TPP), and ammonium polyphosphate (APP). Each of the fertilizers was applied to the surface of soil columns. The authors found the distribution of the P fertilizers through the soil varied with the length of time it took the fertilizers to precipitate with iron or aluminum. The highest concentration of DAP in the soil column diffused 3 mm from the application site while the highest concentrations of TPP and APP diffused 13 mm and 8 mm, respectively. TPP and APP moved significantly further down the soil columns than DAP; however, P applied as DAP remained more water soluble for a longer period of time.

1.1.5 Sulfate for hard red spring wheat

After nitrogen, sulfur (S) is the second most deficient nutrient in the soils of the Columbia Plateau region including NC Oregon (Chao et al., 1959; Rasmussen, 1996). The Mediterranean climate and basalt parent material are inherently responsible for the low S content of the soil (Rasmussen and Kresge, 1986). In addition to naturally low level of S in the soil, Koehler (1965) cited two reasons S is low in agriculture soils. First, a large portion of S in soil is organic S. Sulfur in soils decrease as organic matter is lost from more intense cropping systems and as soil containing organic matter is eroded. Second, fertilizers, such as superphosphate, have higher and higher concentrations of N and P and lower concentrations of S. The risk of S deficiency and the lack of a reliable, accurate test for S lead to routine application of S in NC Oregon (Castellano and Dick 1991; Rasmussen and Allmaras, 1986).

Sulfur deficiencies in both spring and winter wheat have been recorded in the Walla Walla soil series in NC Oregon (Chao et al., 1959; Rasmussen et al., 1977). Many sulfur studies have been conducted on winter wheat, but few exist for spring wheat and even fewer for hard red spring wheat. Rasmussen et al.. (1977) recorded similar levels of reduced vegetative growth and grain yield in both white spring and winter wheat with S deficiency. In the study, however, most of the data reported were for winter wheat. Likewise, in a review of the plant response to S in the Western United States, Rasmussen and Kresge (1986) mentioned winter wheat, but did not present data for spring wheat despite citing 80 sources.

The lack of research on spring wheat is the most likely reason fertilizer guides recommend the same level of S fertilization for both winter and spring wheat. University of Idaho fertilizer guides instruct growers to apply 16 to 22 kg S/ha to soils testing less than 10 ppm (or 4 ppm in the top 30.5 cm) for both spring and winter wheat (Mahler and Guy, 1998a and 1998b). Thus, there is a need for research on soil fertility management for spring wheat and a specific need for research that addresses how DS-AC systems influence spring wheat production.

Because of the lack of literature on spring wheat response to S, most examples given in the following section of the review will be for winter wheat. Similarities between spring and winter wheat response to S and requirements of S allow the winter wheat examples to be related to spring wheat.

Sulfur is a secondary macronutrient that is required for vigorous crops. Most S is absorbed by plant roots as SO_4^{2-}, but plants can also acquire small amounts of sulfur through their leaves from SO_2 in the atmosphere (Havlin et al., 1999). Sulfur is required for the synthesis of several vital cellular components in plants. Ninety percent of the S in plants is used to synthesize the amino acids cystine, cysteine, and methionine (Havlin et al., 1999). Sulfur forms disulfide bonds between two cysteine amino acids to fold proteins into a tertiary structure necessary for protein function. Sulfur also is needed for synthesis of coenzyme A. Coenzyme A in plants is used in the Krebs cycle to produce adenosine triphosphate (ATP) (Moore et al., 1995). The synthesis of chlorophyll also requires S (Havlin et al., 1999). And the Fe-S protein, ferredoxin, in chloroplasts contains S. Ferredoxin is an electron carrier in the energy producing reactions of photosynthesis and is also important in the reduction of NO^{2-} and SO_4^{2-} in the plant (Taiz and Zeiger, 1998).

Organic sources of S, such as plant residues, soil microorganisms, and animal waste, account for approximately 90% of the total S present in most topsoils (Germida, 1999). Soil organic matter, therefore, has the potential to supply plants with a substantial amount of S. The ultimate determinant of the inorganic supply of S from organic S is the ratio of nutrients in the OM returned to the soil (Tracy et al., 1990).

Sulfur mineralization is ultimately regulated by the C:N:S ratio of the organic matter and soil. S is only mineralized and available to plants if soil microorganisms have C, N, and S in sufficient quantity; if one nutrient is limiting, that nutrient will be immobilized in the biomass of the soil microorganism population (Brady and Weil, 1999). Mineralization of S occurs when the C:S ratio is at or below 200:1 and immobilization is favored at a ratio higher than 200:1. At a C:S ratio above 400:1, immobilization is sure to occur (Havlin et al., 1999; Goh, 1988; Tabatabai and Chae, 1991). Wheat straw has a high C:S ratio which leads to slow S mineralization without S fertilization (Castellano and Dick, 1988).

The N:S ratio is key in wheat nutrition because both nutrients are required for protein synthesis in the plant. Sulfur alone does not increase wheat yield; yield increase from S application requires optimum soil N levels (Koehler, 1959; Rasmussen et al., 1975). Optimum N fertilization also increases S uptake as the plant's requirements increase and more soil is explored by growing roots (Rasmussen et al., 1975; Douglas et al., 1980).

In dryland agriculture, water plays such a central role in crop use of N that the interaction of soil moisture and N, and their combined influence on S uptake, are almost inseparable. Water stress coupled with excessive N fertilization limits yield response to S in winter wheat (Ramig et al., 1975). When N rates are excessive in relation to the amount of water available for wheat, the plant will deplete the water stored in the soil before grain filling is complete. In fact, the addition of S to water limited soil or soil with high N levels, can cause a yield reduction (Ramig et al., 1975). Therefore, an optimum level of N in relation to the amount of available water is necessary for increasing wheat yield with S application (Koehler, 1959; Rasmussen and Kresge, 1986).

Accumulation of NO_3- in wheat tissue as a result of S deficiency drive the N:S ratio up (Moodie, 1967). A shoot N/S ratio in the range of 14 to 17 is the critical value above which S is deficient and below which N is deficient (Rasmussen et al., 1975; Zhao et al., 1996). The N/S ratio varies at different points of the growth stage because N and S are translocated from straw to grain at different rates. The adverse affect of moisture stress on grain yield and dry matter production can also skew the N/S ratio. Therefore, caution should be used when diagnosing S deficiency using the N/S ratio of plant tissue. The N/S ratio of wheat grain is approximately 17/1 and is often less variable than the ratio of N/S in tissue (Moodie, 1967; Zhao et al., 1996).

Tillage systems also influence the supply of S from organic matter (Koehler, 1979; Tracy et al., 1990). Wheat straw plowed into the soil decomposes rapidly and releases more S in a shorter period of time than straw left on the soil surface in a direct seed system (Douglas et al., 1980). Over time, though, higher levels of organic matter in a direct seed system will increase the amount of S released into the soil (Harward et al., 1962; Tracy et al., 1990). Thus, S deficient soil in a DS-AC system should be fertilized every year until brought up to adequate S levels and then fertilizer could be applied every other year as slow mineralization of S in residue could supply sufficient S between applications.

Residual S plays an important role in straw and grain yield in areas with low rainfall and calcic horizons – sometimes increasing yield more than S fertilization in the season of application. Residual S is found in soil because wheat straw decomposition over time slowly releases S (Rassmussen et al., 1975; Castellano and Dick, 1988). Ramig et al. (1975) measured a winter wheat grain yield increase of about 500 kg/ha from S application, in conjunction with optimum N rates, seven years after initial application. In the study, data collected from a winter wheat – pea rotation initiated in 1931 in Pendleton, OR, showed applications of 14 kg S/ha supplied sufficient S for a second wheat crop while 28 kg S/ha supplied sufficient S for a third wheat crop.

Calcic horizons also may influence the supply of S to plants if roots reach the calcic horizon (Rasmussen and Allmaras, 1986; Castellano and Dick, 1988). In Pendleton, OR, a calcic horizon exists approximately 0.9 m deep below long term, annually cropped wheat research plots (Rasmussen and Allmaras, 1986). Sulfur fertilizer treatments on this soil from 1931 to 1950 ranged from 270 to 1570 kg S/ha. Twenty-five years after the last S application extractable S in the 0.9 to 1.2 m depth ranged from 6 to 16 kg S/ha for the 270 and 1570 kg S/ha treatments, respectively. Approximately 35% of the S applied was retained in the calcic horizon (Rasmussen and Allmaras, 1986).

Any environmental factor that affects the growth of soil microorganisms will also influence the mineralization and immobilization of S (Havlin et al., 1999). Thus, soil moisture, temperature and pH each influence the supply of S to the plant. Optimum mineralization of S occurs from 20 to 40 °C. Mineralization is drastically reduced at 10

°C and greater than 40 °C (Havlin et al., 1999). Optimum soil moisture content for S mineralization is 60% of field moist capacity. Soil moisture less than 15% and greater than 40% of field capacity depresses S mineralization (Havlin et al., 1999).

Changes in soil temperature and moisture with seasons cause a seasonal fluctuation in extractable SO_4^{2-}. Higher extractable SO_4^{2-} levels occur in the winter when soils are too cool for maximum soil microorganism activity than in the spring when soils warm and before the soil dries (Castellano and Dick, 1991). Arylsulfatase, an enzyme produced by microorganisms that cleaves SO_4^{2-} from aromatic SO_4 esters, can be used as an indicator of microorganism activity. As soil temperature warms in spring and moisture is plentiful, arylsulfatase activity increases and SO_4^{2-} levels in soil drop as S is immobilized (Castellano and Dick, 1991).

The effect of pH on mineralization of S is variable (Havlin et al., 1999). Soil pH affects both SO_4^{2-} adsorption and mineralization. Sulfate adsorbtion occurs in acidic soils below pH 6.5. Sulfate precipitates with $CaCO_3$ as $CaCO_3$-$CaSO_4$ which can be a significant source of S in calcareous soil. Rasmussen and Allmaras (1986) found that a calcareous zone located greater than 90 cm below the soil surface retained approximately 35% of the total S applied. Sulfur can be mineralized from the calcic horizons. The availability of SO_4^{2-} coprecipitated with $CaCO_3$ increases with decreasing pH, increasing soil moisture, and particle size of $CaCO_3$ (Havlin et al., 1999). Microorganisms are the most important factor in S mineralization (Germida, 1999) and they are most active at a soil pH near neutral. Thus, S mineralization is generally correlated with near neutral pH (Goh, 1988; Havlin et al., 1999).

Just as direct seeding plays a role in S mineralization so does annual cropping because it alters the soil environment. Soils with plants growing in them have been shown to mineralize more S than soils without plants (Havlin et al., 1999; Castellano and Dick, 1991). Amino acids and sugars excreted by plant roots into the rhizoshere stimulate microorganism activity. It follows that the greater frequency of cropping would stimulate more microorganism activity in the rhizosphere, consequently more S would be mineralized over time. In addition, the absence of plants in a fallow field in combination with winter precipitation may cause S to be leached into the subsoil (Rasmussen and Allmaras, 1986). Young wheat plants may show signs of S deficiency until their roots reach the S that has been adsorbed in the subsoil (Havlin et al., 1999). Furthermore, a crop grown every year in the same field exerts a greater demand on the soil for S than a crop grown in the same field every two years.

Organic S must first be oxidized to inorganic SO_4^{2-} for plant root absorption. Many sulfur-containing fertilizers with S as H_2SO_4 do not need to be oxidized before plants can obtain the SO_4^{2-} they require. The following are sources of S: elemental S (S^0), dispersible, granular S^0, S^0 suspensions, ammonium thiosulfate [$(NH_4)_2S_2O_3$], ammonium polysulfide (NH_4S_x), and urea-sulfuric acid [$CO(NH_2)_2*H_2SO_4$]. Havlin et al. (1999) report the effectiveness of SO_4^{2-}sources are generally equal, but others have found S^0 does not mineralize as rapidly as other sources. Often, S^0 supplies adequate S the season after application. Higher rates of S^0 mineralization can be achieved by increasing the surface area available to oxidizing bacteria. Applying smaller particle sizes of S^0 or higher rates of S^0 both increase the surface area available for bacteria (Koehler, 1965). Although soil type and environment ultimately determine the rate of S mineralization, lime and phosphate additions increase the supply of S from a source (Chao et al., 1959; Chatupote et al., 1988).

1.1.6 Soil testing with ion exchange membranes

Soil tests help determine nutrients present in the soil that contribute to plant vigor and increase crop yield. In agriculture, soil analyses are vital to crop management. Therefore, it is worthwhile to investigate any soil test that carries the promise of increased accuracy and sensitivity, is relatively easy to use and understand, and is cost effective.

Synthetic ion-exchange resins and membranes have been used for many years as soil tests, yet they have not been as widely used as the "conventional" chemical extractant soil tests (Qian and Schoenau, 2002). Ion-exchange membranes (IEM) are accurate, simple to use, and cost effective (Searle, 1988; Skogley et al., 1990; Schoenau and Huang, 1991). The use of IEM in soil fertility management for hard red spring wheat may be useful in assessing patterns of P and S uptake in a DS-AC system. The following portion of this review focuses on IEM with emphasis on a patented form of IEM called a plant root simulator (PRS) probe.

The requirements for a good soil test can be more specifically defined by determining what makes a soil test accurate and by comparing the time and labor involved in various soil tests. Havlin, et al. (1999) states, "An effective soil test will simulate plant removal of nutrients with subsequent re-supply to the solution from nutrient pools that control availability." Similarly, Schoenau and Huang (1991) emphasize the criteria for a good soil test are: 1) extraction of levels of a nutrient in amounts relevant to what is available to plants over a growing season and 2) test results that can be easily interpreted at a routine test lab. Schoenau and Huang (1991) state few tests meet both of those properties.

Nutrient uptake by roots depends on the affinity of a root for a certain nutrient and the concentration of the nutrient at the root surface (Brady and Weil, 1999). Emphasis is placed on available nutrients rather than total nutrients because nutrients can precipitate with compounds and/or form complexes with the crystalline structure of minerals that make then unavailable to plants. Measuring total nutrients would not give an accurate measurement of the nutrients roots might absorb from the soil solution. The amount of available nutrient at the root surface is a function of the quantity and intensity of a nutrient. "Quantity" is the amount of nutrient in solid phase that is potentially available to the plant while "intensity" is the soil solution concentration. In addition to quantity and intensity, cation and anion exchange capacity regulate the availability of nutrients. Cation exchange capacity (CEC), anion exchange capacity (AEC) and soil chemistry are inherent properties that differ with soil type.

Strong correlation between the concentration of nutrients in plant tissue with results from a soil test indicate a soil test is measuring plant available nutrients. In summary, a good soil test measures the quantity and intensity of soil nutrients affected by the chemistry of the soil in such a way that the amount of nutrients measured correspond to the amount of nutrient in the plant.

Yet, a soil test that measures plant available nutrients well, but that was costly and time consuming would be of limited use. Soil tests are central to mapping the fertility status of soil, calculating fertilizer application for maximum economic yield, assessing potential nutrient deficiency prior to planting a crop, and understanding crop response to fertilizers. A soil test too costly would curb responsible soil fertility management hurting both growers and researchers. An inexpensive and relatively rapid soil test would be one that does not rely too heavily on instruments and chemicals that are available only in limited research labs.

According to Skogley, et al. (1990), accuracy, simplicity and costliness are not the only factors of a good soil test. These researchers believe universality and standardization are also important when defining a good soil test. Many chemical extractants exist, but each nutrient requires a different chemical extractant. Thus, it is difficult to measure more than one or two nutrients because of the time and expense involved in the analysis of each separate nutrient. A test that uses a universal extractant is needed.

A hinderance to standardization is different labs use different chemical extractants. For example, common soil tests for P such as, Bray-1 P, Olsen-P, and Mehlich-P each have different critical soil test levels. High test levels for P are approximately 25, 13, and 28 ppm for Bray-1 P, Olsen-P, and Mehlich-P, respectively (Havlin et al., 1999). Skogely et al. (1990) point out that labs within the same region often utilize different tests and argue that standardization can only be realized with the adoption of a single test methodology. Standardization and universality are important to the communication of researchers and growers alike and to the advancement of efficient soil management.

Western Ag Innovations Inc., a research company in Saskatchewan Canada, expanded on the method of using ion-exchange membranes as a soil test by developing the Plant Root Simulator (PRS) probe. The PRS probe is an ion-exchange resin in membrane form that is enclosed in plastic for ease of use. They are called "plant root simulators" because they exchange and adsorb ions similar to plant roots.

Nutrient uptake by roots occurs by the exchange of ions between the root surface and soil solution ion. Roots release bicarbonate (HCO_3^-) and hydroxide (OH^-) when they absorb anions from the soil solution and exchange H^+ for cations in the soil solution. The PRS probe exchange membrane is chemically treated with sodium bicarbonate ($NaHCO_3$) to charge the probe with exchangeable ion species. Some of the following citations will refer to PRS probes specifically while some will refer to IEM in general.

The fact that IEMs simulate plant roots by exchanging ion lends to the accuracy of this soil test. The IEM is sensitive to changes in the soil solution resulting from the buffer capacity of a soil. As the IEM adsorbs nutrients from the soil solution, the decrease of that particular nutrient from the soil solution causes desorption of the nutrient from the soil colloid. The nutrient free in solution is subsequently adsorbed to the ion-exchange membrane. The similarity between modes of ion exchange from the plant root and from the IEM ensures the IEM measures available nutrients rather than total nutrients (Schoenau and Huang, 1991).

Schoenau and Huang demonstrated the sensitivity of an AEM to the anion exchange capacity of soil. They measured membrane extracted P in saturated soil pastes. The shape of the P adsorption curve over time was asymptotic. The asymptote can be explained by the initial rapid release of phosphate from soil solution and the most soluble P-containing minerals followed by a gradual increase of P as less soluble P minerals were released into the soil solution.

As with a plant root, direct exchange occurs between the ions adsorbed to the exchange membrane and those in the soil solution. Skogley, et al. (1990) determined anion exchange resins were sensitive to diffusion by measuring the adsorption of potassium (K^+) by an anion exchange resin over time. A rapid increase of adsorbed K^+ occurred when the resin was initially placed into a saturated soil paste. This rapid increase over a short time was the result of soil solution K^+ in immediate contact with the anion exchange resin. The amount of resin-adsorbed K^+ continued to increase with time, however the rate of adsorption decreased because K^+ near the resin was absorbed. The concentration gradient that was created by adsorption of K^+ caused K^+ from further away in the soil to move towards the K^+ depleted area. This observation is consistent with diffusion; it takes time for a nutrient to diffuse causing the rate of adsorption to decrease.

Soil water content limits diffusion and mass flow therefore this soil condition should also influence adsorption of nutrients to IEMs. Soil water content is necessary diffusion of P. In dry soil, the pathway of diffusion is tortuous; therefore, it takes more time for a nutrient to move through the soil. Soil water content is also necessary for the mass flow of S. If insufficient soil water exists to transport S through the soil, S must move by diffusion, which, as mentioned previously, is slow in dry soil. Schoenau et al. (2001) measured relatively large decreases in amounts of N, P, K^+, and S adsorbed by IEM below 70% of field capacity.

Soil temperature also limits diffusion by influencing the activity of soil microorganism essential to nutrient mineralization. If a low amount of nutrient is being mineralized, the rate of diffusion will be slow. For example, diffusion rates of P increased as temperature increased from 10 to 50 °C (Skogley et al., 1990). Perhaps, though, the nutrient uptake IEM might measure under dry or cool soil conditions is not relevant because plant growth and nutrient assimilation also slow under such conditions (Schoenau et al., 2001).

The PRS probe is a universal soil test because it is independent of soil type. Searle (1988) used IEMs in 33 different New Zealand soils representing various management histories while Schoenau and Huang (1991) selected 17 contrasting soils for the study. Schoenau et al. (2001) used 135 different soils from samples submitted to the University of Saskatechewan Soil Testing Laboratory by farmers for routine analysis. In each study, there was a strong correlation between IEMs and concentrations of nutrients in plant tissue.

A strong correlation between IEM and plant tissue would occur if increases in plant tissue concentration of a nutrient are reflected correspondingly by the IEM. IEMs have shown strong correlation with K^+ and S in spring wheat (Skogley et al., 1990) and with P, K^+, N, and S in canola (Qian and Schoenau, 2001). Correlation coefficients vary among plant species.

The ion species on the exchange membrane that stimulate nutrient adsorption may have an affect on the amount of nutrients adsorbed from the soil solution. For example, a cation exchange membrane (CEM) treated with $NaHCO_3$ extracted 70% of the K^+ from soil solution as a CEM treated with NH_4HCO_3 (Liu, 1994). Ammonium was more effective in displacing K^+ because it has greater adsorption strength than Na^+. Schoenau and Huang (1991) measured higher r^2 values in the regression of plant available P measured by anion exchange membranes (AEM) on P uptake by canola ($r^2 = 0.86 - 0.90$ from a multiple regression model) than regression of AEM measured P on uptake of P by wheat ($r^2 = 0.73 - 0.78$ from a multiple regression model). Canola acidifies the rhizosphere more so than wheat. The acidic canola root surface may be more similar to the ionic charge of the IEM than the wheat root surface. In both studies, though, the amount of a particular nutrient adsorbed by the IEM was significantly correlated with plant uptake of the nutrient (Liu, 1994; Schoenau and Huang, 1991).

Until the IEM becomes standard, the soil test results it provides must be checked against the familiar values from chemical extractant soil tests. Anion exchange membrane extraction of $H_2PO^4/HPO_4^{2-}$is significantly correlated ($r^2 = 0.89 – 0.96$) with bicarbonate-extractable inorganic P (Olsen P) (Schoenau and Huang , 1991). Nitrate and SO_4^{2-} extracted by IEMs were highly correlated with $CaCl_2$ extraction (Schoenau and Haung, 2001). However, the IEM removed slightly more SO_4^{2-} than $CaCl_2$. The AEM may have been more efficient at adsorbing S that was precipitated with $CaCO_3$ than $CaCl_2$. Furthermore, the coefficients of variaton for the AEM to chemical soil test relationship were small (Schoenau and Huang, 2001).

If the IEM is to measure available nutrients, it must measure significant quantities without becoming saturated. A saturated membrane would not measure the same amount of nutrients as plants take from the soil. The quantity of nutrients adsorbed by PRS probes is sufficient to ensure PRS probes are capable of adsorbing relevant levels of nutrient from the soil. Plant root simulator probes, with 17.5 cm^2 membrane surface area per probe, adsorbed approximately 2100 μg $NH_4^+/10$ cm_2 and 400 μg $NO_3^-/10$ cm^2 from a soil solution of 0.5M NH_4NO_3 (Salisbury, 2000).

The length of time IEMs are left in the soil does not significantly alter their ability to measure the quantity of plant available nutrients. Greater amounts of P were removed as extraction time increased from 1 - 16 hours, however, the same relative amounts of nutrient were measured for each extraction time (Schoenau and Huang, 1991).

Common chemicals and standard soil test lab procedures and equipment are used to analyze IEM samples. IEMs must be treated with an ionic solution to charge the membrane with exchangeable ions (Schoenau and Huang, 1991). Plant root simulator probes are soaked in 0.5N NaHCO3 (pH 8.5) to coat the membrane with HCO3- ions. Each PRS probes is prepared for analysis by eluating with 17.5 mL of 0.5M HCl. Routine soil test labs are capable of analyzing the eluate. Nitrate-N and NH4-N can be analyzed by colorimetry using an auto-analyzer while most other nutrients can be analyzed by inductively coupled plasma (ICP).

The membrane form of ion exchange resin is convenient. Ion exchange beads, another common form of ion exchange resin (Skogley et al., 1990), can be cumbersome as one deals with numerous round objects and material needed to enclose the beads (Qian and Schoenau, 2001). Soil sampling with IEMs reduces labor and time because soil sampling is eliminated. Traditional soil tests require collection, weighing, mixing and grinding of soil samples prior to analysis.

The simplicity of IEM use is enhanced by their capability to adsorb many nutrients at the same time. Chemical extractants used in traditional soil tests are nutrient specific and measure only one or two nutrients per chemical (Havlin et al., 1999). Anion exchange membranes predict quantities of NO_3^-, PO_4^{2-}, SO_4^{2-}, $BO^{3-}{}_3$, and Cl^- in the soil while cation exchange membranes predict quantities of K^+, Na^+, Ca^{++}, Mg^{++}, and NH_4^+ in the soil. Likewise, eluating IEMs is done with a single extractant, HCl, for all nutrients (WAII, 2001).

Though not currently a standard soil test, IEMs have the potential to be beneficial to growers and researchers. The factors that make IEM a good candidate for a standard soil test are cost effectiveness, accuracy, simplicity, and the potential for universality.

In conclusion, soil biology, chemistry and physical properties are altered in a DS-AC system from a conventionally tilled, wheat-fallow system. Phosphorus and S fertility is affected by the changes in these soil properties. However, the best management of P and S fertility for hard red spring wheat is not clear.

Ion exchange membranes are a promising soil test because they simulate plant root uptake of nutrients. Testing the soil nutrients using IEMs may clarify how to optimize hard red spring wheat yield in DS-AC systems in NC Oregon.

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CHAPTER 2.

Identifying Environmental Constraints To Field Use Of Anion Exchange Membranes

2.1 ABSTRACT

To better understand early season phosphorus (P) and sulfur (S) nutrition for dryland, minimally tilled, continuously cropped spring wheat (*Triticum aestivum*), anion exchange membranes (AEM) were buried in spring wheat fields to measure the supply rate of P and S from fertilized soil. Low soil water content and cool soil temperature caused poor correlation between the soil supply rate of P and S and wheat uptake of P and S. AEM placed in the wheat row and therefore near the fertilizer band did not consistently measure higher supply rates of P or S than AEM placed between rows because low soil water content and low soil temperature slowed mineralization of P and S. Plant roots growing through the soil intercept nutrients and may not be affected by sluggish nutrient mineralization and subsequent diffusion to the same degree as AEM. These results suggest AEMs are not an accurate soil test during drought and cool temperatures.

2.2 INTRODUCTION

Dryland growers in North Central (NC) Oregon have increasingly turned to conservation tillage as a way to mitigate erosion and improve water infiltration and soil quality. Unfortunately, wheat (*Triticum aestivum*) yields in NC Oregon tend to decline when conservation tillage is implemented (Rasmussen, 1996). Yield loss in minimally tilled fields results from delayed growth caused by cool soil temperatures (Klepper et al., 1982).

Phosphorus (P) and sulfur (S) containing fertilizers stimulate spring wheat growth early in the season when applied as a subsurface band at planting (Klepper et al., 1983; Rasmussen, 1996; Havlin et al., 1999). In order to enhance early root growth, it is important to understand the supply rate of P and S fertilizers applied in cool soil. A soil test that is capable of measuring the flux of nutrients in situ over time would supply valuable information on how to overcome spring wheat yield loss in conservation tillage systems.

Anion exchange membranes (AEM) have proven to be useful indicators of plant available P and S in lab experiments (Searle, 1988; Skogley et al., 1990; Subler et al., 1995). In these studies, supply rates measured by AEMs were highly correlated with plant nutrient uptake and were related to standard chemical soil tests. AEMs left in soil solution for more than 24 hours measure the concentration of nutrient ions in solution as well as the diffusion-controlled flux of nutrient ions over time (Skogley et al., 1990; Yang et al., 1991). Because AEMs are sensitive to soil conditions controlling diffusion, they have been promoted for use in the field.

A few *in situ* studies have been conducted with favorable results (Pare et al., 1995; Huang and Schoenau, 1996; Jowkin and Schoenau; 1998; Ziadi et al., 1999). Pare et al.(1995) measured the supply rate of NO_3 in a fertilized corn field and found the results correlated well with KCl-extractable NO_3. However, the authors noticed the relationship between NO_3 measured by AEM and a standard chemical extractant (KCl) was not linear. Pare et al. (1995) hypothesized the discrepancy may have resulted from a number of factors related to *in situ* use. These factors included competition with soil microorganisms and the affect of soil water content and temperature on AEM retention of

NO_3. Ziadi et al. (1999) used AEMs to measure the supply rate of NO_3 in forage grass plots located in farmers' fields. Supply rates of NO_3 from AEMs in their study were strongly correlated with forage uptake of NO_3 and with water-extractable NO_3. AEMs reflected NO_3 fluxes from fertilizer in both the Pare et al. (1995) and Ziadi et al. (1999) studies.

AEMs have been used to measure differences in nitrogen availability between chemical fallow and tillage fallow systems in the semi-arid prairies of southwestern Saskatchewan, Canada (Jowkin and Schoenau, 1998). Like Pare et al. (1995) and Ziadi et al. (1999), Jowkin and Schoenau (1998) measured a decline in the NO_3 supply rate over the growing season as the crop assimilated the nutrient. However, in the study by Jowkin and Schoenau (1998) low soil water content late in the growing season may have limited the differences in NO3 supply rates between the chemical fallow and tillage fallow treatments as measured by AEM. Because the AEM method is sensitive to field soil water content and temperature, it potentially is useful for determining the supply rate of P and S in minimally tilled fields in NC Oregon.

In order for NC Oregon growers and researchers to employ ion exchange membranes in conservation tillage systems, it is important to assess their ability to measure plant available nutrients in NC Oregon's soil and climate. In this study, AEMs were used in dryland, continuously cropped, conservation tillage sites in four counties across NC Oregon. The objectives of this study were: 1) to explore the use of AEM to aid in understanding of P and S dynamics for HRS wheat in a dryland, continuously cropped, minimally tilled system and 2) to compare plant available P and S as measured by AEM to HRS wheat uptake of P and S.

2.3 METHODS

2.3.1 Site location and soil

Field experiments were conducted at four sites in NC Oregon on land that has been managed in conservation tillage for two to five years. Two of the sites were on Oregon State University agriculture experiment stations at the Columbia Basin Agriculture Research Center (CBARC) near Pendleton, Oregon (Umatilla County) and at the in Sherman County Experiment Station at Moro, Oregon (Sherman County). The remaining sites were in farmers' fields in Gilliam, Morrow and Wasco Counties, Oregon. The Umatilla, Sherman, and Wasco sites remained in the same location for both years while the Gilliam and Morrow sites were used respectively in 2001 and 2002.

Soils at the Umatilla, Sherman, and Morrow sites are Walla Walla silt loams classified as coarse-silty, mixed, superactive, mesic Typic Haploxerolls. The site in Morrow County is a Morrow silt loam classified as a fine-silty, mixed, superactive, mesic Calcic Argixeroll. All soils are of loessial origin. The long-term mean annual precipitation for these sites is as follows: 265 mm in Gilliam, 305 mm in Morrow, 290 mm in Sherman, 420 mm in Umatilla, and 339 mm in Wasco.

2.3.2 Experimental design and treatments

Experimental design was a split plot design with four replications. Five fertilizer treatments comprised the main plots while the placement of four PRS™ Probes per plot comprised the subplots. To ensure nitrogen (N) was not yield limiting each fertilizer treatment at the Morrow, Sherman, and Wasco sites received the equivalent of 84 kg N/ha while treatments at the Umatilla site received the equivalent of 112 kg N/ha. P and S were applied at rates equal to the minimum amount for a yield response at each site.

The fertilizer treatments were: 1) no fertilizer , 2) N applied as urea at the rate of 112 kg/ha, 3) S plus N (S applied at the rate of 47 kg S/ha as 21-0-0-24 with 102 kg/ha of urea for N), P plus N (P applied at the rate of 43 kg P/ha as 11-52-0 with 108 kg/ha of urea for N, and a combination of S plus P plus N applied at the rate of 80 kg S/ha of 16-20-0-14 with 13 kg P/ha of 11-52-0 and 98 kg/ha of urea.

Hard red spring wheat (var. 936R) was direct-seeded on March 23, 2001 with a Fabro drill at the Umatilla site and on March 28 at the Morrow, Sherman, and Wasco sites. In 2002, the Sherman site was seeded on March 19, Wasco on March 20, Morrow on March 26, and Umatilla on March 27. Seeding depth at all sites was approximately 2.5 cm with a band of fertilizer placed 7.6 cm deep and 2.5 cm to the side of the seed. Seeding rate was 25 seeds/30.5 cm^2 in 30.5 cm wide rows. Individual plots were 2.44 by 9.15 m.

2.3.3 Anion exchange membranes

Anion exchange membranes (AEM) treated with $NaHCO_3$ were used to measure soil nutrient flux (Western Ag Innovations, Inc Saskatoon, SK, Canada). Western Ag Innovations, Inc markets AEM as Plant Root Simulator™ (PRS) Probes. PRS™ probes were inserted into the soil within 24 hours of planting. Four PRS™ Probes per plot were inserted 15 cm into slots in the soil in a pattern consistent across plots and sites. Of the four probes, two PRS™ Probes per plot were placed in the row of wheat and two PRS™ Probes per plot were placed between rows (inter-row). The PRS™ probes were exchanged every two weeks by removing the "old" PRS™ Probe and inserting a "fresh" PRS™ Probe into the same soil slot. In 2001, the PRS™ Probes at the Umatilla and Wasco sites were not reinserted into the same slots, i.e. they were placed in a new slot slightly ahead of the previous slot. Data from these counties were not used. PRS™ Probes were placed into zip-locking bags and transported on ice to a refrigerator for storage until cleaning.

The PRS™ Probes were scrubbed clean of all adhering soil under running deionized water. After cleaning, the PRS™ Probes were shipped to Western Ag Innovations for analysis. Western Ag Innovations elutes the PRS™ probes with 0.5N HCl. Phosphate and sulfate in the eluate were measured via Inductively Coupled Plasma (ICP).

2.3.4 Soil measurements

Two Optic Stowaway temperature probes (Onset Computer Corporation) at each site were used to continuously measure soil temperature from seeding through harvest. In 2001, 15-cm deep soil cores were taken every two weeks at the time of PRS™ Probe exchange to determine gravimetric water content. In 2002, soil water content to 15 cm depth was determined at each PRS™ exchange in Morrow and Umatilla Counties with a Campbell Scientific Water Content Reflectometer. Soil water content at Sherman and Wasco Counties in 2002 was measured as in 2001.

Following harvest, two soil cores per plot at each site were sampled to a depth of 1.22 m with a tractor-mounted soil probe. The soil cores were separated into 30.5 cm depths at the time of sampling. The two samples per plot were combined in the field and soil was dried for 24 hours at 60 °C then ground in a Thomas-Wiley soil grinder and sent to Agri-Check for nitric acid digestion and standard soil testing. Olsen-P (NaH_2CO_3) content was measured on 1.25 gram samples from each plot by colorimetric analysis on a Cole-Palmer 100 RS series Spectrometer at 644 nm (Page, 1982). Sulfur from each sample was extracted with DTPA and analyzed via atomic emission on a Perkin-Elmer ICP Emission Spectrometer Optima 3000 DV (Page, 1982).

2.3.5 Plant sampling

A one-meter length of wheat row was sampled at the five-leaf and soft dough stages and at harvest from each plot across sites. Samples were bundled and transported on ice and stored in a refrigerator until time of plant growth staging. A subsample of 15 plants in 2001 and ten in 2002 was taken from the one-meter row bundle for plant growth staging as described by Klepper et al. (1982). Plant samples were ground using a Thomas-Wiley plant grinder after being oven dried for 24 hours at 60 °C. Ground plant samples were sent to Agri-Check, Inc. of Umatilla, OR for nitric acid digestion and analyses. Sulfate and P were analyzed on a Perkin-Elmer ICP Emission Spectrometer Optima 3000 DV. Samples were prepared and analyzed by Agri-Check as stated above.

In 2001, harvest in Sherman and Wasco Counties took place on July 25 and on July 26 in Morrow and Umatilla Counties. In 2002, Sherman and Wasco Counties were harvested on July 23, Morrow Co. on July 30, and Umatilla Co. on July 31. The wheat was harvested with a plot-sized combine. Grain protein analysis was conducted by Pendleton Flour Mills. Water content was determined after drying one gram samples of grain in a 130 °C oven for 60 minutes. Nitrogen in the grain was analyzed using a LECO Autoanalyzer.

2.3.6 Statistical analyses

Analysis of variance (ANOVA) was used to test the significance of differences among fertilizer treatments, AEM placements, date of AEM exchanges, and subsequent two-way and three-way interactions on the supply rate of P and S adsorbed to the AEM

(SAS Systems version 7). Following this ANOVA, analysis of the relationship between the supply rate of P and S over time was conducted by determining whether the relationship fit a linear equation. This regression in ANOVA was accomplished by partitioning the treatment sum of squares into 1) the sum of squares for the linear regression of supply rate on time and 2) the sum of squares for the failure of the linear regression model to describe the relationship between supply rate and time (Peterson, 1994). A significant F ratio for the failure of linear regression to describe the relationship between supply rate and time indicates a linear model does not describe the relationship. A more complex model, i.e. a quadratic equation, was not tested to describe the relationship between supply rate and time because such a model was not consistent with the hypothesis of a linear decrease in the supply rate of P and S over time. ANOVA was also used to test the significance of differences among fertilizer treatment means on plant biomass, yield, and percent protein. Orthogonal contrasts were used to answer specific questions of interest following significant p-values of 0.05 or less from ANOVA (Peterson, 1994). The questions addressed by the orthogonal contrasts (when the ANOVA produced significant p-values of 0.05 or less) were: 1) Is there a main effect of the S treatment?, 2) Is there a main effect of the P treatment?, and 3) Is there an interaction of S + P? (Peterson, 1994). The correlation values (R^2) for the regression of the supply rate of P or S ($\mu g/10cm^2/14$ days) on uptake of P or S (mg/meter row) were obtained in JMP (SAS Institute, Inc. version 4.0.0).

2.4 RESULTS AND DISCUSSION

2.4.1 Climatic conditions and plant stress

Mean annual precipitation in 2001 and 2002 was below the long-term average at each site with the exception of Gilliam Co. in 2001 (Table 1.1). Throughout the growing season in 2001, gravimetric soil water content ranged from 2 to 17 % across the Gilliam, Sherman, and Wasco sites (Table 1.2). In 2002, gravimetric soil water content ranged from 8 to 16 % across the Morrow, Sherman, Umatilla, and Wasco sites (Table 1.2). The Umatilla site generally receives more precipitation per year than Morrow, Sherman, and Wasco sites which was reflected in 2001 by approximately 9% greater gravimetric soil water content than other sites. Soil temperature in both years remained below 20 °C until mid-May and did not rise above 30 °C during the time the AEM were employed (Fig. 1.1).

In addition to drought conditions and low soil temperature, the Wasco and Umatilla sites were infested with Hessian fly (*Mayetiola destructor*). Of the wheat plants sampled at the five-leaf growing stage, Wasco showed 23% infestation in 2001 and 10% in 2002, respectively. Umatilla showed 59% and 58% infestation in 2001 and 2002, respectively (A.Redman, unpublished data).

Plants at all sites across both years exhibited symptoms of stress including missing tillers and low grain yields. The Umatilla site in 2001 is the only site where treatments produced significantly different grain yields (Table 1.3). The yield from the mean of the treatments that received P was 1250 kg/ha greater than the treatments that did not receive P (p-value 0.0011). Fertilizer treatments had few significant effects on the mean number of plants with the coleoptilar tiller (T0), tiller 1 (T1), tiller 2 (T2), tiller

Table 2.1 Monthly and total precipitation (mm) throughout 2001 and 2002 crop seasons.

Site	Crop Season	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Total	Long-Term Average
Umatilla Co.	2000-2001	63.5	58.7	36.6	20.6	33.5	21.1	39.1	50.8	12.4	38.1	15.0	0.5	389.9	419.9
	2001-2002	9.4	47.0	47.0	29.2	35.3	30.5	35.8	27.3	25.6	34.8	6.1	0.7	328.7	
Gilliam Co.	2000-2001	15.7	61.5	24.4	16.3	24.6	17.5	27.9	56.9	14.5	40.6	10.4	5.8	316.2	265.2
Morrow Co.	2001-2002	10.2	34.8	28.4	22.1	9.9	13.7	12.2	34.8	23.4	40.9	8.6	0.8	239.8	
Sherman Co.	2000-2001	7.6	35.3	15.2	8.9	10.9	13.5	20.6	18.0	8.6	12.7	0.5	5.8	157.7	290.8
	2001-2002	13.5	26.2	51.3	29.7	17.3	16.5	10.7	9.7	16.8	21.6	1.0	0.0	214.1	
Wasco Co.	2000-2001	21.8	20.3	20.8	20.1	25.4	25.1	22.4	24.4	1.3	17.8	5.8	7.4	212.6	339.6
	2001-2002	14.2	26.9	66.8	47.5	22.9	27.2	10.4	11.4	21.8	14.5	6.9	0.3	270.8	

Table 2.2 Gravimetric soil water content (%) for each site. Missing numbers are indicated by "mn".

Year	Date	Gilliam Co.	Sherman Co.	Umatilla Co.	Wasco Co.
2001	19-Apr	mn	mn	mn	11.9
	17-May	mn	mn	17.2	7.5
	25-May	mn	7.6	mn	mn
	1-Jun	mn	mn	13.3	5.1
	15-Jun	mn	mn	11.4	2.3
	21-Jun	3.8	3.4	mn	mn
	9-Jul	15.7	15.7	mn	16.5
		Morrow Co.			
2002	20-Mar	14.4	16.1	26.7	15.4
	2-Apr	17.6	14.7	32.7	13.8
	17-Apr	24.0	14.5	27.4	13.5
	30-Apr	19.9	13.5	22.8	12.5
	16-May	11.4	11.4	17.5	10.4
	30-May	5.4	9.9	7.8	8.3
	13-Jun	22.4	8.5	15.7	7.8

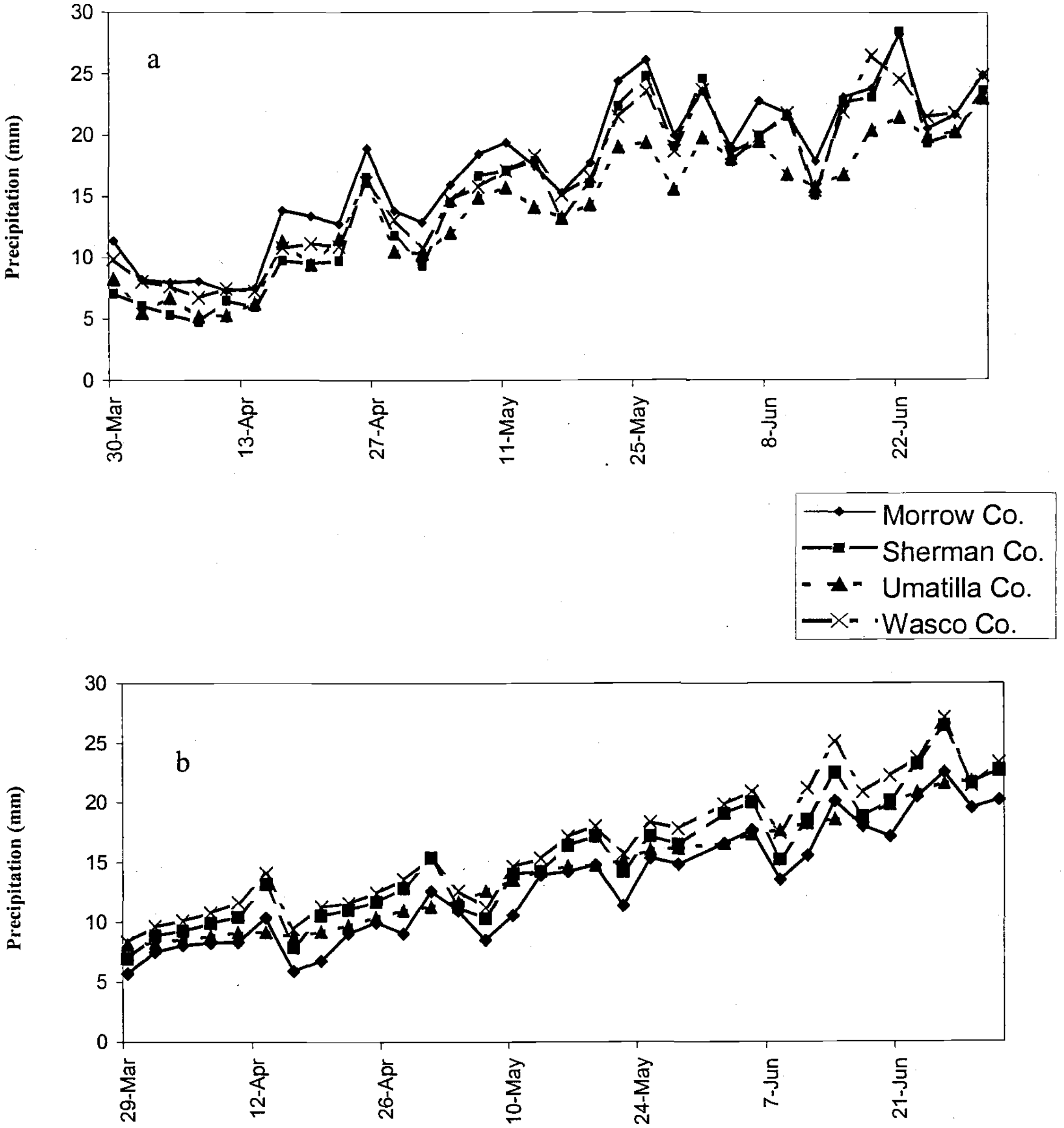


Figure 2.1 Overall trend of soil temperature across sites from seeding through the last AEM exchange in 2001 (a) and 2002 (b).

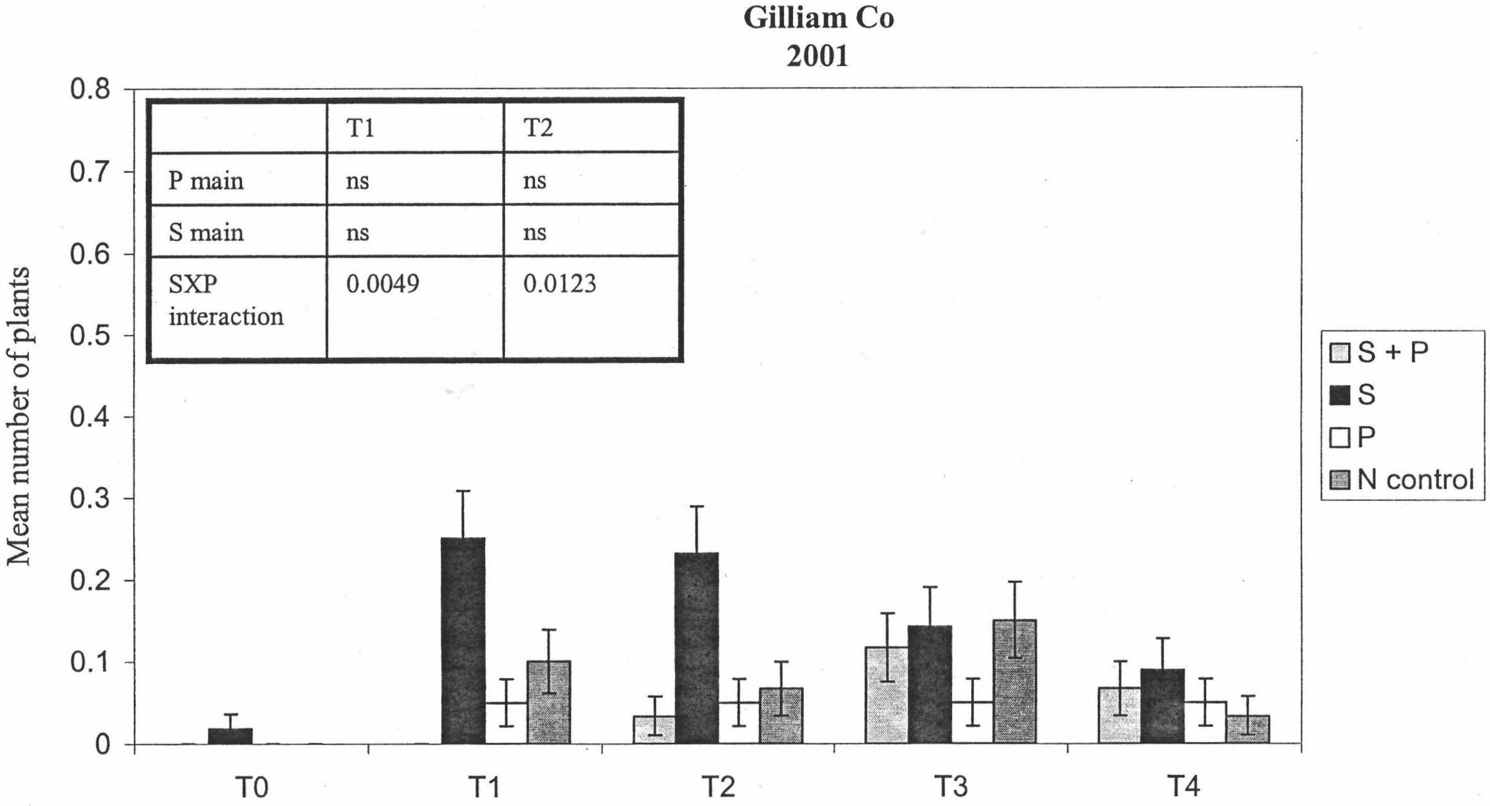
Table 2.3 Mean yield (kg/ha) across treatments in 2001 and 2002. Treatments: P + S = 80 kg/ha 16-20-0-14 and 13 kg/ha 11-52-0 and 98 kg/ha urea, S = 47 kg/ha 21-0-0-14 and 102 kg/ha urea, P = 43 kg P/ha 11-52-0 and 108 kg/ha urea. *Significant at the 0.01 probability level.

Year	Site	Treatment	Yield (kg/ha)	SE	Year	Site	Treatment	Yield (kg/ha)	SE
2001	Gilliam Co.	S + P	936.3	102.5	2002	Morrow Co.	S + P	984.4	24.4
		S	890.9	84.3			S	933.7	22.7
		P	958.1	48.1			P	939.9	50.5
		N control	815.5	61.8			N control	906.5	21.3
2001	Sherman Co.	S + P	1348.2	151.4	2002	Sherman Co.	S + P	895.7	48.5
		S	1533.4	277.7			S	786.1	34.7
		P	776.5	89.6			P	965.0	66.5
		N control	989.2	125.7			N control	905.0	69.4
2001	Umatilla Co.*	S + P	2059.3**a**	136.4	2002	Umatilla Co.	S + P	1473.2	27.6
		S	1262.8**b**	114.9			S	1560.3	45.1
		P	1927.1**a**	112.5			P	1216.0	119.1
		N control	1473.3**b**	252.4			N control	1568.7	116.9
2001	Wasco Co.	S + P	253.2	6.1	2002	Wasco Co.	S + P	1829.6	57.2
		S	279.5	8.0			S	1665.7	68.3
		P	227.0	76.3			P	1556.6	126.4
		N control	266.9	35.6			N control	1690.6	142.4

3 (T3), or tiller 4 (T4) present. When significant treatment effects existed, however, the differences between the numbers of wheat plants with the indicated tiller were large.

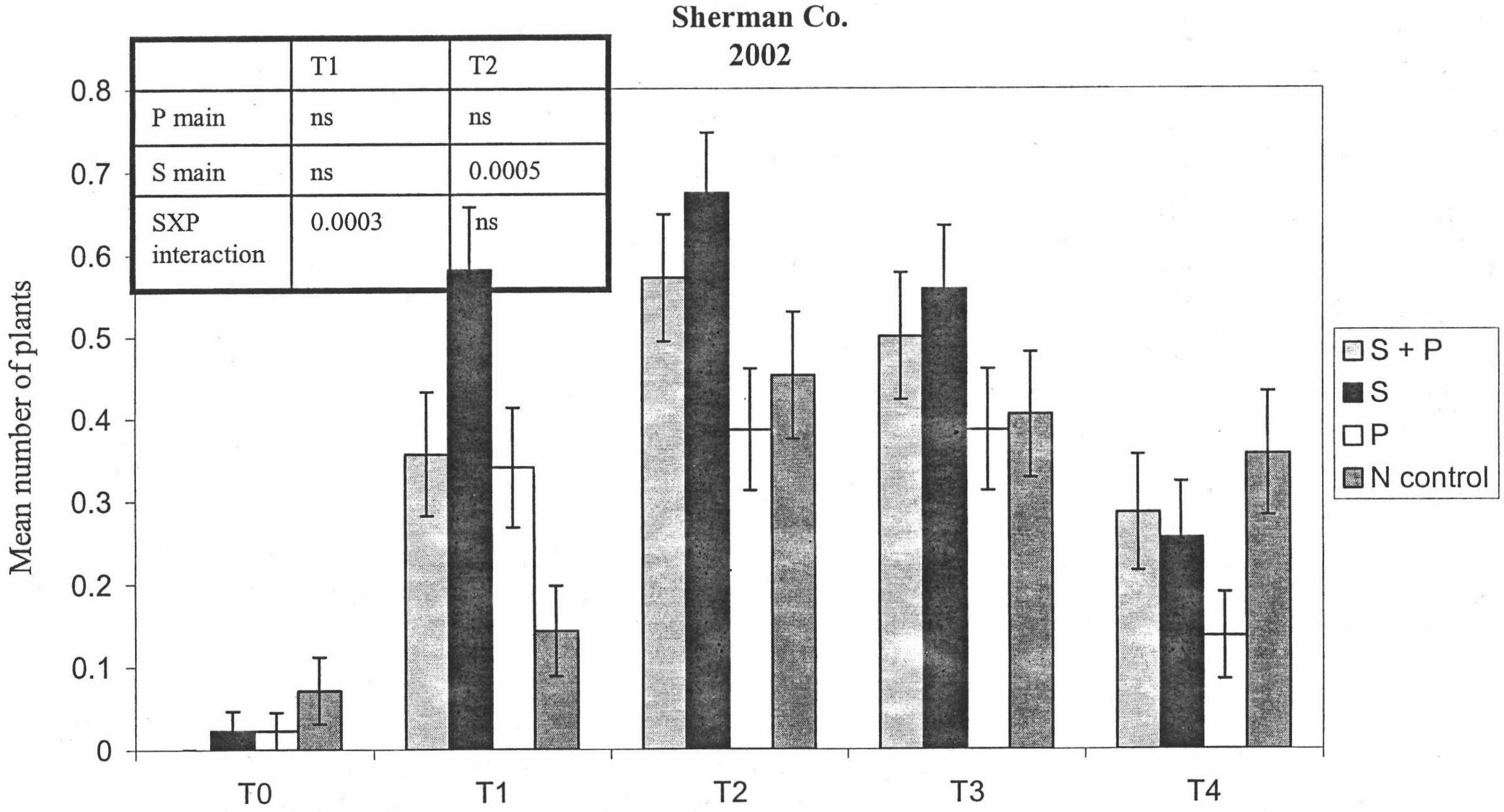
In general, the number of wheat plants that produced T1 and T2 tillers were most often significantly affected by the different treatments. At the Gilliam site in 2001, the mean number of wheat plants with T1 and T2 from the S + P interaction produced 150% and 211%, respectively, less tillers than the S main effect and P main effect treatments (p-value 0.0049 and 0.0123, respectively) (Fig. 1.2). In 2002, wheat plants from the S + P interaction at the Sherman site produced 84% fewer T1 than plants in the S main effect or P main effect treatments (p-value 0.0003) (Fig. 1.3). The only significant S + P treatment effect on the number of plants producing the T0 tiller occurred at the Umatilla site in 2001. The S + P interaction at the Umatilla site in 2001 caused 11% fewer wheat plants to produce T0 than the mean of the S main effect and P main effect treatments (p-value 0.0135) (Fig. 1.4).

The S treatment and the P treatment also produced differences in the number of plants producing T1 and T2 tillers. At the Wasco site in 2001, the S main effect caused 222% more wheat plants to produce T2 than the mean of the P main effect (p-value 0.0013) (Fig. 1.5). The main effect of S also caused more plants to produce T2 (p-value 0.0005) at the Sherman site (Fig. 1.3) and T1 (p-value 0.0039), T2 (p-value 0.001), and T3 (p-value 0.0012) at the Umatilla site (Fig. 1.6) than the P main effect in 2002. At the Morrow site in 2002, the S main effect and the P main effect caused between 172% and 213% more wheat plants to produce T1 and T2 tillers than the mean of the S + P interaction (p-values ranged between 0.0001 and 0.0263) (Fig. 1.7). Although the treatment effects on the mean number of plants with T0, T1, T2, T3 or T4 were large,



	T1	T2
P main	ns	ns
S main	ns	ns
SXP interaction	0.0049	0.0123

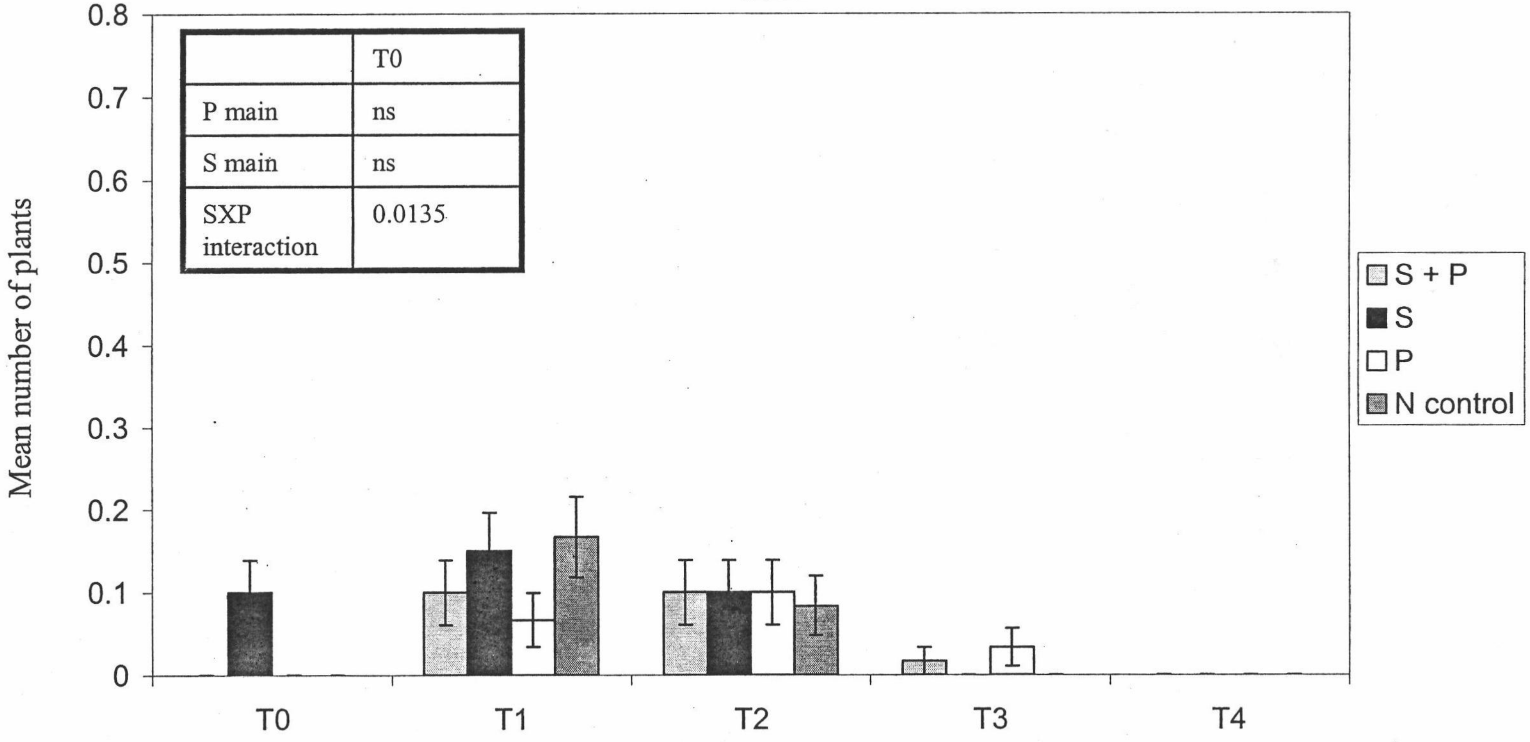
Fig. 2.2 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Gilliam site in 2001. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. The table indicates whether the P main effect, S main effect, or S X P interaction is significant (probability level = 0.05).



	T1	T2
P main	ns	ns
S main	ns	0.0005
SXP interaction	0.0003	ns

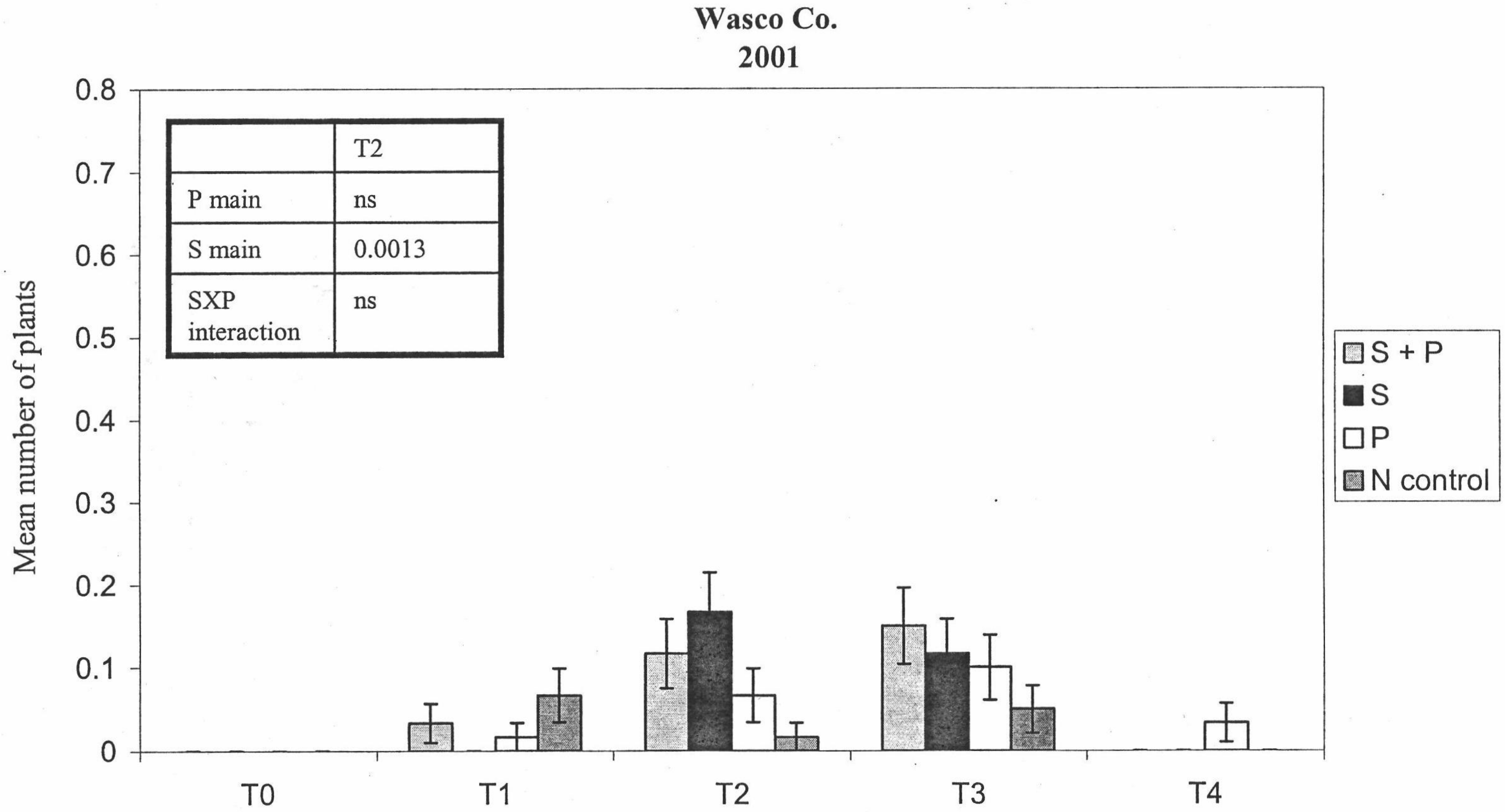
Fig. 2.3 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Sherman site in 2002. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. The table indicates whether the P main effect, S main effect or S X P interaction is significant (probability level = 0.05).

Umatilla Co.
2001



	T0
P main	ns
S main	ns
SXP interaction	0.0135

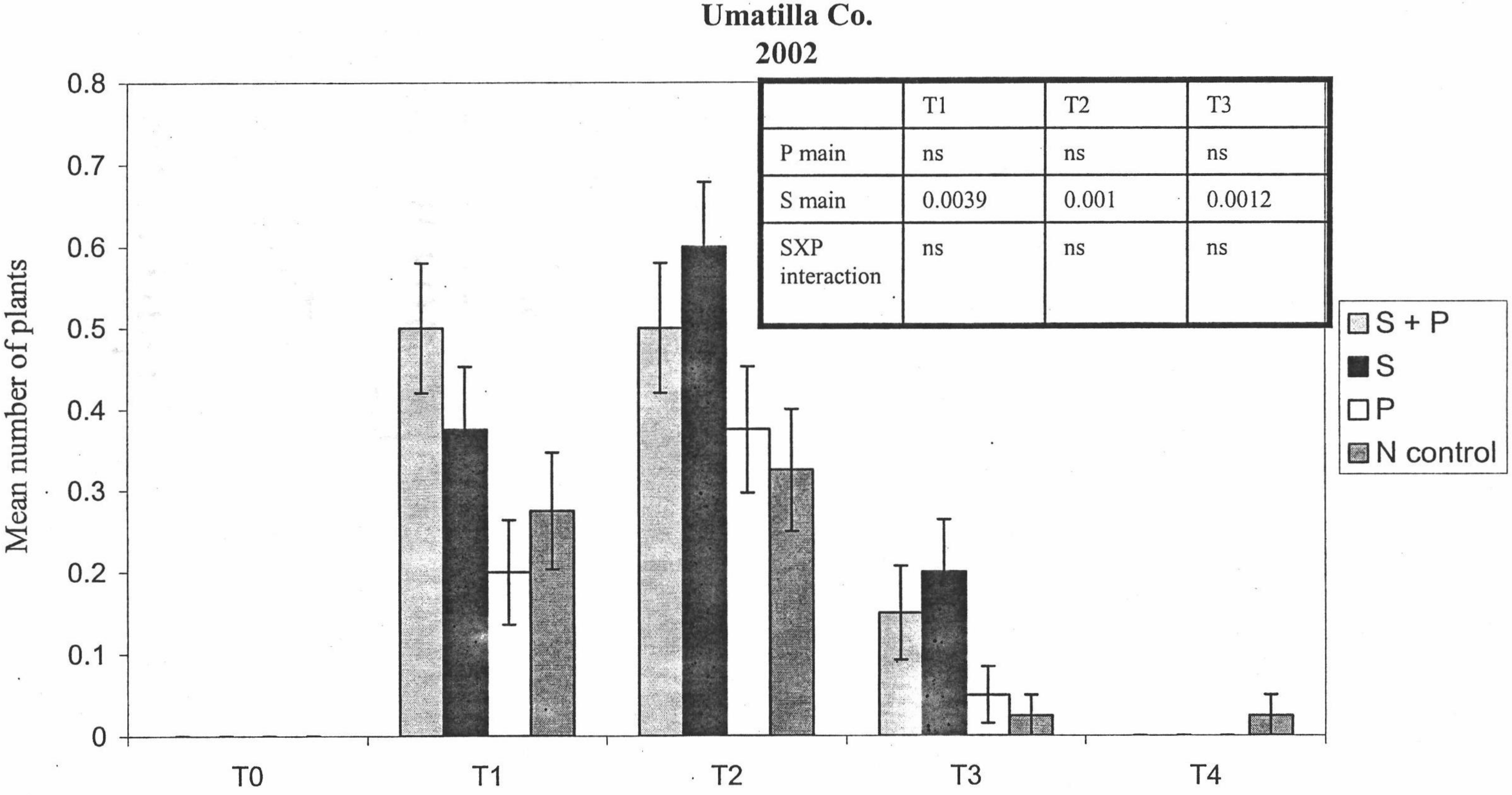
Fig. 2.4 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Umatilla site in 2001. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. The table indicates whether the P main effect, S main effect or S X P interaction is significant (probability level = 0.05).



**Wasco Co.
2001**

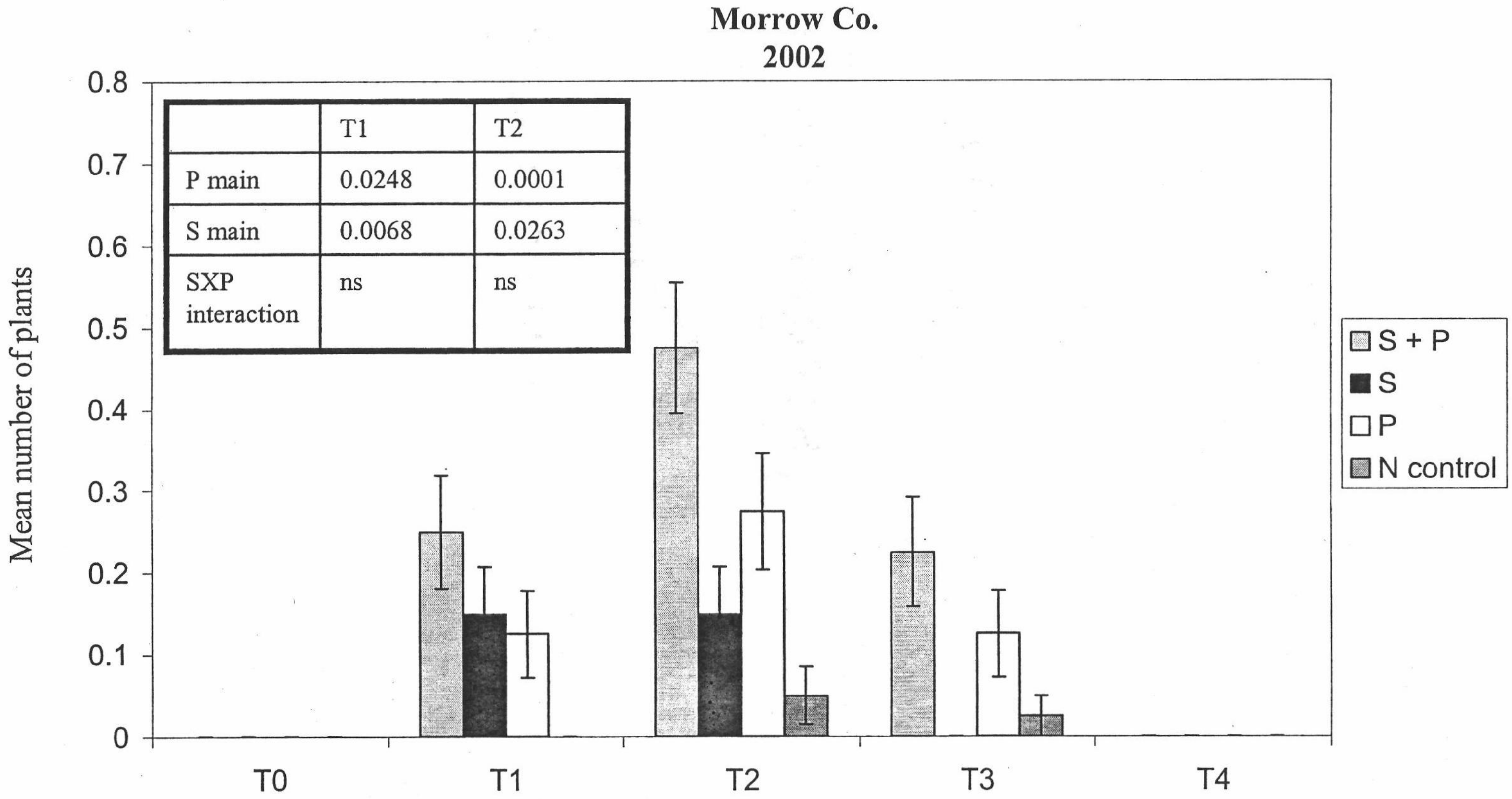
	T2
P main	ns
S main	0.0013
SXP interaction	ns

Fig. 2.5 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Wasco site in 2001. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. The table indicates whether the P main effect, S main effect, or S X P interaction is significant (probability level = 0.05).



	T1	T2	T3
P main	ns	ns	ns
S main	0.0039	0.001	0.0012
SXP interaction	ns	ns	ns

Fig. 2.6 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Umatilla site in 2002. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. Within each group of tillers, different letters indicate significant treatment effects at p ≤0.05. The table indicates whether the P main effect, S main effect or S X P interaction are significant (probability level = 0.05).



	T1	T2
P main	0.0248	0.0001
S main	0.0068	0.0263
SXP interaction	ns	ns

Fig. 2.7 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Morrow site in 2002. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. The table indicates whether the P main effect, S main effect, or S X P interaction is significant (probability level = 0.05).

they did not occur across sites or in each tiller group in 2001 or 2002. Therefore, it is likely the low number of plants with tillers are a symptom of a stressful growing environment and are not the result of fertilizer treatments.

The absence of specific tillers can be used to determine when the plant was stressed (Huan, 1973; Karow et al.., 1993). T0 tillers typically do not develop unless growing conditions are ideal. However spring wheat in NC Oregon commonly produces T1-T4. The overall lower percentage of tillers numbers 1 - 4 in 2001 as compared to 2002 (Fig. 1.2 - Fig. 1.7) may be a repercussion of the lower gravimetric soil water content in 2001 than in 2002.

Low soil water content, cool soil temperature, and Hessian fly infestation caused low wheat yield in 2001 and 2002 across treatments. Consecutive seasons of below average precipitation and subsequent low yields of wheat have not depleted soil P and S from previous seasons of fertilization. Therefore, adequate residual P and S remained in the soil for wheat to obtain sufficient P and S regardless of fertilizer addition (A.Redman, Manuscript II).

2.4.2 AEM supply rates and wheat uptake

In general, the AEM were poorly and inconsistently correlated with hard red spring (HRS) wheat uptake of P and S (Table 1.4). Correlation values (R^2) for wheat uptake of P across treatments at the five-leaf stage averaged 0.04 while correlation values for wheat uptake of S across treatments averaged 0.03.

Decreasing soil water content slows diffusion of nutrients through soil as the path of diffusion becomes more tortuous and water molecules become tightly bound

Table 2.4 R^2 values for the correlation between supply rate of P and S (μg/10cm^2/14 days) and wheat uptake of P and S (mg/meter row) in 2001 and 2002. Supply rates from the first burial through the five leaf stage of the wheat were summed together for the correlation.

		P		S	
Year	Site	Row	Interrow	Row	Interrow
2001	Gilliam Co.	0.07	0.03	0.00	0.02
	Sherman Co.	0.09	0.08	0.22	0.06
2002	Morrow Co.	0.07	0.03	0	0.02
	Sherman Co.	0.01	0.01	0.01	0.05
	Umatilla Co.	0.07	0.04	0.01	0.07
	Wasco Co.	0	0.01	0.02	0

by soil particles (Barber, 1962; Brady and Weil, 1999). Soil water content may decrease below a critical level impairing the ability of the AEM to accurately measure plant available nutrients. A sluggish diffusion rate affects a plant root less than it does an AEM because plant roots contact a greater volume of soil than the AEM. The chance of intercepting nutrients is, therefore, enhanced by root growth.

Furthermore, as roots absorb water, a water potential gradient is created between the rhizosphere and the bulk soil. Even in soil with low water content (though above -1500 kPa), the water potential gradient created as roots absorb water can cause soil water to move towards the root (Taiz and Zeiger, 1998). This phenomenon is important to nutrients such as SO_4 because they reach roots primarily via mass flow (Barber, 1962). The ability of the root to obtain water and nutrients in limited water conditions may lead to disparity between the amount of nutrients adsorbed by AEM and the plant.

Most studies involving the correlation of ion exchange membranes with plant uptake have been conducted in saturated soil pastes in the lab (Skogley et al., 1990; Schoenau and Huang, 1991; Qian and Schoenau, 2000). Of the few studies conducted in the field, the reporting of soil water content during the course of the study has not been routine. Pare et al. (1995) found AEMs used *in situ* to be highly correlated with KCl-extractable NO_3, but did not correlate NO_3 supply rates with plant uptake. Ziadi et al. (1999) reported strong relationships between NO_3 supply rates from AEM used in the field, forage grass uptake, and water-extractable NO_3. However, annual precipitation in the years of Ziadi et al.'s study averaged 130 mm more than annual precipitation in the present study.

Due to the influence of soil texture on soil water content, it is important to identify the soil texture in all AEM studies. Both Pare et al. (1995) and Ziadi et al. (1999) conducted their studies in fine-textured Typic Endoaquoll clay loams. The fine-texture of the soil in the Pare et al. (1995) and Ziadi et al. (1999) studies have higher water holding capacity than the silt loam of this study. Furthermore, greater precipitation from the aquic moisture regime of the Endoaquoll implies a wetter environment whereas the present study was conducted in a xeric moisture regime.

Soil temperature also affects diffusion of nutrients in the soil, but does so indirectly (Barber, 1962; Yang et al., 1991a). Cool soil temperature decreases the diffusion of nutrients by slowing the activity of soil microorganisms crucial to nutrient cycling. Soil microorganisms are active throughout a large range of soil temperatures, however, in temperate regions, the microorganisms with a prominent role in nutrient cycling are mesophilic (Alexander, 1999). The temperature range for maximum mesophilic activity, and therefore optimum nutrient cycling in soils of temperate regions, ranges between 15 and 35 °C. Soil temperatures in this study rose to 15 °C approximately 4 to 5 weeks after planting in 2001 and 2002, however, the soil temperature did not remain above 15 °C until approximately 6 to 8 weeks after planting (Fig. 1.1). Similar to soil water content, the amount of nutrients obtained by both plant roots and AEM is limited by the rate of nutrient cycling. Plant roots contact a larger volume of soil which, even in cool soil, allows them to come in contact with more nutrients than an AEM. AEM limitations in cool soil temperatures may decline to a point where AEMs can no longer represent plant uptake.

Burying several AEM in a vertical transect of consecutively deeper burials may improve the ability of AEMs to accurately measure plant available P and S (Fig. 1.8). AEMs buried vertically would represent a greater volume of soil such that they mimic root systems more accurately. Vertical burial might place AEMs in subsurface soil horizons where soil water content is often greater than in the surface horizon (Brady and Weil, 1999). AEMs may correlate better with plant uptake if they also measure subsurface supply rates.

2.4.3 Supply rate of P and S over time

Throughout the plots, AEM placed in the wheat row consistently measured higher supply rates of P (Fig. 1.9 – Fig. 1.11) and S (Fig. 1.12 and Fig. 1.13) over time than AEM placed in the inter-row. Cumulative supply rates of P in the row at the Gilliam (Fig. 1.9) site in 2001 (p-value <.0001) and at the Umatilla (Fig. 1.10) and Wasco (Fig. 1.11) sites in 2002 (p-value 0.0411 and 0.0341, respectively) were significantly greater than supply rates in the inter-row over time. Cumulative supply rates of S in the row at the Gilliam site (Fig. 1.12) in 2001 (p-value 0.0542) and at the Sherman site (Fig. 1.13) in 2002 (p-value 0.0079) were significantly greater than the supply rates in the inter-row over time. Although the supply rates of P and S in the row at the remaining sites were greater than the supply rates in the inter-row, the differences were not significant. Despite higher supply rates in the row than in the inter-row, it appears that similar processes of mineralization and immobilization were occurring in each AEM placement because the curves parallel one another in spite of different supply rates.

However, we did not expect row and inter-row supply curves to reflect similar supply rates. It was expected that the curve from the row AEM would display an initial

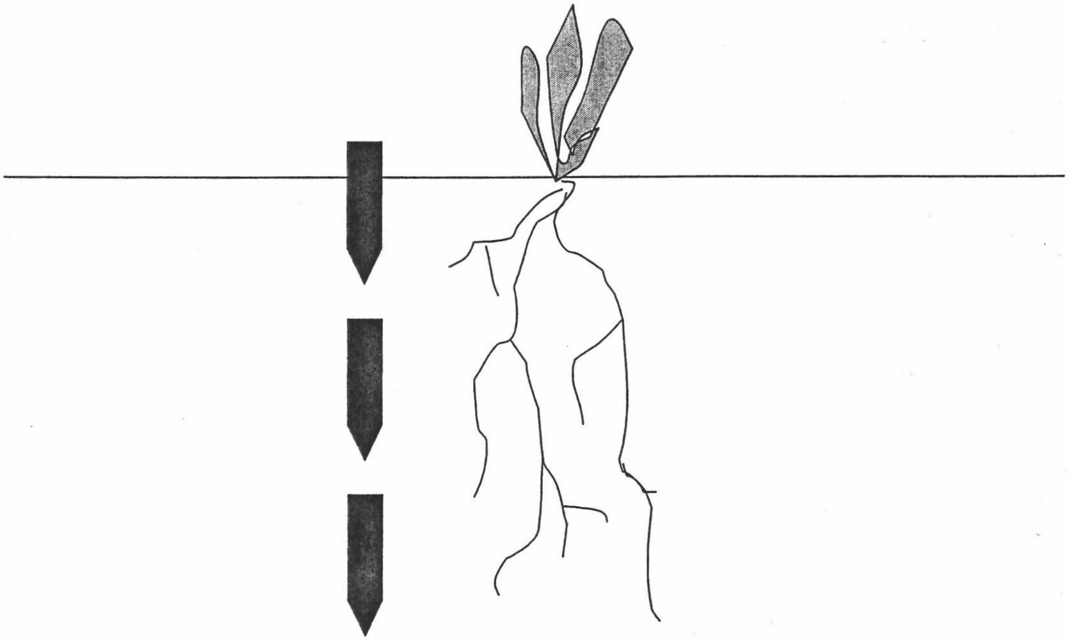


Fig. 2.8 Diagram showing burial of AEM in a vertical transect down into the soil.

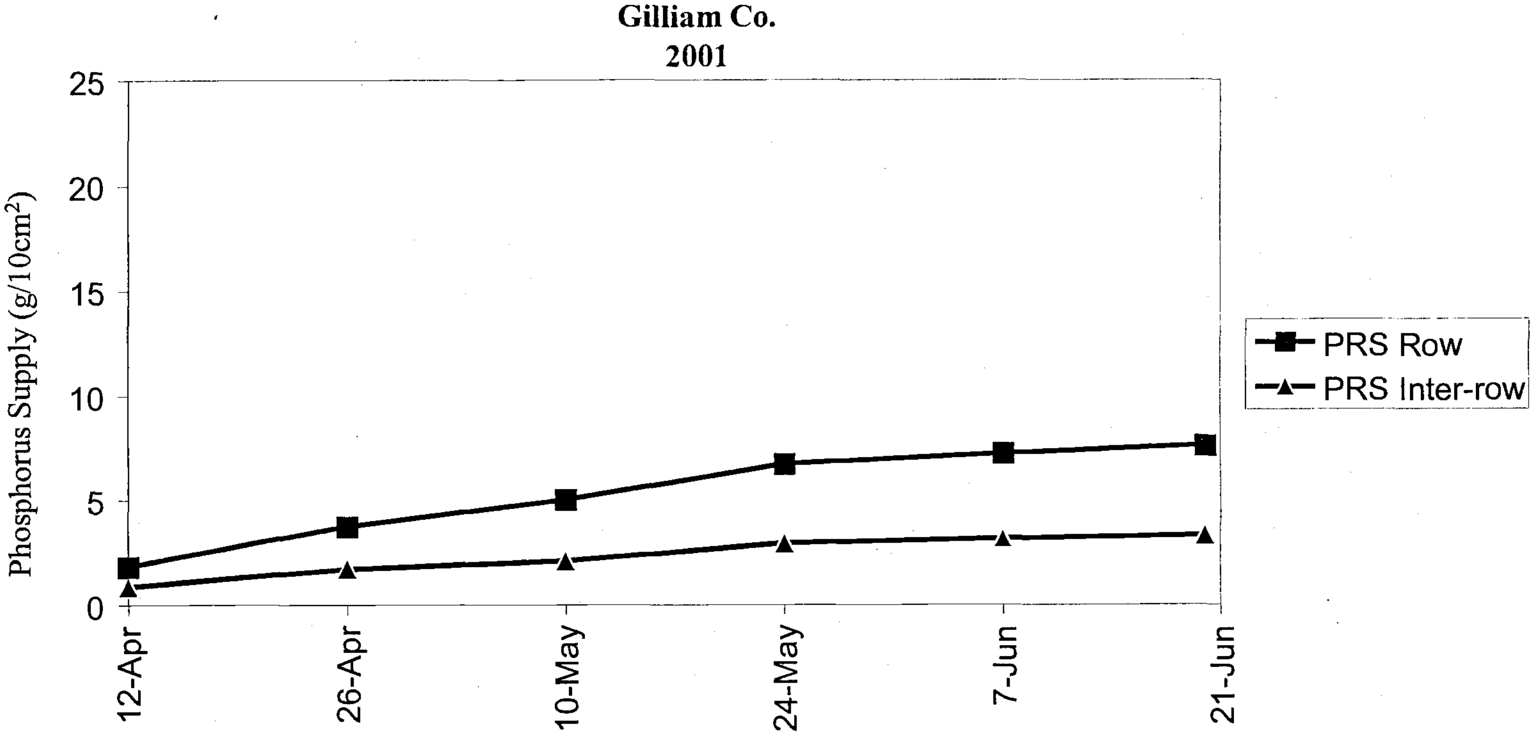


Fig. 2.9 Cumulative P supply rate during the first 10 weeks of spring wheat growth at the Gilliam site in 2001. Two PRS Probes, one in the wheat row and one in the inter-row, were buried for consecutive two week intervals. The supply rate of P in the row is significantly greater than the supply rate of P in the inter-row (probability level = 0.05.)

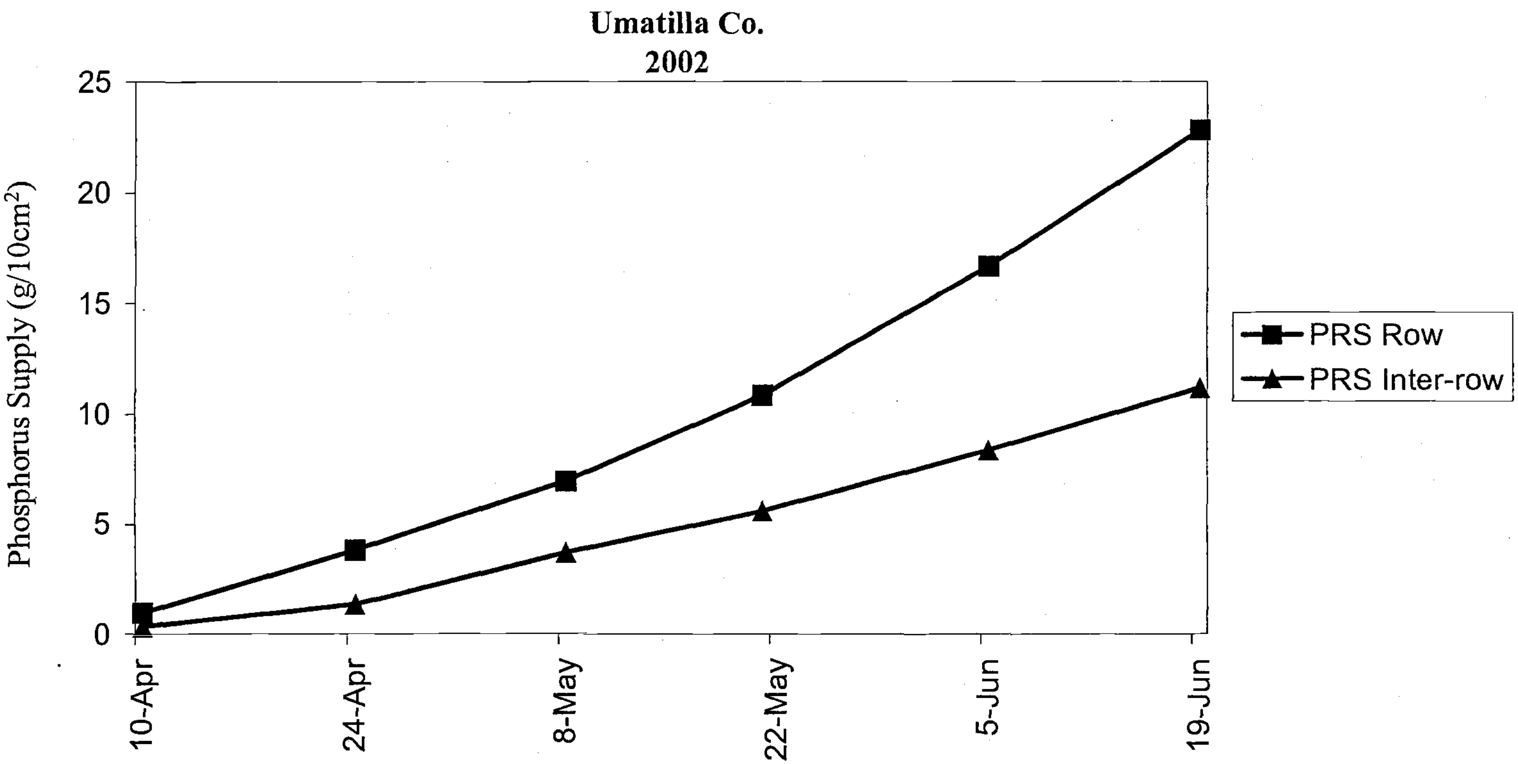


Fig. 2.10 Cumulative P supply rate during the first 10 weeks of spring wheat growth at the Umatilla site in 2002. Two PRS Probes, one in the wheat row and one in the inter-row, were buried for consecutive two week intervals. The supply rate of P in the row is significantly greater than the supply rate of P in the inter-row (probability level = 005).

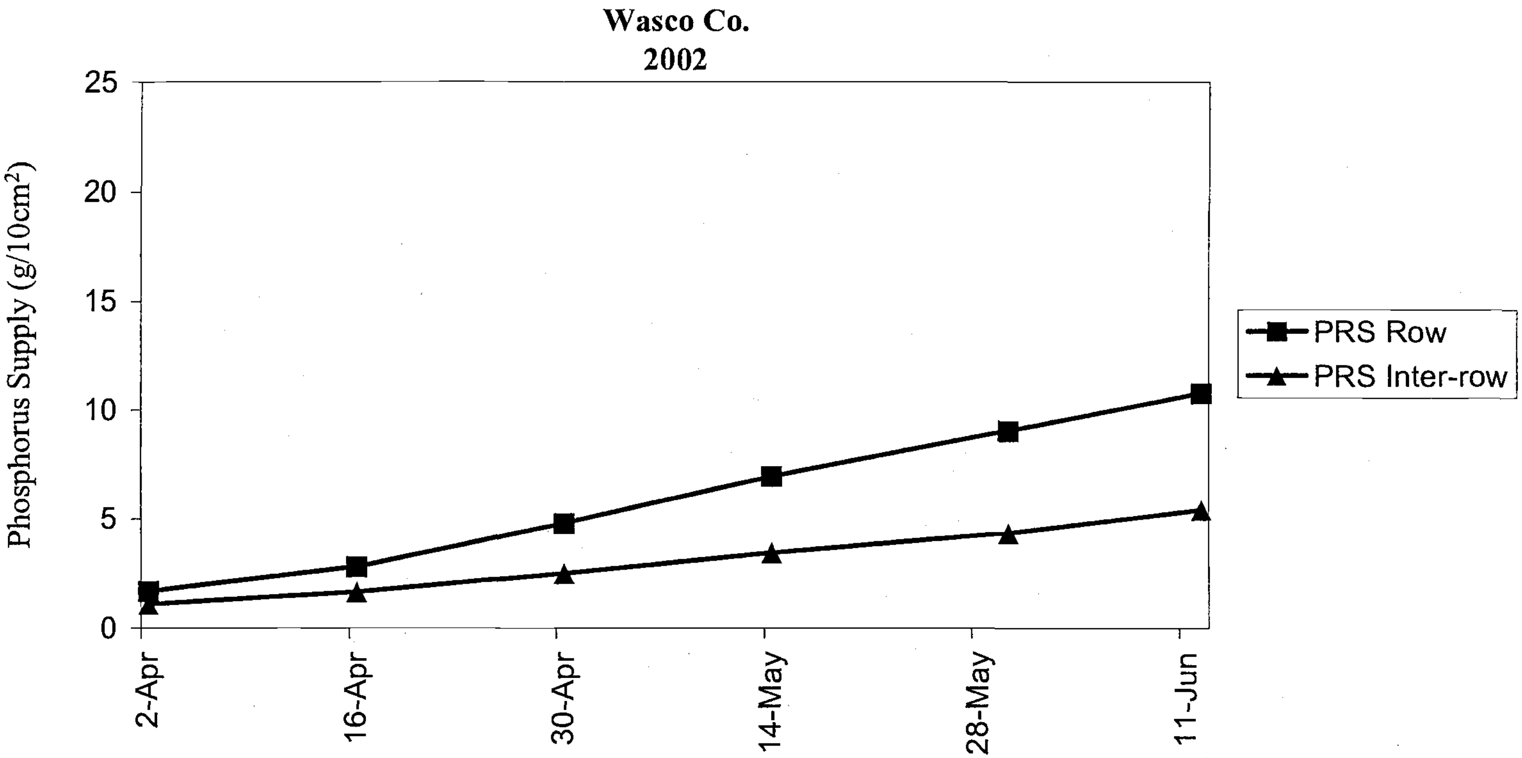


Fig. 2.11 Cumulative P supply rate during the first 10 weeks of spring wheat growth at the Wasco site in 2002. Two PRS Probes, one in the wheat row and one in the inter-row, were buried for consecutive two week intervals. The supply rate of P in the row is significantly greater than the supply rate of P in the inter-row (probability level = 0.05).

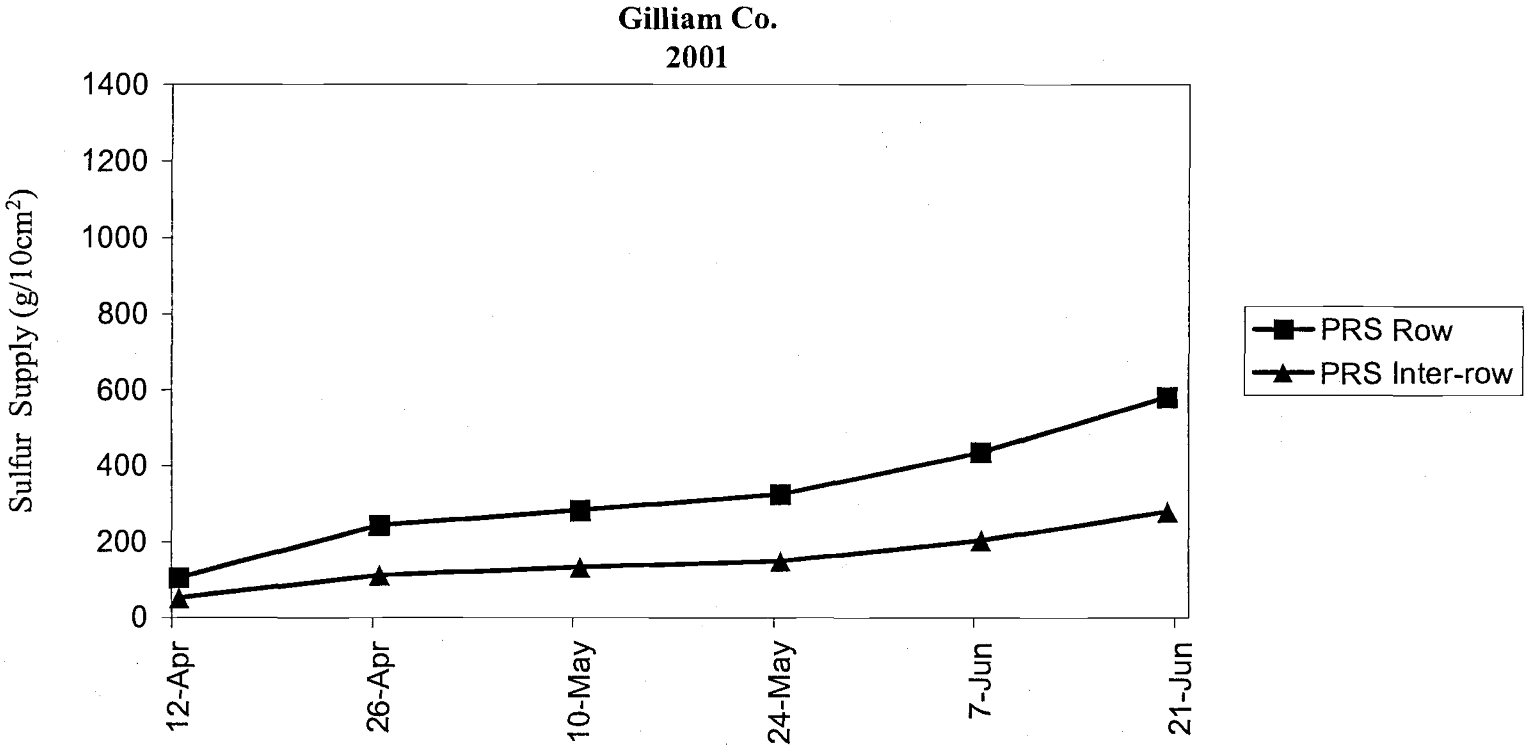


Fig. 2.12 Cumulative S supply rate during the first 10 weeks of spring wheat growth at the Gilliam site in 2001. Two PRS Probes, one in the wheat row and one in the inter-row, were buried for consecutive two week intervals. The supply rate of S in the row is significantly greater than the supply rate of S in the inter-row (probability level = 0.05).

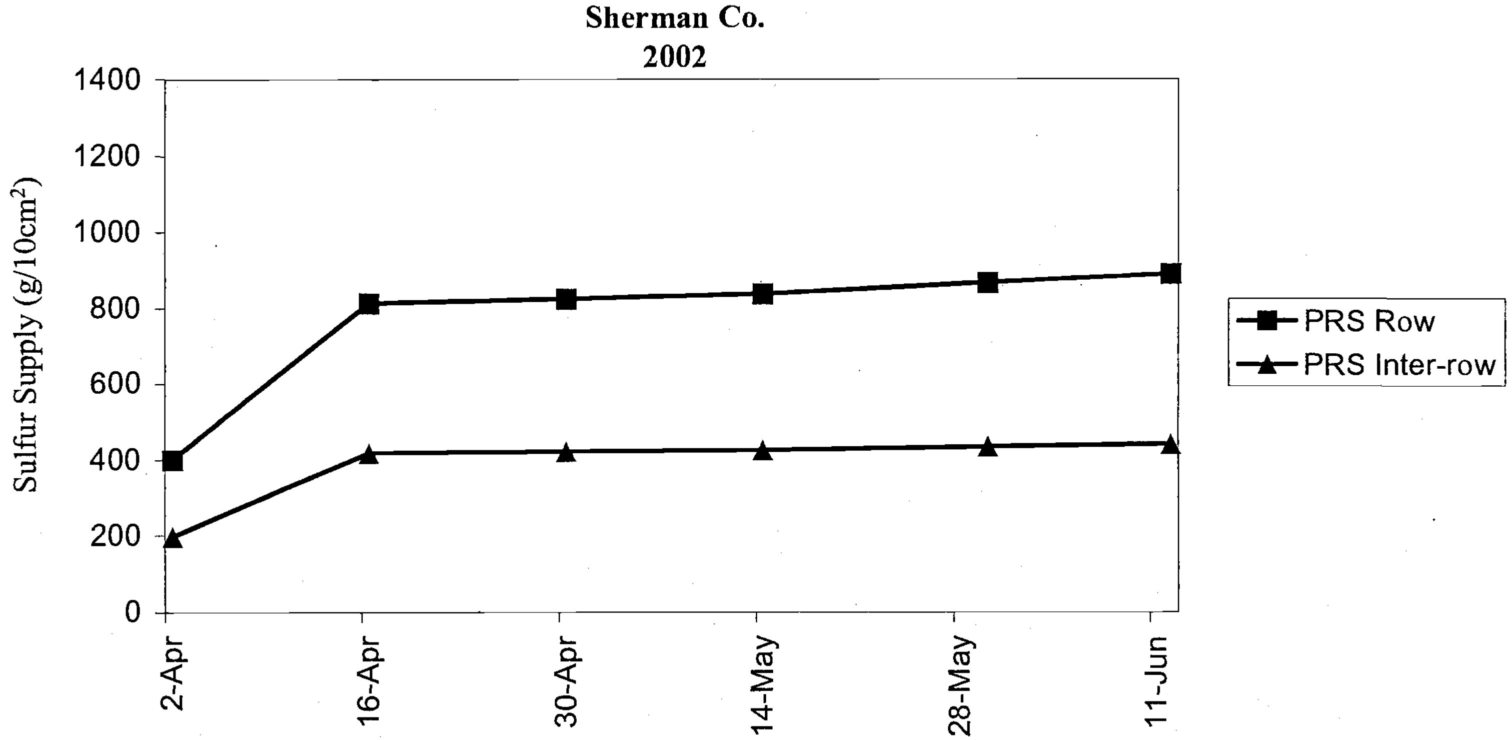


Fig. 2.13 Cumulative S supply rate during the first 10 weeks of spring wheat growth at the Sherman site in 2002. Two PRS Probes, one in the wheat row and one in the inter-row, were buried for consecutive two week intervals. The supply rate of S in the row is significantly greater than the supply rate of S in the inter-row (probability level = 0.05).

high supply rate followed by a decline in supply rate over time. This linear relationship would exist if soil conditions were ideal for mineralization of fertilizer and if plants and microorganisms immobilized the P and S following the flux of nutrients from fertilization (Havlin et al., 1999). Rapid supply rates of P and S were not expected because the inter-row AEMs were placed further away from the fertilizer than the row AEM. The varying supply rates would occur as microscale soil processes in the vicinity of the inter-row AEM caused P and S to be mineralized and immobilized.

The general absence of a linear relationship between supply rates of P and S in the row over time indicate soil conditions may have restricted the supply of P and S from fertilizers. In 2001 and 2002, the supply rate of P over time reflected no consistent pattern. The supply rate of P over time is represented in Figure 1.14 and Figure 1.15 by graphs of the P supply rate at the Sherman site in 2001 and 2002, respectively. Though the graphs show data from the Sherman site, the data are representative of the other sites because all sites had similarly variable supply rates of P. At each site the supply rate of SO_4 in 2002 was rapid following fertilization and declined over time as expected, but in 2001 the supply rate was variable across sites. The supply rate of S over time at the Sherman site in 2001 (Fig. 1.16) and 2002 (Fig. 1.17) was representative of all other sites.

In soil with water content near field capacity and temperature between 20 to 40 °C, sulfur moves to the root via mass flow while P is transported to the root by diffusion (Barber, 1962). Consequently S generally moves further through the soil than P. The distance of SO_4 diffusion is approximately 1 cm in soil with water content at field capacity (Havlin et al., 1999). In soil with 19% water content, Khasawneh et al. (1974) demonstrated diammonium orthophosphate (DAP), triammonium pyrophosphate (TPP),

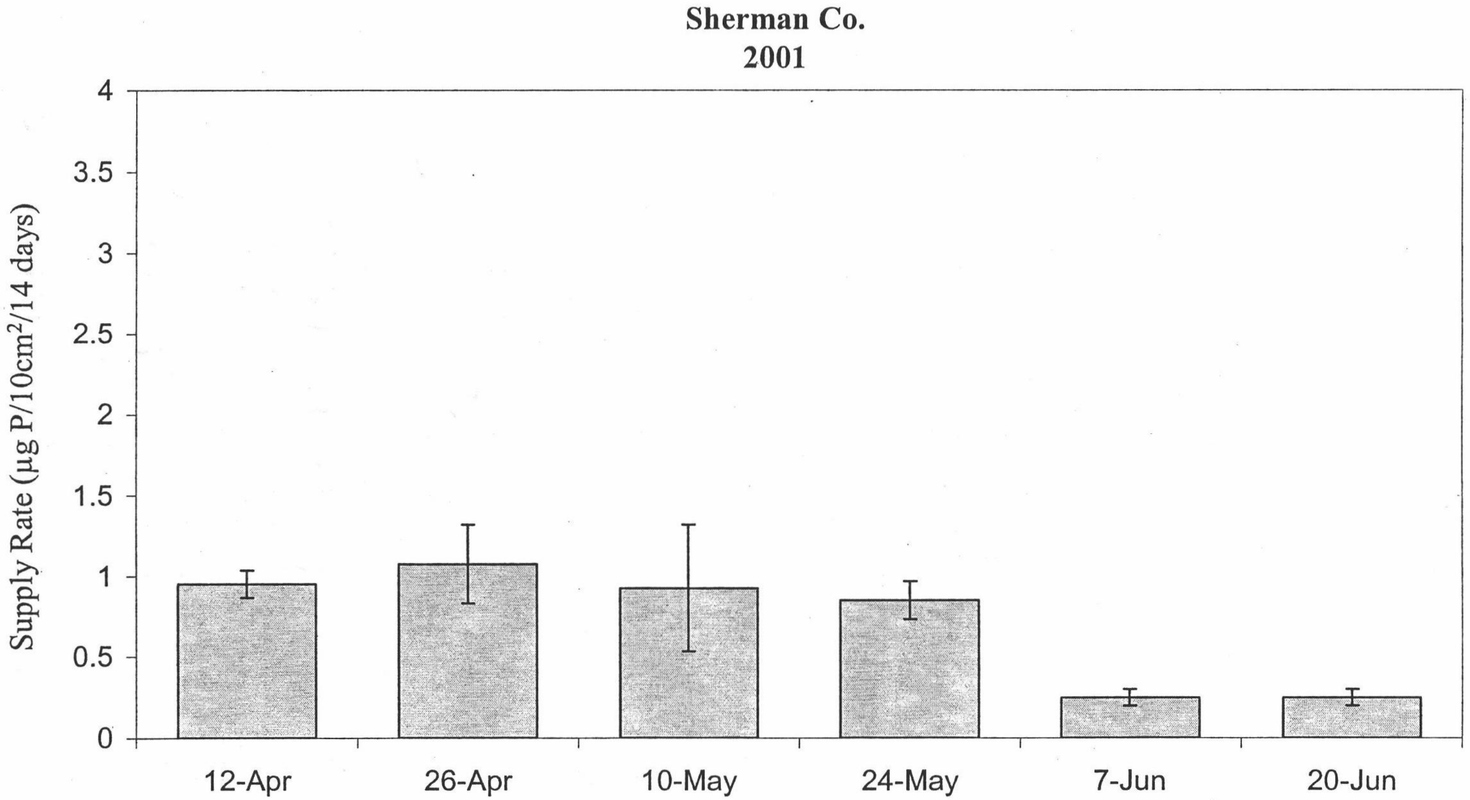


Fig. 2.14 Supply rate of P from row AEM at each 14 day exchange at the Sherman site in 2001. The supply rate of P was significantly different over time ($p<0.0001$), however, the relationship between P supply rate and time was not linear (p-value for $F_L = <0.0001$). F_L is a test of the hypothesis that a linear regression model describes the relationship between supply rate of P and time. A significant F_L indicates a significant lack of fit between supply rate and time.

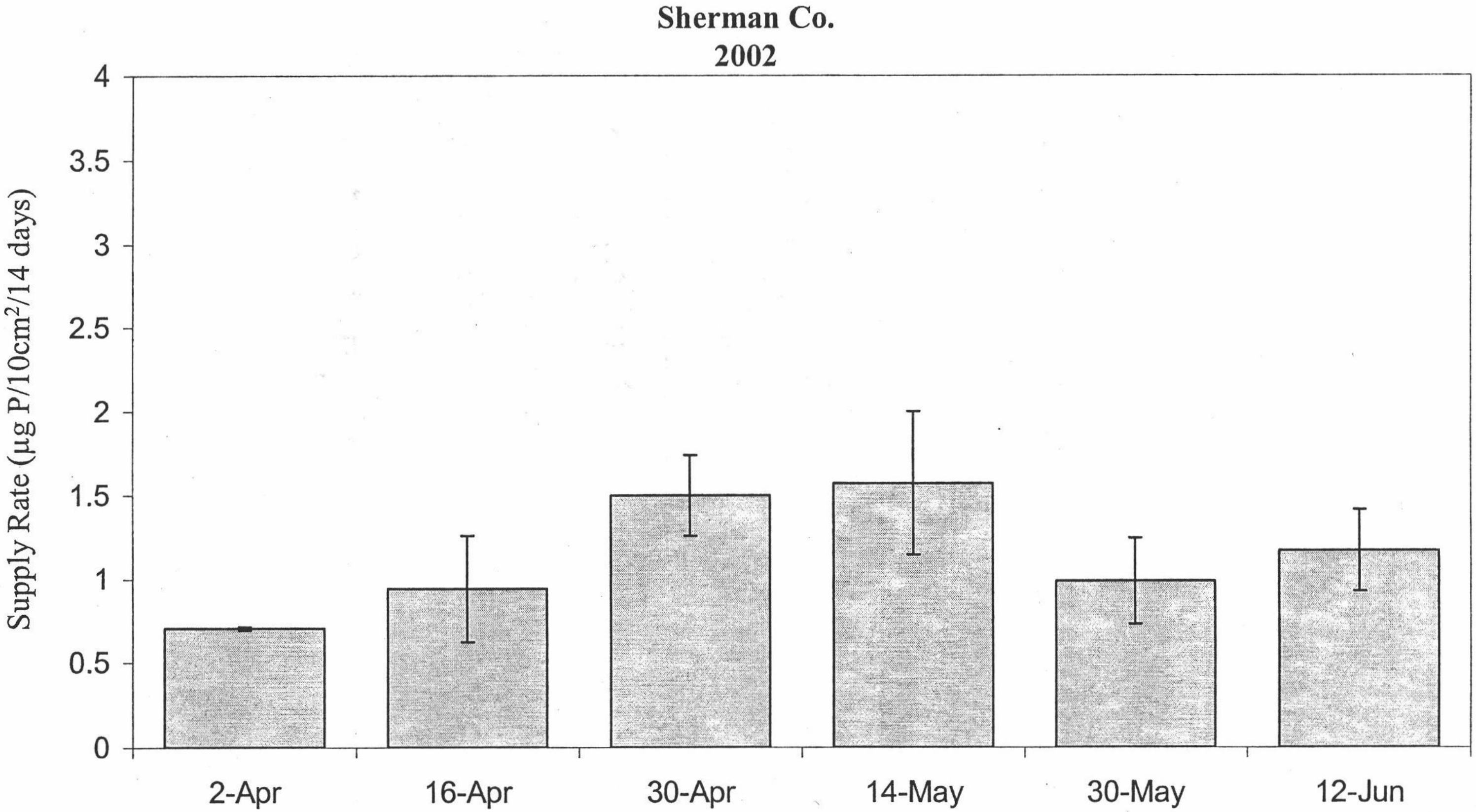


Fig. 2.15 Supply rate of P from row AEM at each 14 day exchange at the Sherman site in 2002. The supply rate of P was significantly different over time ($p<0.0001$), however, the relationship between P supply rate and time was not linear (p-value for $F_L = <0.0001$). F_L is a test of the hypothesis that a linear regression model describes the relationship between supply rate of P and time. A significant F_L indicates a significant lack of fit between supply rate and time.

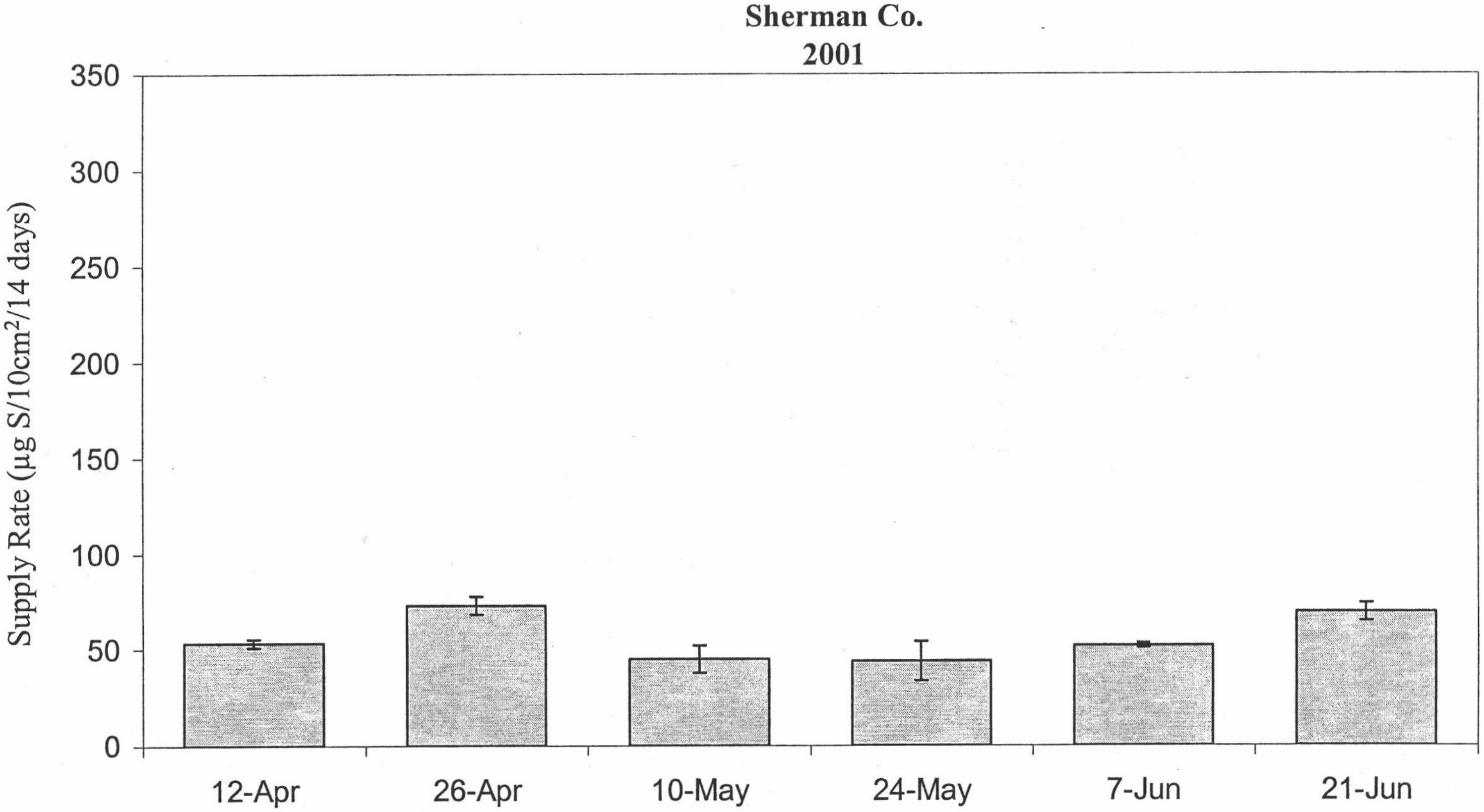


Fig. 2.16 Supply rate of S from row AEM at each 14 day exchange at the Sherman site in 2001. The supply rate of S was significantly different over time ($p<0.0001$), however, the relationship between S supply rate and time was not linear (p-value for $F_L = <0.0001$). F_L is a test of the hypothesis that a linear regression model describes the relationship between supply rate of S and time. A significant F_L indicates a significant lack of fit between supply rate and time.

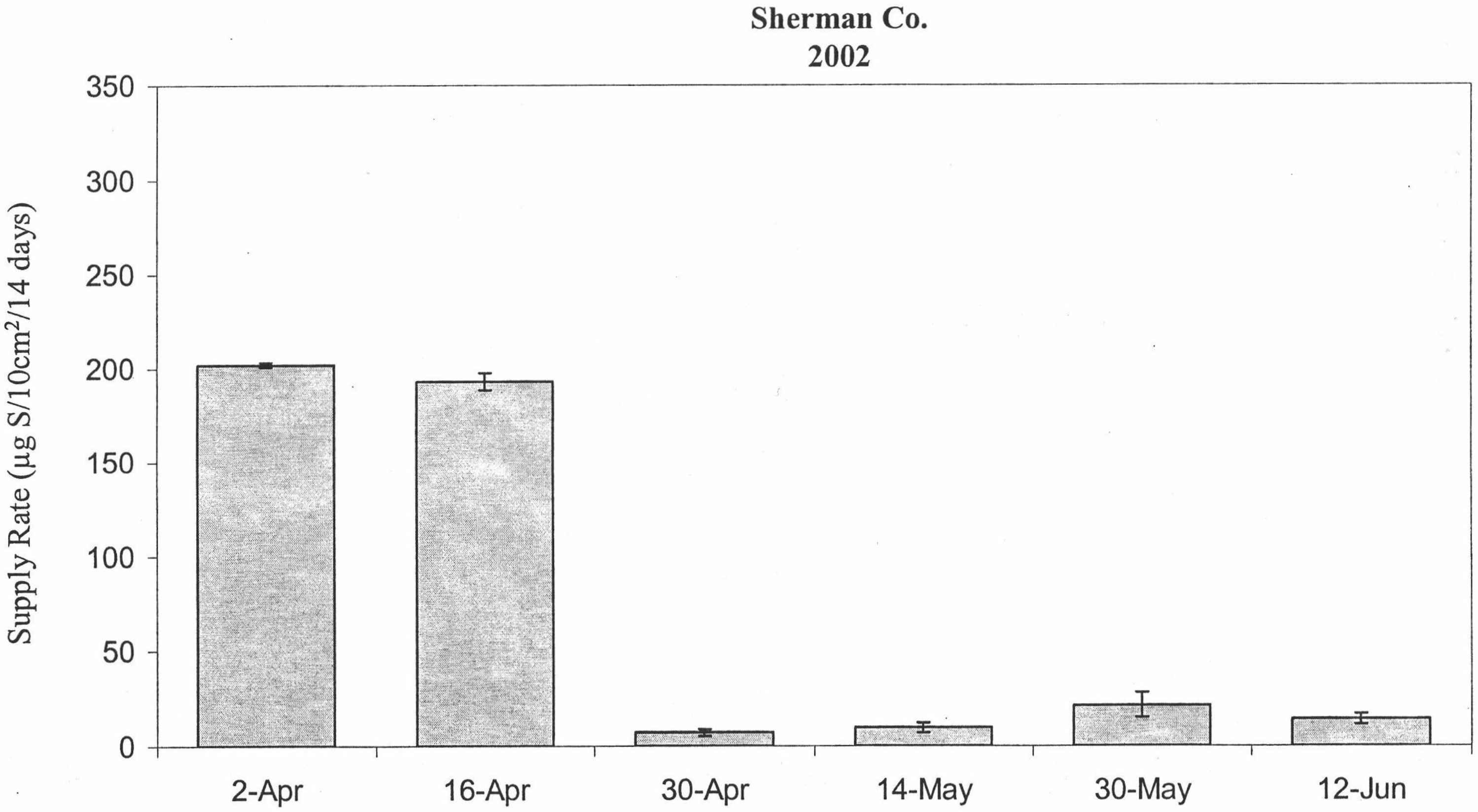


Fig. 2.17 Supply rate of S from row AEM at each 14 day exchange at the Sherman site in 2002. The supply rate of S was significantly different over time ($p<0.0001$), however, the relationship between S supply rate and time was not linear (p-value for $F_L = <0.0001$). F_L is a test of the hypothesis that a linear regression model describes the relationship between supply rate of S and time. A significant F_L indicates a significant lack of fit between supply rate and time.

and ammonium polyphosphate (APP) diffused 3, 13, and 8 mm from the application site, respectively.

In 2001, low soil water content likely limited the mineralization and subsequent diffusion of P and S to such an extent that even AEM in the row did not receive diffusion of P and S from the fertilizer. Slightly greater soil water content in 2002 may have been adequate for mineralization of S fertilizer and subsequent mass flow to the AEM, but was below a critical level for rapid P supply.

AEM buried in close proximity to a root system, may suffer from root competition for nutrients (Pare et al., 1995; Western Ag Innovations, Inc., 2001). Western Ag Innovations, Inc., the company responsible for the design and analysis of AEM extractions used in the present study, suggest burying the AEM in root exclusion cylinders. The root exclusion cylinder is PVC pipe (suggested 10 cm diameter) pounded into the soil and into which the AEM are buried and plants are removed. Though I chose not to use root exclusion cylinders in this study, I do not believe competition from plant roots for P and S in this study was a major factor in AEM values. The cumulative supply rate of P and S from the inter-row AEM seemed to closely resemble that of the row nutrients (Fig 1.9 – Fig. 1.13). If wheat roots were out-competing the AEM for P and S, the supply curves for row AEM would rapidly decrease while inter-row supply curves increased or maintained over time.

Due to possible environmental constraints negatively affecting the ability of the AEM to measure plant available nutrients, soil water content and temperature data should be considered when interpreting AEM supply rate measurements. Short-term, one hour to 3 day *in situ* burials in which the soil is artificially moistened upon AEM placement may be a more valuable use of AEM than long-term burials (Searle, 1988; Schoenau and Huang, 1991; Qian and Schoenau, 2002). While cumulative uptake curves could not be produced from one-hour burials, the use of AEMs provides other benefits. One-hour burials may be valuable because of the ability of a single AEM to adsorb multiple anion species and because AEM are simple-to-use field soil test.

2.5 CONCLUSION

Dry soil and cool soil temperatures common in the dryland, minimum tillage systems in NC Oregon, are not conducive to *in situ* use of AEM. Though previous studies have shown strong correlation between the supply rate of nutrients measured by AEM and plant uptake, these studies have either been conducted under ideal conditions in the lab or in fields where soil water content and temperature do not limit diffusion of nutrient ions. Anion exchange membranes cannot simulate uptake of P and S by plants in soils with limited water content and cool temperature because they cannot grow through the soil and therefore cannot intercept nutrients as plant roots can. Nor can AEM create the water potential gradient that is critical for mass flow of S as living plant roots can. Thus, AEMs are restricted in their ability to measure plant available nutrients in less than ideal environmental conditions.

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CHAPTER 3.

Drought Effects on Soil Phosphorus and Sulfur In Dryland Agriculture

3.1 ABSTRACT

Anion exchange membranes (AEM) and tissue samples from the five-leaf growth stage of hard red spring (HRS) wheat were used to aid in the understanding of phosphate (P) and sulfate (S) dynamics in a dryland farming system. Three consecutive years of drought resulted in sufficient residual soil P and S to supply the wheat crop with P and S to meet maximum yield requirements at four sites for two years. Low soil water content and cool soil temperatures are common in north central Oregon and these environmental conditions slowed the mineralization and diffusion of P and S from subsurface banded fertilizers in this study. These results suggest young HRS wheat plants in north central Oregon may not be accessing P and S early in the growing season as is necessary to reach maximum yield potential. Further research is needed to identify efficient P and S fertilization practices in conservation tillage, annually cropped, dryland farming systems. The objectives of this study were to 1) determine HRS wheat growth and yield response to P and S in a dryland, annually cropped, minimum till system and to 2) explore the use of PRS Probes to aid in understanding of P and S dynamics of spring wheat in early growth stages.

3.2 INTRODUCTION

Growers in the dryland region of north central (NC) Oregon are turning from conventional farming methods to an annual crop, conservation tillage system as soil erosion causes increasingly lower soil productivity. Conventional farming involves a winter wheat (*Triticum aestivum*) - fallow cycle in which several tillage operations are used to prepare the seedbed and control weeds (Jennings et al., 1990). The successive tillage operations and lack of plant cover increase erosion rates in the hilly and windy region of NC Oregon's dryland agriculture. In contrast to conventional tillage, conservation tillage is a minimal soil disturbance tillage system that leaves 30% or more residue cover on the soil surface (ERS/USDA, 1997). Less tillage coupled with greater plant cover and increased soil organic matter content decrease erosion rates in conservation tillage systems (PNW, 1999).

Higher levels of residue cover in conservation tillage fields increase soil moisture content. The residue reflects solar radiation as well as slows evaporation of moisture from the soil (AAFRD, 1999). By storing more water in the soil, dryland growers are able to produce consecutive wheat crops (PNW Extension, 1999). Unfortunately, solar reflection restricts the ability of solar radiation to warm the soil (AAFRD, 1999).

The potential yield from annual crop production in NC Oregon is often dampened by delayed root access of fertilizer in cool soil (Klepper et al., 1983; Rasmussen, 1996). To offset delayed access to nutrients, fertilizers are banded near the seed so that growing seminal roots tap the fertilizer band (Klepper et al., 1983). Banding phosphate (P) containing fertilizer is particularly important because P is immobile. Spring wheat yields in conservation tillage systems increase when P-containing fertilizers are banded at planting (Klepper et al., 1983).

Soil water also affects spring wheat response to P. In semi-arid soil conditions in eastern Montana, with 28.0 to 50.4 kg of $NaHCO_3$-soluble P per hectare, Power et al. (1961) reported an approximate 2.47 kg per hectare spring wheat yield increase with every 2.5 cm of additional soil moisture. Power et al. (1961) caution that 12.7 cm of available soil water at seeding is required to gain an economic yield response to P when the soil Olsen-P test is between 28 to 50 kg P/ha.

The extent to which cool soil and limited soil water influence the supply rate of P is important in determining potential spring wheat yield response to P fertilizer. By monitoring the supply of P from fertilizers and measuring plant uptake of P in dryland, conservation tillage systems efficient P fertilizer recommendations can be made to combat the yield loss in NC Oregon.

Sulfur also plays a role in dryland wheat production in NC Oregon. In annually-cropped wheat fields in NC Oregon, yield is increased by sulfate (S) fertilization (Rasmussen, 1996). Awareness of wheat response to sulfur in the dryland region, has caused growers to routinely apply 12 to 20 kg S/ha when they perceive an S deficiency. Residual S availability is common in NC Oregon because annual precipitation is usually less than 400 mm (Rasmussen, 1996). In fact, Rasmussen and Kresge (1986) report 10 to 20 kg S/ha can supply sufficient S for two consecutive wheat crops in regions receiving less than 400 mm mean annual precipitation. Despite the greater need for S fertilization in annual cropped wheat fields, several consecutive years of drought, as have been experienced in NC Oregon from 1999 to 2002, may have allowed residual S to accumulate.

In order to determine the growth response of HRS wheat to P and S fertilization in minimumally tilled, annually-cropped wheat in years of drought, we measured wheat uptake of P and S at the five-leaf growth stage. To address the effects of fertilizer treatments on P and S supply, we used anion exchange membranes (AEM) in the field to measure the rate of P and S supply during two seasons of drought in minimum tillage systems. The objectives of this study were 1) to determine the effect of P and S fertilizer treatments on HRS wheat growth, 2) to determine fertilizer treatment effects on P availability, and 3) to determine fertilizer treatment effects on S availability.

3.3 METHODS

3.3.1 Site location and soil

Field experiments were conducted at four sites in NC Oregon on land that has been managed in conservation tillage for two to five years. Two of the sites were on Oregon State University agriculture experiment stations at the Columbia Basin Agriculture Research Center (CBARC) near Pendleton, Oregon (Umatilla County) and at the in Sherman County Experiment Station at Moro, Oregon (Sherman County). The remaining sites were in farmers' fields in Gilliam, Morrow and Wasco Counties, Oregon. The Umatilla, Sherman, and Wasco sites remained in the same location for both years while the Gilliam and Morrow sites were used respectively in 2001 and 2002.

Soils at the Umatilla, Sherman, and Morrow sites are Walla Walla silt loams classified as coarse-silty, mixed, superactive, mesic Typic Haploxerolls. The site in Morrow County is a Morrow silt loam classified as a fine-silty, mixed, superactive, mesic Calcic Argixeroll. All soils are of loessial origin. The long-term mean annual precipitation for these sites is as follows: 265 mm in Gilliam, 305 mm in Morrow, 290 mm in Sherman, 420 mm in Umatilla, and 339 mm in Wasco.

3.3.2 Experimental design and treatments

Experimental design was a split plot design with four replications. Five fertilizer treatments comprised the main plots while the placement of four PRS™ Probes per plot comprised the subplots. To ensure nitrogen (N) was not yield limiting each fertilizer treatment at the Morrow, Sherman, and Wasco sites received the equivalent of 84 kg N/ha while treatments at the Umatilla site received the equivalent of 112 kg N/ha. P and S were applied at rates equal to the minimum amount for a yield response at each site. The fertilizer treatments were: 1) no fertilizer , 2) N applied as urea at the rate of 112 kg/ha, 3) S plus N (S applied at the rate of 47 kg S/ha as 21-0-0-24 with 102 kg/ha of urea for N), P plus N (P applied at the rate of 43 kg P/ha as 11-52-0 with 108 kg/ha of urea for N, and a combination of S plus P plus N applied at the rate of 80 kg S/ha of 16-20-0-14 with 13 kg P/ha of 11-52-0 and 98 kg/ha of urea.

Hard red spring wheat (var. 936R) was direct-seeded on March 23, 2001 with a Fabro drill at the Umatilla site and on March 28 at the Morrow, Sherman, and Wasco sites. In 2002, the Sherman site was seeded on March 19, Wasco on March 20, Morrow on March 26, and Umatilla on March 27. Seeding depth at all sites was approximately 2.5 cm with a band of fertilizer placed 7.6 cm deep and 2.5 cm to the side of the seed. Seeding rate was 25 seeds/30.5 cm^2 in 30.5 cm wide rows. Individual plots were 2.44 by 9.15 m.

3.3.3 Anion exchange membranes

Anion exchange membranes (AEM) treated with $NaHCO_3$ were used to measure soil nutrient flux (Western Ag Innovations, Inc Saskatoon, SK, Canada). Western Ag Innovations, Inc markets AEM as Plant Root Simulator™ (PRS) Probes. PRS™ probes were inserted into the soil within 24 hours of planting. Four PRS™ Probes per plot were inserted 15 cm into slots in the soil in a pattern consistent across plots and sites. Of the four probes, two PRS™ Probes per plot were placed in the row of wheat and two PRS™ Probes per plot were placed between rows (inter-row). The PRS™ probes were exchanged every two weeks by removing the "old" PRS™ Probe and inserting a "fresh" PRS™ Probe into the same soil slot. In 2001, the PRS™ Probes at the Umatilla and Wasco sites were not reinserted into the same slots, i.e. they were placed in a new slot slightly ahead of the previous slot. Data from these counties were not used. PRS™ Probes were placed into zip-locking bags and transported on ice to a refrigerator for storage until cleaning.

The PRS™ Probes were scrubbed clean of all adhering soil under running deionized water. After cleaning, the PRS™ Probes were shipped to Western Ag Innovations for analysis. Western Ag Innovations elutes the PRS™ probes with 0.5N HCl. Phosphate and sulfate in the eluate were measured via Inductively Coupled Plasma (ICP).

3.3.4 Soil measurements

Two Optic Stowaway temperature probes (Onset Computer Corporation) at each site were used to continuously measure soil temperature from seeding through harvest. In 2001, 15-cm deep soil cores were taken every two weeks at the time of PRS™ Probe exchange to determine gravimetric water content. In 2002, soil water content to 15 cm depth was determined at each PRS™ exchange in Morrow and Umatilla Counties with a Campbell Scientific Water Content Reflectometer. Soil water content at Sherman and Wasco Counties in 2002 was measured as in 2001.

Following harvest, two soil cores per plot at each site were sampled to a depth of 1.22 m with a tractor-mounted soil probe. The soil cores were separated into 30.5 cm depths at the time of sampling. The two samples per plot were combined in the field and soil was dried for 24 hours at 60 °C then ground in a Thomas-Wiley soil grinder and sent to Agri-Check for nitric acid digestion and standard soil testing. Olsen-P (NaH_2CO_3) content was measured on 1.25 gram samples from each plot by colorimetric analysis on a Cole-Palmer 100 RS series Spectrometer at 644 nm (Page, 1982). Sulfur from each sample was extracted with DTPA and analyzed via atomic emission on a Perkin-Elmer ICP Emission Spectrometer Optima 3000 DV (Page, 1982).

3.3.5 Plant sampling

A one-meter length of wheat row was sampled at the five-leaf and soft dough stages and at harvest from each plot across sites. Samples were bundled and transported on ice and stored in a refrigerator until time of plant growth staging. A subsample of 15 plants in 2001 and ten in 2002 was taken from the one-meter row bundle for plant growth staging as described by Klepper et al. (1982). Plant samples were ground using a Thomas-Wiley plant grinder after being oven dried for 24 hours at 60 °C. Ground plant samples were sent to Agri-Check, Inc. of Umatilla, OR for nitric acid digestion and analyses. Sulfate and P were analyzed on a Perkin-Elmer ICP Emission Spectrometer Optima 3000 DV. Samples were prepared and analyzed by Agri-Check as stated above.

In 2001, harvest in Sherman and Wasco Counties took place on July 25 and on July 26 in Morrow and Umatilla Counties. In 2002, Sherman and Wasco Counties were harvested on July 23, Morrow Co. on July 30, and Umatilla Co. on July 31. The wheat was harvested with a plot-sized combine. Grain protein analysis was conducted by Pendleton Flour Mills. Water content was determined after drying one gram samples of grain in a 130 °C oven for 60 minutes. Nitrogen in the grain was analyzed using a LECO Autoanalyzer.

3.3.6 Statistical analyses

Analysis of variance (ANOVA) was used to test the significance of differences among fertilizer treatments, AEM placements, date of AEM exchanges, and subsequent two-way and three-way interactions on the supply rate of P and S adsorbed to the AEM (SAS Systems version 7). Following this ANOVA, analysis of the relationship between the supply rate of P and S over time was conducted by determining whether the relationship fit a linear equation. This regression in ANOVA was accomplished by partitioning the treatment sum of squares into 1) the sum of squares for the linear regression of supply rate on time and 2) the sum of squares for the failure of the linear regression model to describe the relationship between supply rate and time (Peterson, 1994). A significant F ratio for the failure of linear regression to describe the relationship between supply rate and time indicates a linear model does not describe the relationship. A more complex model, i.e. a quadratic equation, was not tested to describe the relationship between supply rate and time because such a model was not consistent with the hypothesis of a linear decrease in the supply rate of P and S over time. ANOVA was also used to test the significance of differences among fertilizer treatment means on plant biomass, yield, and percent protein. Orthogonal contrasts were used to answer specific questions of interest following significant p-values of 0.05 or less from ANOVA (Peterson, 1994). The questions addressed by the orthogonal contrasts (when the ANOVA produced significant p-values of 0.05 or less) were: 1) Is there a main effect of the S treatment?, 2) Is there a main effect of the P treatment?, and 3) Is there an interaction of S + P? (Peterson, 1994). The correlation values (R^2) for the regression of the supply rate of P or S (μg/10cm^2/14 days) on uptake of P or S (mg/meter row) were obtained in JMP (SAS Institute, Inc. version 4.0.0).

3.4 RESULTS AND DISCUSSION

3.4.1 Climatic conditions and plant stress

Mean annual precipitation in 2001 and 2002 was below the long-term average at each site with the exception of Morrow Co. in 2001 (Table 3.1). Throughout the growing season in 2001, gravimetric soil water content ranged from 2 to 17 % across the Morrow, Sherman, and Wasco sites (Table 3.2). In 2002, gravimetric soil water content ranged from 8 to 16% across the Morrow, Sherman, Umatilla, and Wasco sites (Table 3.2). The Umatilla site generally receives more precipitation per year than Morrow, Sherman, and Wasco sites which was reflected in 2001 by approximately 9% greater gravimetric soil moisture content than other sites. Soil temperature in both years remained below 20 °C until mid-May and did not rise above 30 °C during the time the AEM were employed (Fig. 3.1).

In addition to drought conditions and low soil temperature, the Wasco and Umatilla sites were infested with Hessian fly (*Mayetiola destructor*). Of the wheat plants sampled at the five-leaf growing stage, Wasco showed 23% infestation in 2001 and 2002, respectively. Umatilla showed 59% and 58% infestation in 2001 and 2002, respectively (A.Redman, unpublished data).

Plants at all sites across both years exhibited symptoms of stress including missing tillers and low grain yields. The Umatilla site in 2001 is the only site where treatment effects produced significantly different grain yields (p-value 0.0011) (Table 3.3).

Table 3.1 Monthly and total precipitation (mm) throughout 2001 and 2002 crop seasons.

Site	Crop Season	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Total	Long-Term Average
Umatilla Co.	2000-2001	63.5	58.7	36.6	20.6	33.5	21.1	39.1	50.8	12.4	38.1	15.0	0.5	389.9	419.9
	2001-2002	9.4	47.0	47.0	29.2	35.3	30.5	35.8	27.3	25.6	34.8	6.1	0.7	328.7	
Gilliam Co.	2000-2001	15.7	61.5	24.4	16.3	24.6	17.5	27.9	56.9	14.5	40.6	10.4	5.8	316.2	265.2
Morrow Co.	2001-2002	10.2	34.8	28.4	22.1	9.9	13.7	12.2	34.8	23.4	40.9	8.6	0.8	239.8	
Sherman Co.	2000-2001	7.6	35.3	15.2	8.9	10.9	13.5	20.6	18.0	8.6	12.7	0.5	5.8	157.7	290.8
	2001-2002	13.5	26.2	51.3	29.7	17.3	16.5	10.7	9.7	16.8	21.6	1.0	0.0	214.1	
Wasco Co.	2000-2001	21.8	20.3	20.8	20.1	25.4	25.1	22.4	24.4	1.3	17.8	5.8	7.4	212.6	339.6
	2001-2002	14.2	26.9	66.8	47.5	22.9	27.2	10.4	11.4	21.8	14.5	6.9	0.3	270.8	

Table 3.2 Gravimetric soil water content (%) for each site. Missing numbers are indicated by "mn".

Year	Date	Gilliam Co.	Sherman Co.	Umatilla Co.	Wasco Co.
2001	19-Apr	mn	mn	mn	11.9
	17-May	mn	mn	17.2	7.5
	25-May	mn	7.6	mn	mn
	1-Jun	mn	mn	13.3	5.1
	15-Jun	mn	mn	11.4	2.3
	21-Jun	3.8	3.4	mn	mn
	9-Jul	15.7	15.7	mn	16.5
		Morrow Co.			
2002	20-Mar	14.4	16.1	26.7	15.4
	2-Apr	17.6	14.7	32.7	13.8
	17-Apr	24.0	14.5	27.4	13.5
	30-Apr	19.9	13.5	22.8	12.5
	16-May	11.4	11.4	17.5	10.4
	30-May	5.4	9.9	7.8	8.3
	13-Jun	22.4	8.5	15.7	7.8

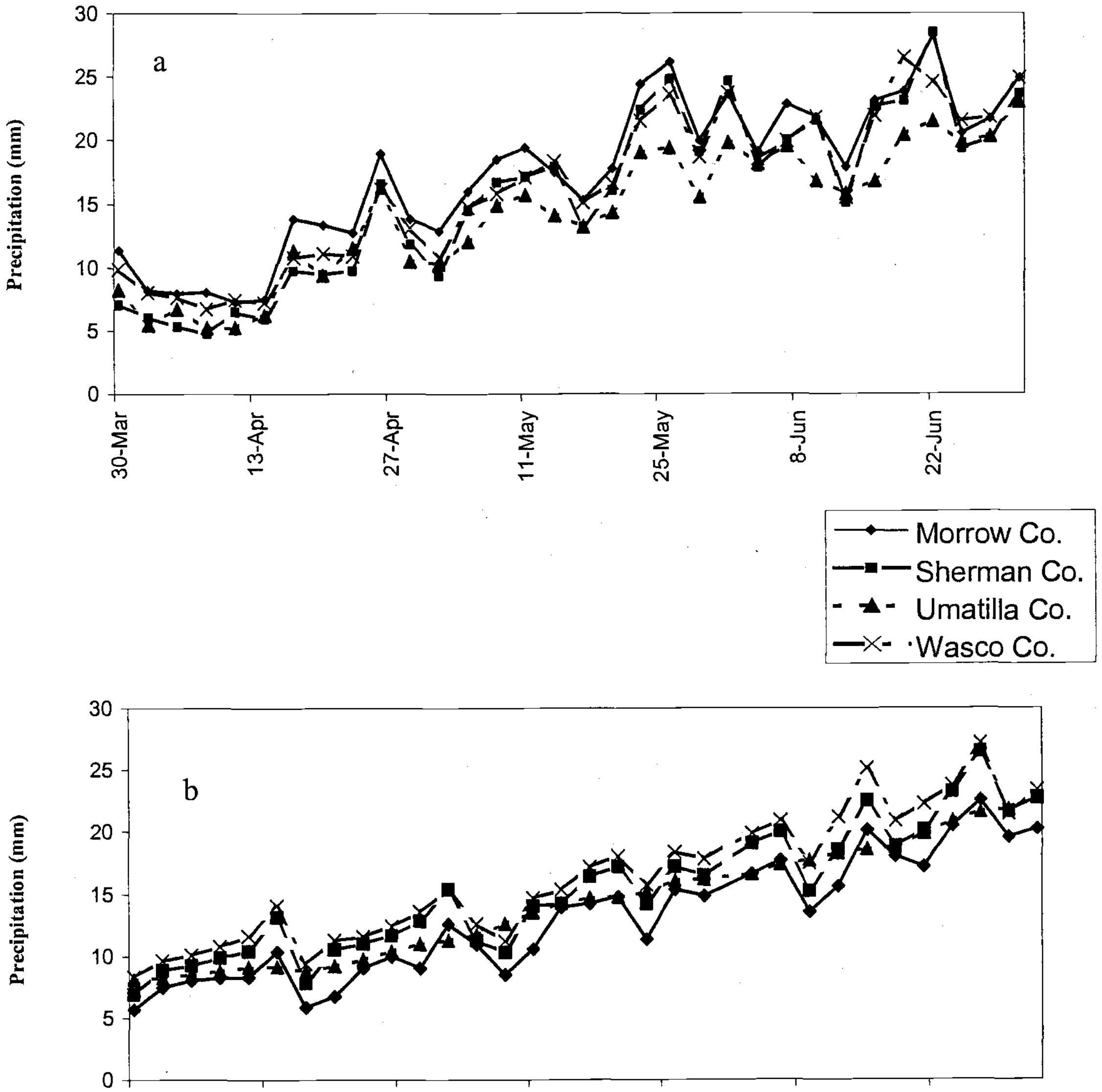


Figure 3.1 Overall trend of soil temperature across sites from seeding through the last AEM exchange in 2001 (a) and 2002 (b).

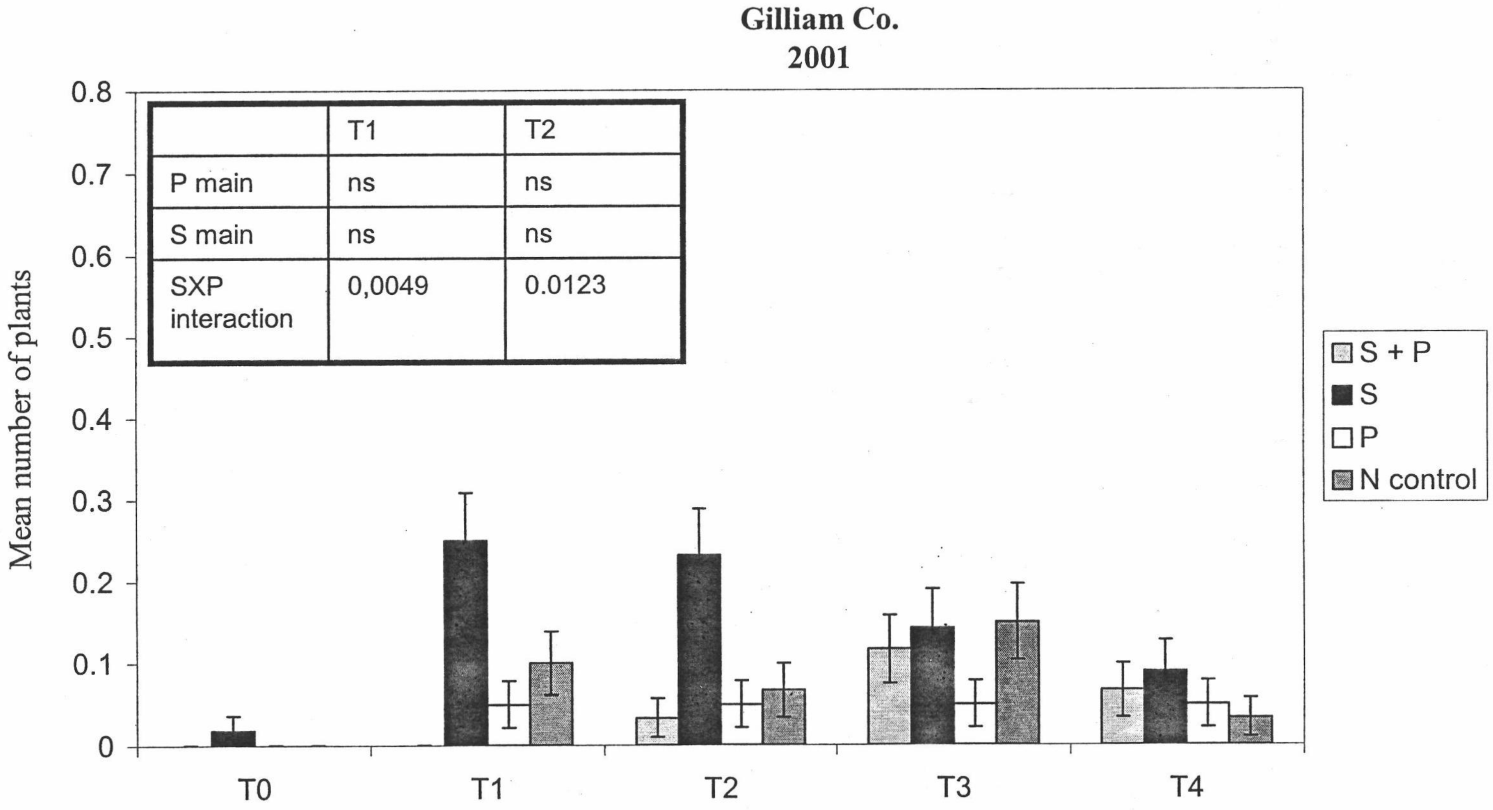
Table 3.3 Mean yield (kg/ha) across treatments in 2001 and 2002. Treatments: P + S = 80 kg/ha 16-20-0-14 and 13 kg/ha 11-52-0 and 98 kg/ha urea, S = 47 kg/ha 21-0-0-14 and 102 kg/ha urea, P = 43 kg P/ha 11-52-0 and 108 kg/ha urea. *Significant at the 0.01 probability level.

Year	Site	Treatment	Yield (kg/ha)	SE	Year	Site	Treatment	Yield (kg/ha)	SE
2001	Gilliam Co.	S + P	936.3	102.5	2002	Morrow Co.	S + P	984.4	24.4
		S	890.9	84.3			S	933.7	22.7
		P	958.1	48.1			P	939.9	50.5
		N control	815.5	61.8			N control	906.5	21.3
2001	Sherman Co.	S + P	1348.2	151.4	2002	Sherman Co.	S + P	895.7	48.5
		S	1533.4	277.7			S	786.1	34.7
		P	776.5	89.6			P	965.0	66.5
		N control	989.2	125.7			N control	905.0	69.4
2001	Umatilla Co.*	S + P	2059.3**a**	136.4	2002	Umatilla Co.	S + P	1473.2	27.6
		S	1262.8**b**	114.9			S	1560.3	45.1
		P	1927.1**a**	112.5			P	1216.0	119.1
		N control	1473.3**b**	252.4			N control	1568.7	116.9
2001	Wasco Co.	S + P	253.2	6.1	2002	Wasco Co.	S + P	1829.6	57.2
		S	279.5	8.0			S	1665.7	68.3
		P	227.0	76.3			P	1556.6	126.4
		N control	266.9	35.6			N control	1690.6	142.4

Fertilizer treatments had few significant effects on the mean number of plants with the coleoptilar tiller (T0), tiller 1 (T1), tiller 2 (T2), tiller 3 (T3), or tiller 4 (T4) present. When significant treatment effects existed, however, the differences between the numbers of wheat plants with the indicated tiller were large.

In general, the number of wheat plants that produced T1 and T2 tillers were most often significantly affected by the different treatments. At the Gilliam site in 2001, the mean number of wheat plants with T1 and T2 from the S + P interaction produced 150% and 211%, respectively, less tillers than the S main effect and P main effect treatments (p-value 0.0049 and 0.0123, respectively) (Fig. 3.2). In 2002, wheat plants from the S + P interaction at the Sherman site produced 84% fewer T1 than plants in the S main effect or P main effect treatments (p-value 0.0003) (Fig. 3.3). The only significant S + P treatment effect on the number of plants producing the T0 tiller occurred at the Umatilla site in 2001. The S + P interaction at the Umatilla site in 2001 caused 11% fewer wheat plants to produce T0 than the mean of the S main effect and P main effect treatments (p-value 0.0135) (Fig. 3.4).

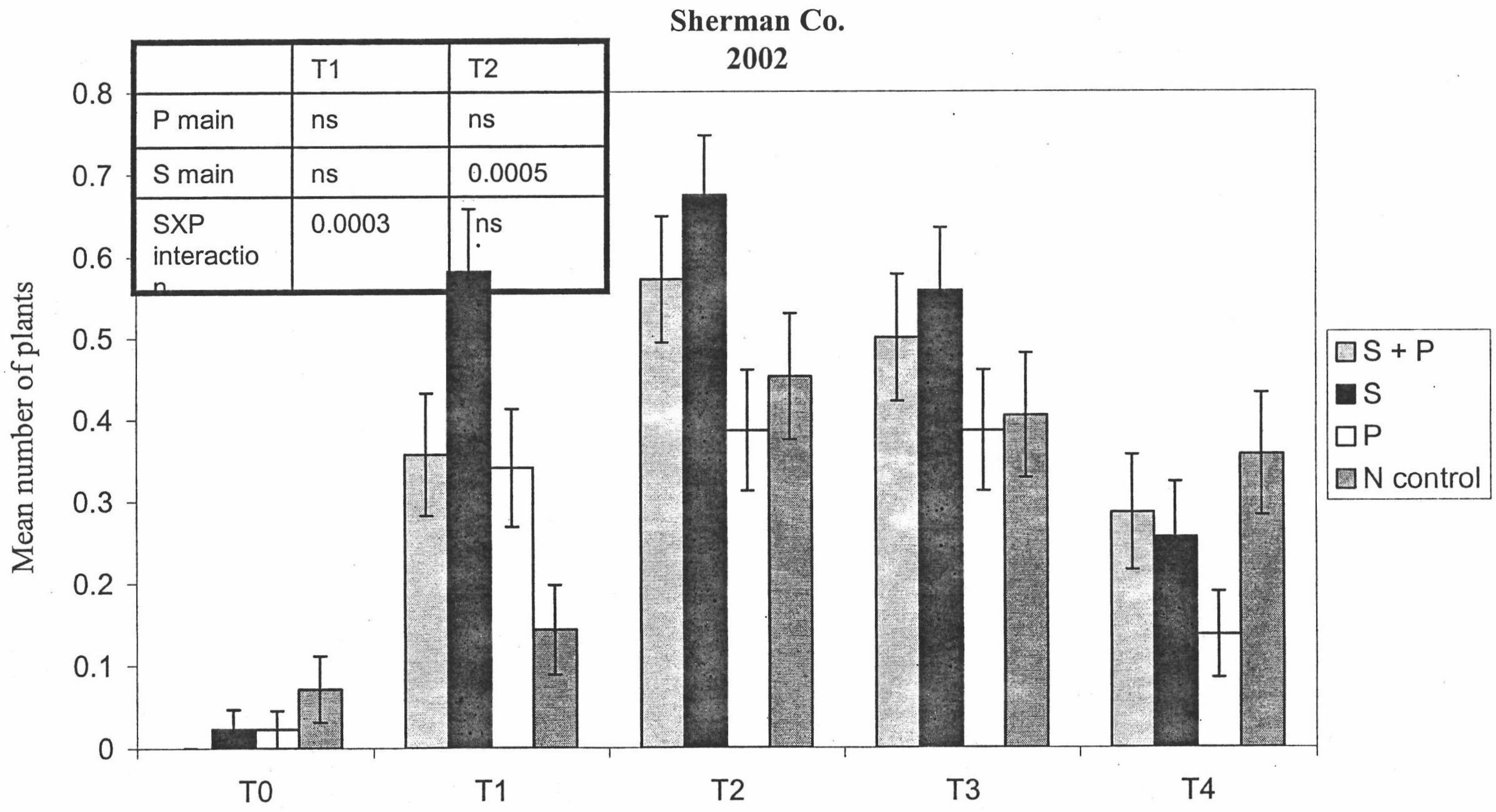
The S treatment and the P treatment also produced differences in the number of plants producing T1 and T2 tillers. At the Wasco site in 2001, the S main effect caused 222% more wheat plants to produce T2 than the mean of the P main effect (p-value 0.0013) (Fig. 3.5). The main effect of S also caused more plants to produce T2 (p-value 0.0005) at the Sherman site (Fig. 3.3) and T1 (p-value 0.0039), T2 (p-value 0.001), and T3 (p-value 0.0012) at the Umatilla site (Fig. 3.6) than the P main effect in 2002. At the Morrow site in 2002, the S main effect and the P main effect caused between 172% and 213% more wheat plants to produce T1 and T2 tillers than the mean of the S + P



Gilliam Co.
2001

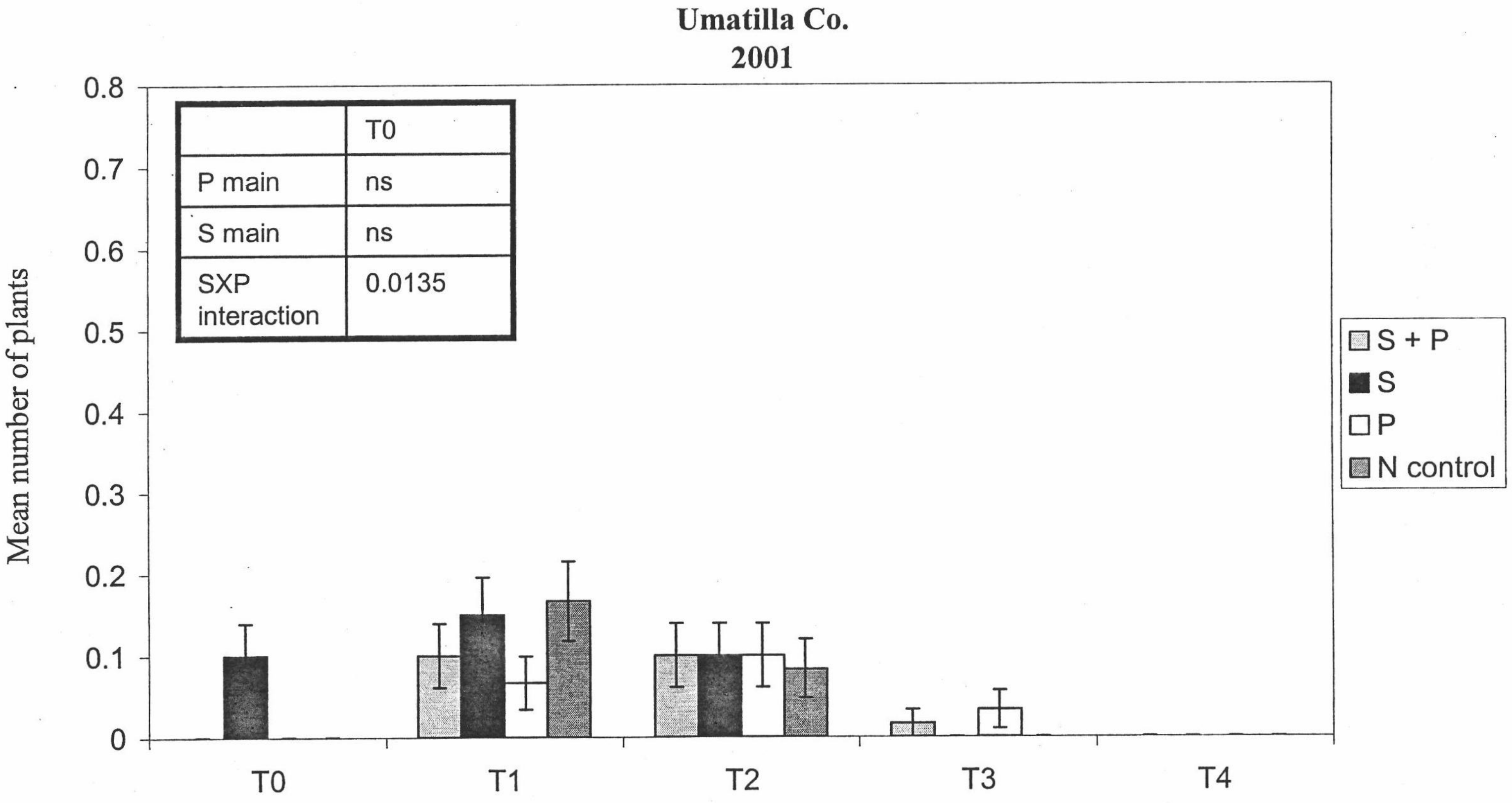
	T1	T2
P main	ns	ns
S main	ns	ns
SXP interaction	0,0049	0.0123

Fig. 3.2 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Gilliam site in 2001. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. The table indicates whether the P main effect, S main effect, or S X P interaction is significant (probability level = 0.05).


Sherman Co.
2002

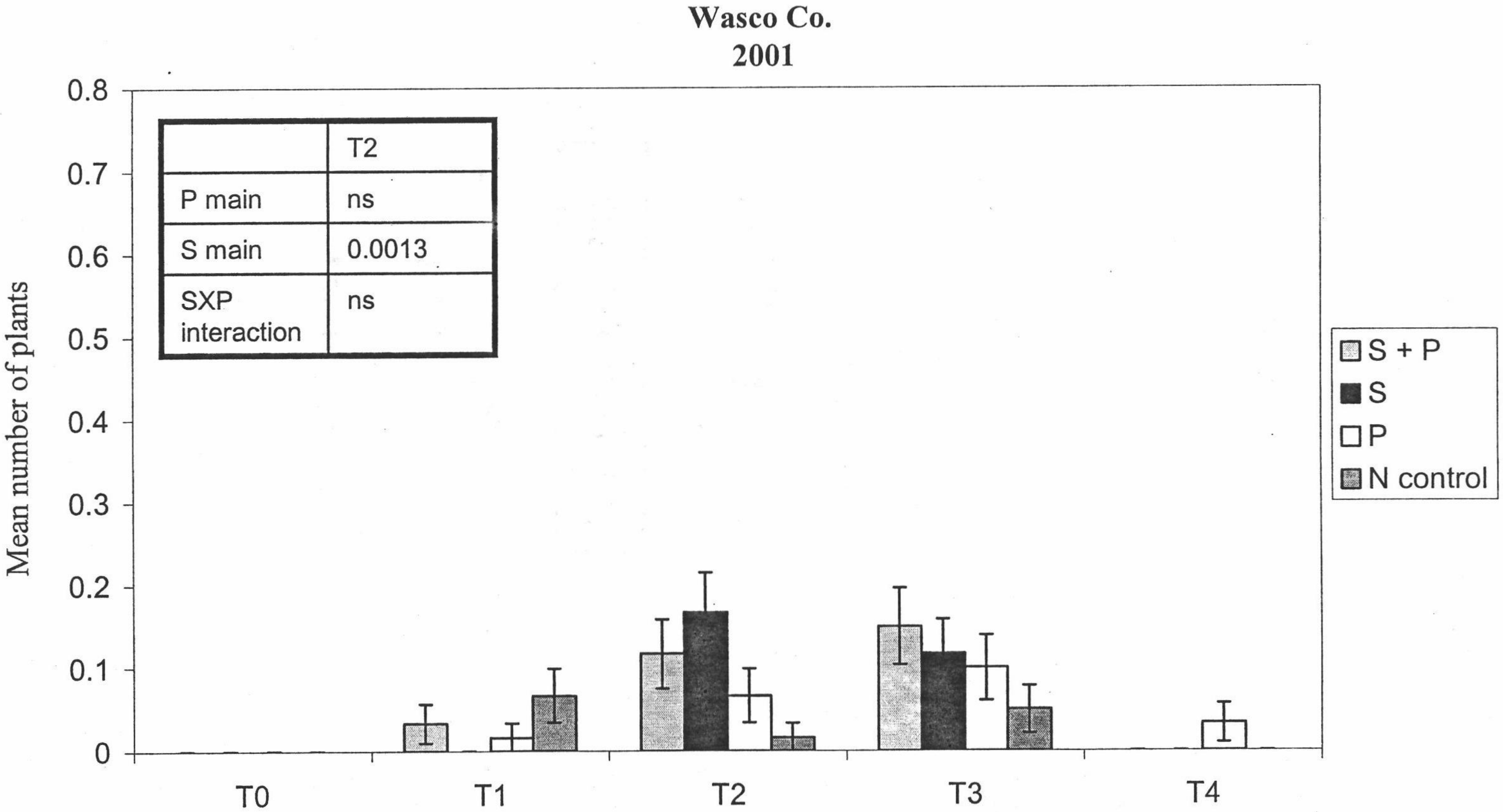
	T1	T2
P main	ns	ns
S main	ns	0.0005
SXP interactio n	0.0003	ns

Fig. 3.3 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Sherman site in 2002. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. The table indicates whether the P main effect, S main effect or S X P interaction is significant (probability level = 0.05).



	T0
P main	ns
S main	ns
SXP interaction	0.0135

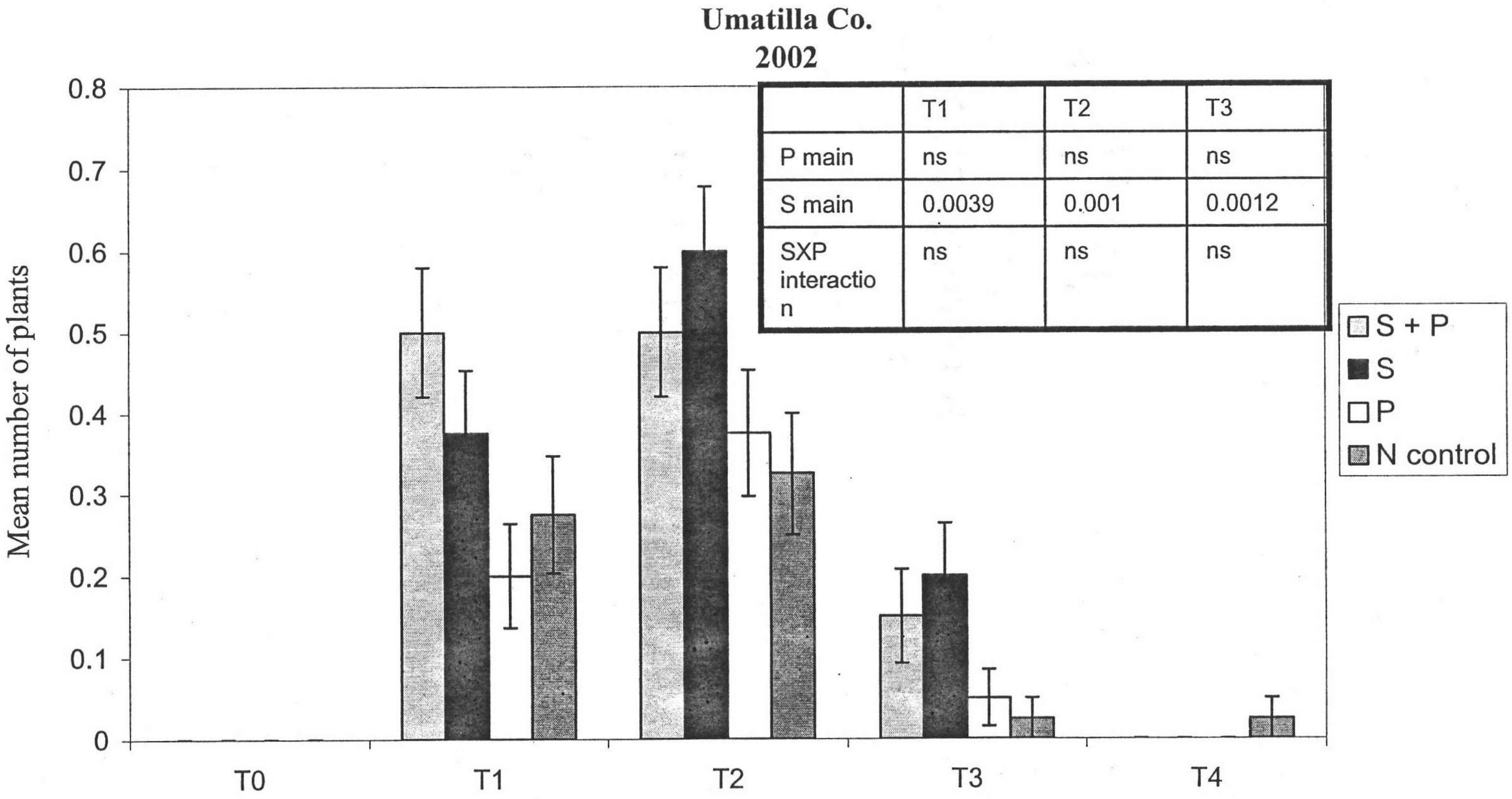
Fig. 3.4 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Umatilla site in 2001. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. The table indicates whether the P main effect, S main effect or S X P interaction is significant (probability level = 0.05).



Wasco Co.
2001

	T2
P main	ns
S main	0.0013
SXP interaction	ns

Fig. 3.5 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Wasco site in 2001. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. The table indicates whether the P main effect, S main effect, or S X P interaction is significant (probability level = 0.05).


Umatilla Co.
2002

	T1	T2	T3
P main	ns	ns	ns
S main	0.0039	0.001	0.0012
SXP interactio n	ns	ns	ns

Fig. 3.6 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Umatilla site in 2002. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. Within each group of tillers, different letters indicate significant treatment effects at $p \leq 0.05$. The table indicates whether the P main effect, S main effect or S X P interaction are significant (probability level = 0.05).

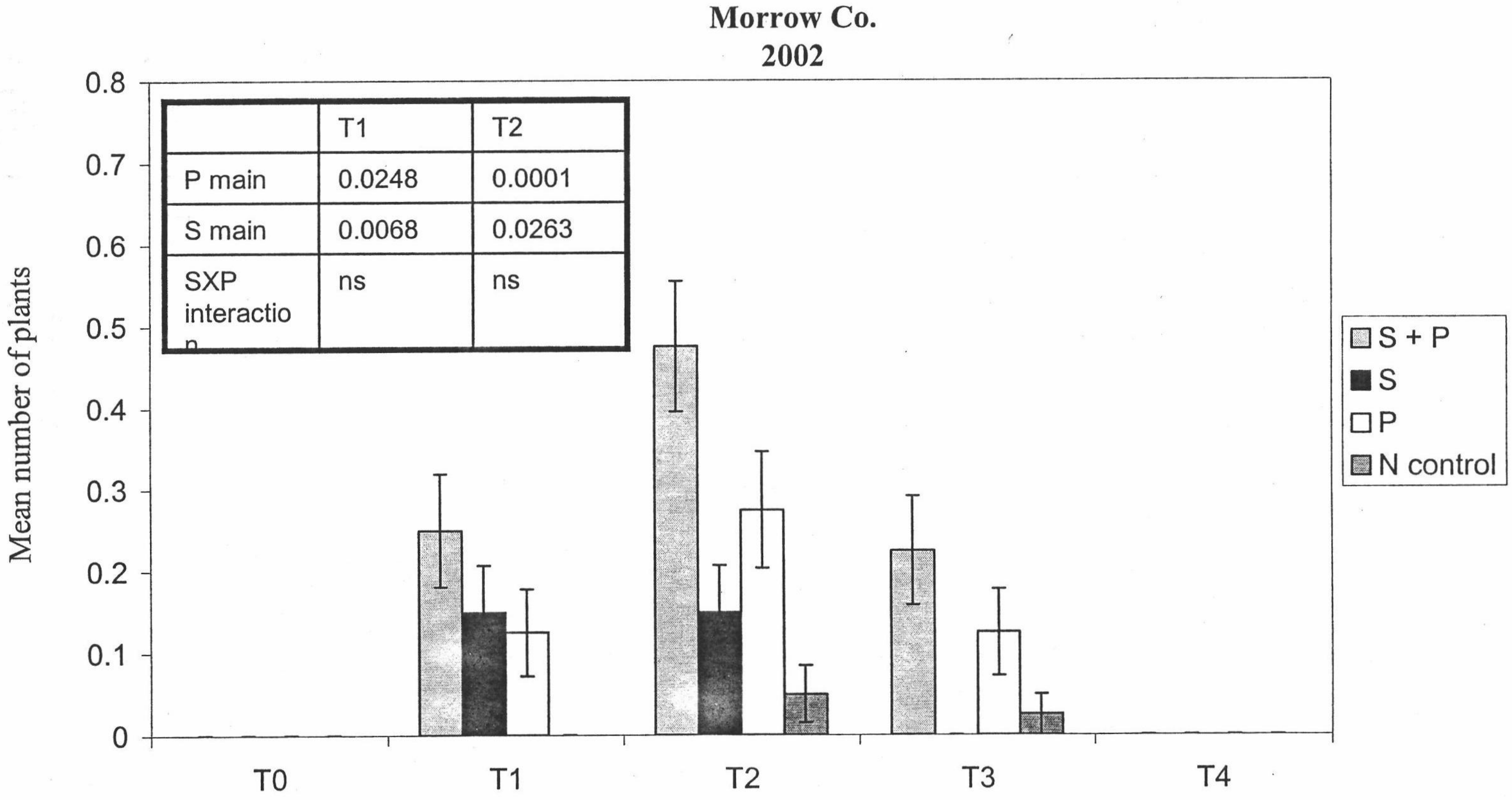
interaction (p-values ranged between 0.0001 and 0.0263) (Fig. 3.7). Although the treatment effects on the mean number of plants with T0, T1, T2, T3 or T4 were large, they did not occur across sites or in each tiller group in 2001 or 2002. Therefore, it is likely the low number of plants with tillers are a symptom of a stressful growing environment and are not necessarily the result of fertilizer treatments.

The absence of specific tillers can be used to determine when the plant was stressed (Huan, 1973; Karow et al.., 1993). Spring wheat grown in NC Oregon does not usually produce T0 because the soil remains cool for the first few weeks following planting. However spring wheat in NC Oregon usually does produce T1-T4. The overall lower percentage of tillers numbers 1 - 4 in 2001 as compared to 2002 (Fig. 3.2 - Fig. 3.7) may be a result of the lower gravimetric soil water content in 2001 than in 2002.

3.4.2 Drought affects wheat response to P and S

Wheat tissue concentration of P and S was optimum for maximum yield potential in 2001 and 2002 across sites regardless of fertilizer treatment. At the five-leaf stage, spring wheat tissue concentration of P ranged from 0.20 ppm to 0.37 ppm and S ranged from 0.14 ppm to 0.49 ppm (Table 3.4). Tissue concentration met sufficiency recommendations for optimum growth regardless of fertilizer treatment; the sufficiency range for spring wheat is 0.20 ppm to 0.50 ppm and 0.15 ppm to 0.40 ppm for P and S, respectively (Havlin et al., 1999).

Wheat plants occasionally responded to the P treatment by having higher concentrations of P in their tissue as a result of fertilization (Table 3.4). In 2001, the tissue concentration of P increased in response to the P treatment only at the Wasco site;



	T1	T2
P main	0.0248	0.0001
S main	0.0068	0.0263
SXP interaction	ns	ns

Fig. 3.7 The effect of P and S fertilizer treatments on the mean number of plants with the indicated tiller, i.e. T0, T1, T2, T3 or T4, at the Morrow site in 2002. Fifteen plants were sampled from each plot and the presence or absence of each tiller per plant was recorded. The table indicates whether the P main effect, S main effect, or S X P interaction is significant (probability level = 0.05).

Table 3.4 Tissue concentration (ppm) of P and S at the five leaf growth stage of HRS wheat. Different letters within a column by site and by year indicate significant fertilizer treatment effects on the tissue concentration of S or P (probability level = 0.05). Treatments: P + S = 80 kg/ha 16-20-0-14 and 13 kg/ha 11-52-0 and 98 kg/ha urea, S = 47 kg/ha 21-0-0-14 and 102 kg/ha urea, P = 43 kg P/ha 11-52-0 and 108 kg/ha urea.

		2001				**2002**			
Site	Treatment	P	SE	S	SE	P	SE	S	SE
Gilliam Co.	S + P	0.25	0.02	0.31	0.01	0.37**a**	0.03	0.49**c**	0.02
	S	0.25	0.01	0.32	0.01	0.26**b**	0.01	0.39**b**	0.03
	P	0.23	0.01	0.3	0.01	0.41**a**	0.01	0.41**a**	0.02
	N control	0.23	0.02	0.31	0.02	0.26**b**	0.01	0.38**ab**	0.02
Sherman Co.	S + P	0.35	0.02	0.22**a**	0.02	0.34**a**	0.01	0.30	0.01
	S	0.31	0.03	0.25**a**	0.02	0.28**b**	0.02	0.29	0.02
	P	0.37	0.01	0.14**b**	0.00	0.30**a**	0.02	0.28	0.02
	N control	0.35	0.01	0.17**b**	0.02	0.29**b**	0.03	0.31	0.02
Umatilla Co.	S + P	0.30	0.03	0.38**a**	0.02	0.23	0.01	0.26	0.03
	S	0.20	0.01	0.44**a**	0.02	0.20	0.01	0.23	0.00
	P	0.29	0.02	0.31**b**	0.01	0.21	0.00	0.18	0.01
	N control	0.28	0.04	0.32**b**	0.03	0.23	0.01	0.25	0.03
Wasco Co.	S + P	0.36**a**	0.01	0.31	0.03	0.30	0.04	0.23	0.01
	S	0.32**b**	0.01	0.33	0.02	0.28	0.01	0.27	0.02
	P	0.36**a**	0.02	0.33	0.04	0.29	0.02	0.24	0.02
	N control	0.30**b**	0.01	0.34	0.02	0.29	0.01	0.25	0.02

the mean tissue concentration of P from the P and S + P treatments was 16% greater than mean tissue P from wheat in the S and control treatments (p-value 0.0032). Wheat also responded to P at the Sherman site and Morrow site in 2002. At the Morrow site, the mean tissue concentration of P was 50% greater in wheat from the P and P + S treatments than from mean tissue concentration of P from wheat in the S and control treatments (p-value <0.0001). Mean tissue concentration of P in wheat from the Sherman site, was 11% greater from the P and S + P treatments than from wheat in the S and control treatments (p-value 0.05).

Wheat response to S generally resulted in a greater increase in tissue S concentration than the responses gained from P fertilization. Wheat at the Sherman and Umatilla sites in 2001 responded to S fertilization. Mean tissue concentration of S in plants was 52% and 30% greater from the S and S + P treatments than from the mean of tissue S in plants from the P and control treatments at the Sherman (p-value 0.0011) and Umatilla (p-value 0.0005) sites, respectively (Table 3.4). At the Morrow site in 2002, the mean concentration of S in the wheat tissue was enhanced by P fertilization and by S fertilization, but not by the interaction of the two nutrients. The mean tissue concentration of S from wheat in the P and S + P treatments was 17% greater than the mean tissue concentration of S from wheat in the S and control plots (p-value <0.0063) (Table 3.4). On the other hand, the mean tissue concentration of S from wheat in the S and S + P treatments was 11% greater than the mean tissue concentration of S from wheat in the P and control treatments (p-value 0.0383). Due to the main effects of S and P on the concentration of S in wheat tissue rather than the interaction of S and P, it is likely N was limiting the growth of wheat at the Morrow site in 2002.

The nitrogen to sulfur (N/S) ratio at the five-leaf stage, an indicator of balanced N and S in plants, was also in the optimum range for maximum grain yield potential across sites with the exception of the Sherman site in 2001 (Table 3.5). An N/S ratio of 17 at tillering (when the mainstem has approximately three to four leaves) indicates sufficient S for wheat grown in the dryland agriculture region of NC Oregon. An N/S value greater than 17 is indicative of S deficiency while a value less than 17 may indicate deficient N (Rasmussen, 1996).

In this study, wheat response to S was also assessed by analyzing the effects of the treatments on the N/S ratio in wheat tissue at the five-leaf stage. The N/S ratio at the Sherman site in 2001 ranged broadly from 15 to 33 (Table 3.5). Due to N/S ratios greater than 17 at this site, S was most likely limiting wheat growth. As further evidence of deficient S at the Sherman site in 2001, the mean N/S ratio in wheat tissue from the S and S + P treatments was 65% less than the mean N/S ratio from the P and S + P treatments (p-value 0.0002). The N/S ratio of wheat at the Umatilla site in 2001 also indicates a response to S despite an N/S ratio below 17. At the Umatilla site in 2001, the mean N/S ratio in wheat tissue from the S and S + P treatments was 28% less than the mean N/S ratio in wheat from the P and S + P treatments (p-value 0.0005). The only interaction of S and P as measured by the N/S ratio occurred in 2002 at the Morrow site. The N/S ratio at this site was 13% lower in wheat from the treatments with S + P than from the treatments in which S and P were applied separately (p-value 0.009).

Accumulation of residual P and S may account for sufficient tissue concentration of P and S in wheat grown from the unfertilized treatment. Drought over the past three years has lowered the average of wheat yields in NC Oregon with the subsequent effect

Table 3.5 Mean N/S ratios at the five-leaf growth stage for the S + P, S, P, and N control treatments in 2001 and 2002. Different letters within a row for each site and year indicate significant treatment effects (probability level = 0.05). Treatments: P + S = 80 kg/ha 16-20-0-14 and 13 kg/ha 11-52-0 and 98 kg/ha urea, S = 47 kg/ha 21-0-0-14 and 102 kg/ha urea, P = 43 kg P/ha 11-52-0 and 108 kg/ha urea.

Year	Site	S + P	S	P	N control
2001	Gilliam Co.	11.9	11.6	11.8	12.0
	Sherman Co.	20.6**ab**	15.6**a**	33.3**b**	26.4**c**
	Umatilla Co.	13.5**a**	11.2**a**	15.8**b**	15.9**b**
	Wasco Co.	12.2	12.3	12.7	11.8
2002	Morrow Co.	8.5**a**	11.2**b**	11.3**b**	11.4**a**
	Sherman Co.	12.4	12.6	12.2	13.3
	Umatilla Co.	11.8	12.7	15.1	14.0
	Wasco Co.	14.4	12.4	13.6	13.0

of removing fewer nutrients from the soil than in years with high yielding crops (Havlin et al., 1999). If fertilizer application is not reduced in accordance with limited precipitation, P and S will remain in the soil in excess of a crop's requirement. Therefore, in the wake of consecutive drought years, dryland growers in NC Oregon should test their soil before fertilizing for the current crop. Growers should consider annual precipitation predictions and fertilize with P and S accordingly.

3.4.3 Supply rate of P and S

The relationship between supply rate of P and S fertilizers and time was not consistently linear (Fig. 3.8 – Fig. 3.11). I expected AEM in the row to measure a rapid supply of P and S from the respective fertilizer treatments after addition to the soil. Ialso expected the supply rate to decline as wheat and soil microorganisms assimilated the nutrients (Brady and Weil, 1999). A decreasing supply rate over time could also be due to a diminished concentration gradient between the zone of soil influenced by the fertilizer band and the bulk soil (Barber, 1962; Khasawneh, 1974).

Other studies have demonstrated rapid supply rates from fertilizers. Nitrate supply rate was rapid following addition of legume and wheat straw amendments to moist soil in a humidified incubator at 40 °C (Subler et al., 1995). Similarly, the supply of N was relatively immediate following addition of manure and urea to soil growth chambers (Qian and Schoenau, 2000). Qian and Schoenau (2000) conducted their experiment at 25 °C during the day, 12 °C during the night and 80% of field capacity. In the present study, soil temperature was at least 20 °C cooler than the Subler et al. (1995) study and 5 °C cooler than the day temperature in the Qian and Schoenau (2000) study.

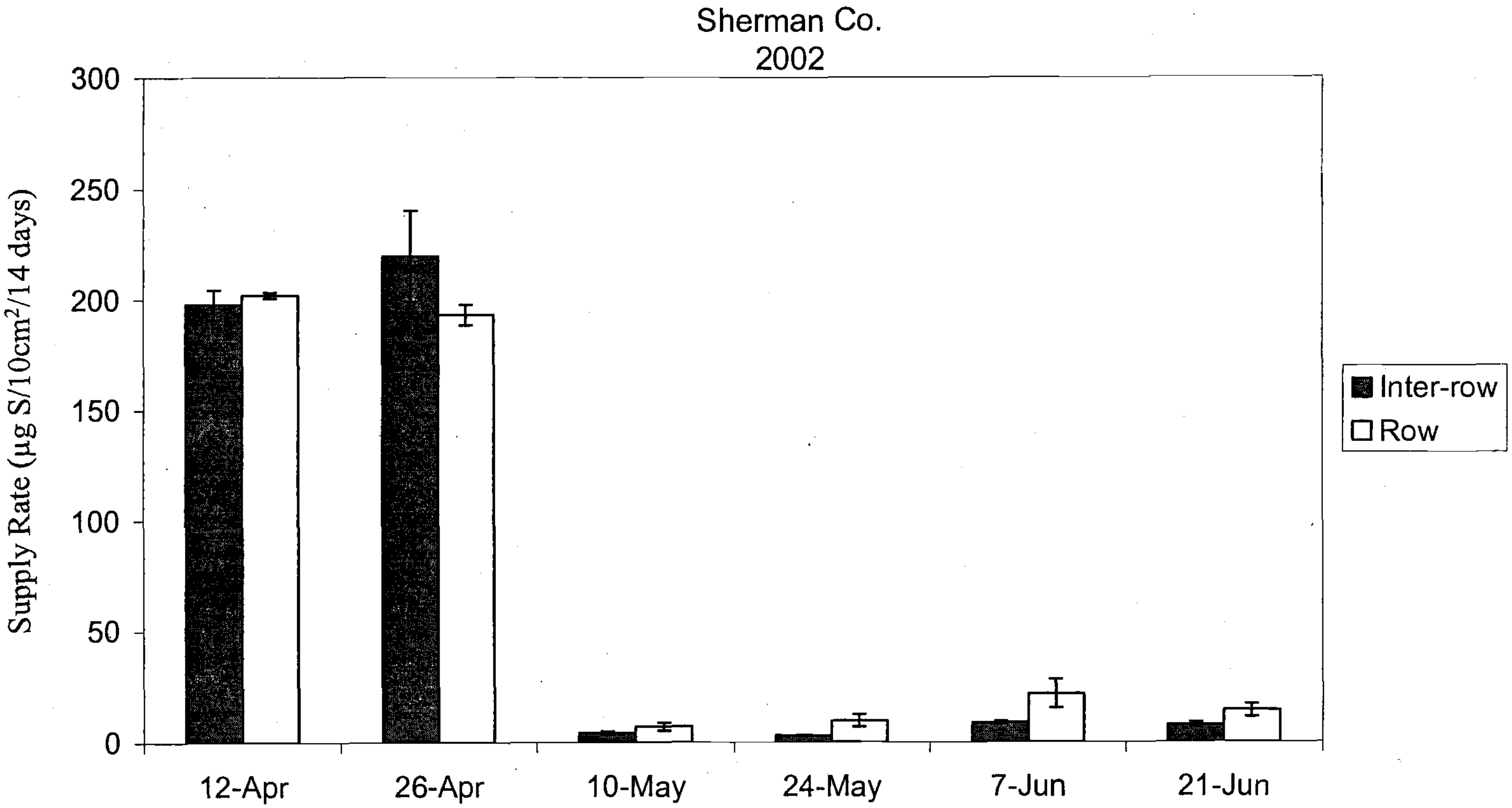


Fig. 3.8 Supply rate of S from row AEM at each 14 day exchange at the Sherman site in 2002. The supply rate of S was significantly different over time ($p < 0.0001$), however, the relationship between S supply rate and time was not linear (p-value for $F_L < 0.0001$). F_L is a test of the hypothesis that a linear regression model describes the relationship between supply rate of P and time. A significant F_L indicates a significant lack of fit between supply rate and time.

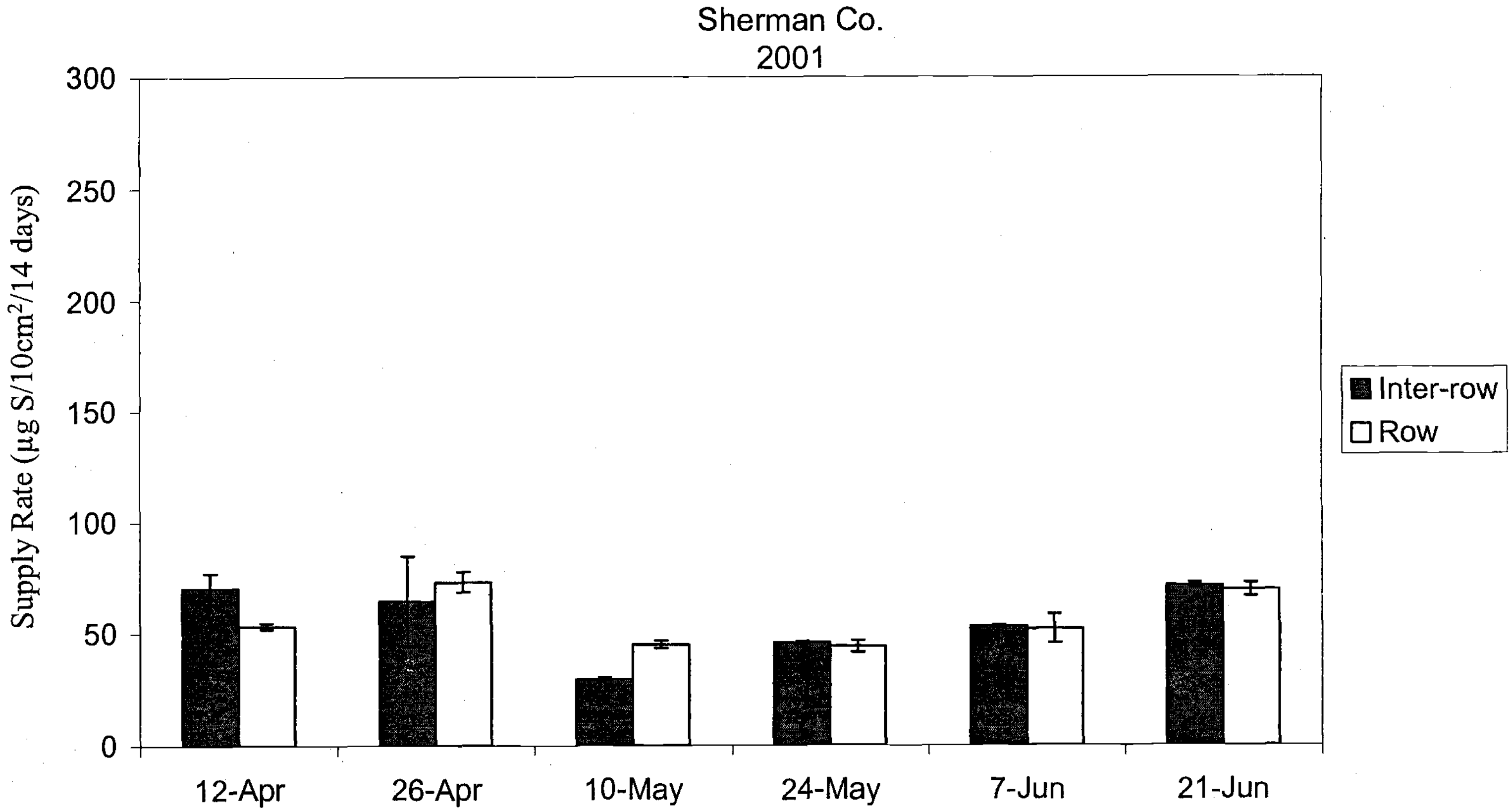


Fig. 3.9 Supply rate of S from row AEM at each 14 day exchange at the Sherman site in 2001. The supply rate of S was significantly different over time ($p < 0.0001$), however, the relationship between S supply rate and time was not linear (p-value for $F_L < 0.0001$). F_L is a test of the hypothesis that a linear regression model describes the relationship between supply rate of P and time. A significant F_L indicates a significant lack of fit between supply rate and time.

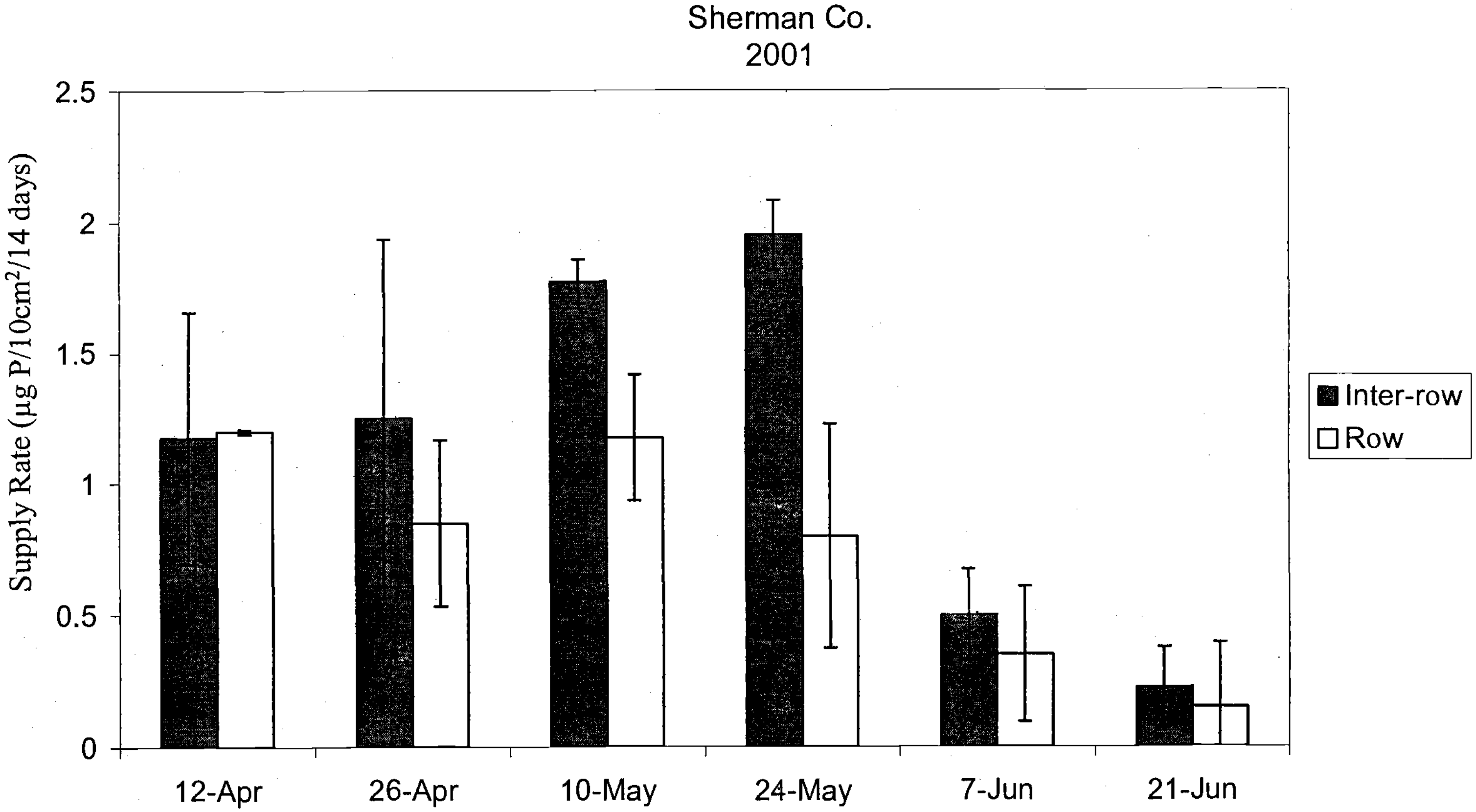


Fig. 3.10 Supply rate of P from row AEM at each 14 day exchange at the Sherman site in 2001. The supply rate of P was significantly different over time ($p < 0.0001$), however, the relationship between P supply rate and time was not linear (p-value for $F_L < 0.0001$). F_L is a test of the hypothesis that a linear regression model describes the relationship between supply rate of P and time. A significant F_L indicates a significant lack of fit between supply rate and time.

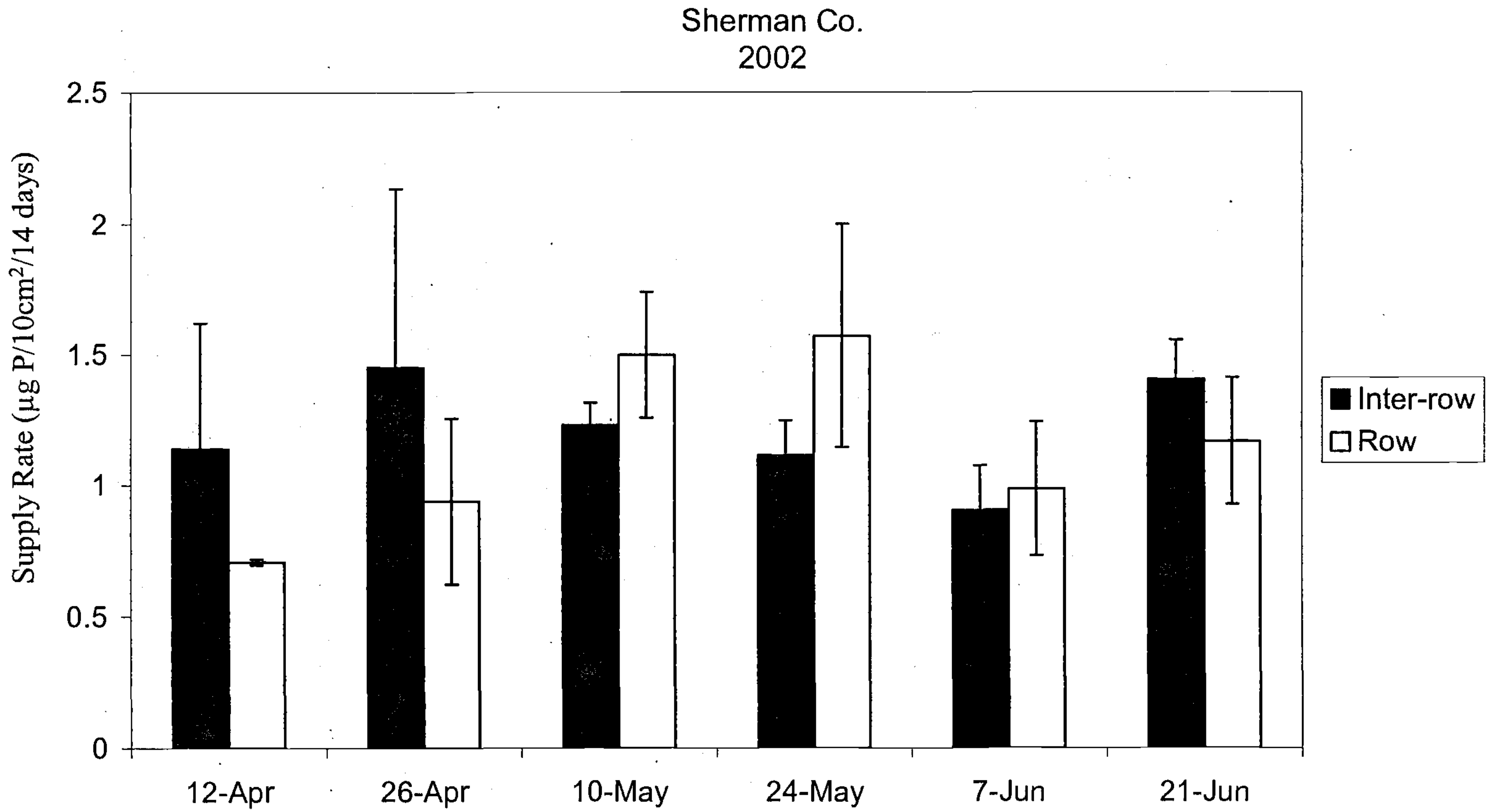


Fig. 3.11 Supply rate of P from row AEM at each 14 day exchange at the Sherman site in 2002. The supply rate of P was significantly different over time ($p < 0.0001$), however, the relationship between P supply rate and time was not linear (p-value for $F_L < 0.0001$). F_L is a test of the hypothesis that a linear regression model describes the relationship between supply rate of P and time. A significant F_L indicates a significant lack of fit between supply rate and time.

Soil moisture content in the present study was also lower than in the Subler et al. (1995) and Qian and Schoenau (2000) studies.

Field studies of fertilizer supply rates have also shown predictable responses in supply rate following synthetic and/or organic N fertilization (Pare et al., 1995; Jowkin and Schoenau, 1998; Ziadi et al. 1999). While Jowkin and Schoenau (1998) and Pare et al. (1995) generally observed a linear decline in supply rate of NO_3 over time, Ziadi et al. (1999) measured inconsistent supplies of NO_3 over time. Annual precipitation in the Ziadi et al. (1999) study was an average of 129.3 mm greater than average precipitation in the present study. Pare et al. (1995) did not report precipitation; however, the study was conducted in a fine-textured Typic Endoaquoll which indicates a higher water regime and a soil with higher water holding capacity than the Typic Haploxeroll of the present study.

The supply rate of S in 2002 was rapid following the addition of fertilizer (Fig. 3.8); however, this trend did not hold true for S in 2001(Fig. 3.9) nor for P in either year (Fig. 3.10 and Fig. 3.11). Precipitation in the winter months preceding the March planting in 2002 was 25 mm more on average across Morrow, Sherman, and Wasco sites than in 2001. It is possible this slight increase in precipitation at some sites resulted in a soil water content high enough for rapid mineralization of S whereas it was below a critical level for P mineralization. In 2001, soil water may have been insufficient for quick mineralization of either P or S. Soil microorganism activity is maximum between 20 to 40 °C and at soil moisture content near field capacity (-33kPa) (Havlin et al., 1999). In 2001 and 2002, soil temperatures were 10 °C at planting and remained below 20 °C for approximately 12 weeks (Fig. 3.1). Furthermore, soil water content declined below 11%

ten weeks after planting in both years. Thus, in soil with low water content and cool temperatures, such as the dryland region in NC Oregon, P and S banded at planting may not mineralize rapidly enough to encourage early HRS wheat growth in minimally tilled fields.

The cumulative supply rates of P and S may provide further insight into how low soil water content influences the supply rates of P and S over time. Cumulative supply rates of P in all P treatments were low and reached a plateau in 2001. The cumulative supply rate of P at the Sherman site in 2001 is representative of the other sites in 2001 (Fig. 3.12). In 2002, the cumulative supply rates of P were higher and continued to increase throughout the first 12 weeks following planting (Fig. 3.13). Again, the Sherman site in 2002 is representative of the other sites in 2002. In the lab AEMs reflect diffusion rates of nutrients influenced directly by soil moisture and indirectly by soil temperature (Barber, 1962; Skogley et al., 1990; Yang et al., 1991a). Phosphate moves through the soil by diffusion which might explain why lower soil moisture in 2001 than in 2002 caused the rate of P diffusion to be slower in 2001 than in 2002.

The cumulative supply rates of S were opposite from that of P in 2001 and 2002. In 2001, in which there was less mean annual precipitation, the cumulative supply rate of S was low, but continued to rise in the 12 weeks following planting (Fig. 3.14). The cumulative supply rates of S in 2002 were much higher than 2001, but leveled by April 16 in Sherman and Wasco and by April 24 in Morrow and Umatilla (Fig 3.15). In contrast to P, S is predominantly transported to the root by mass flow when soil moisture is adequate and sufficient quantities of S exist in the soil solution (Barber, 1962). In the drier soil of 2001, soil moisture may have been insufficient to transport S by mass flow;

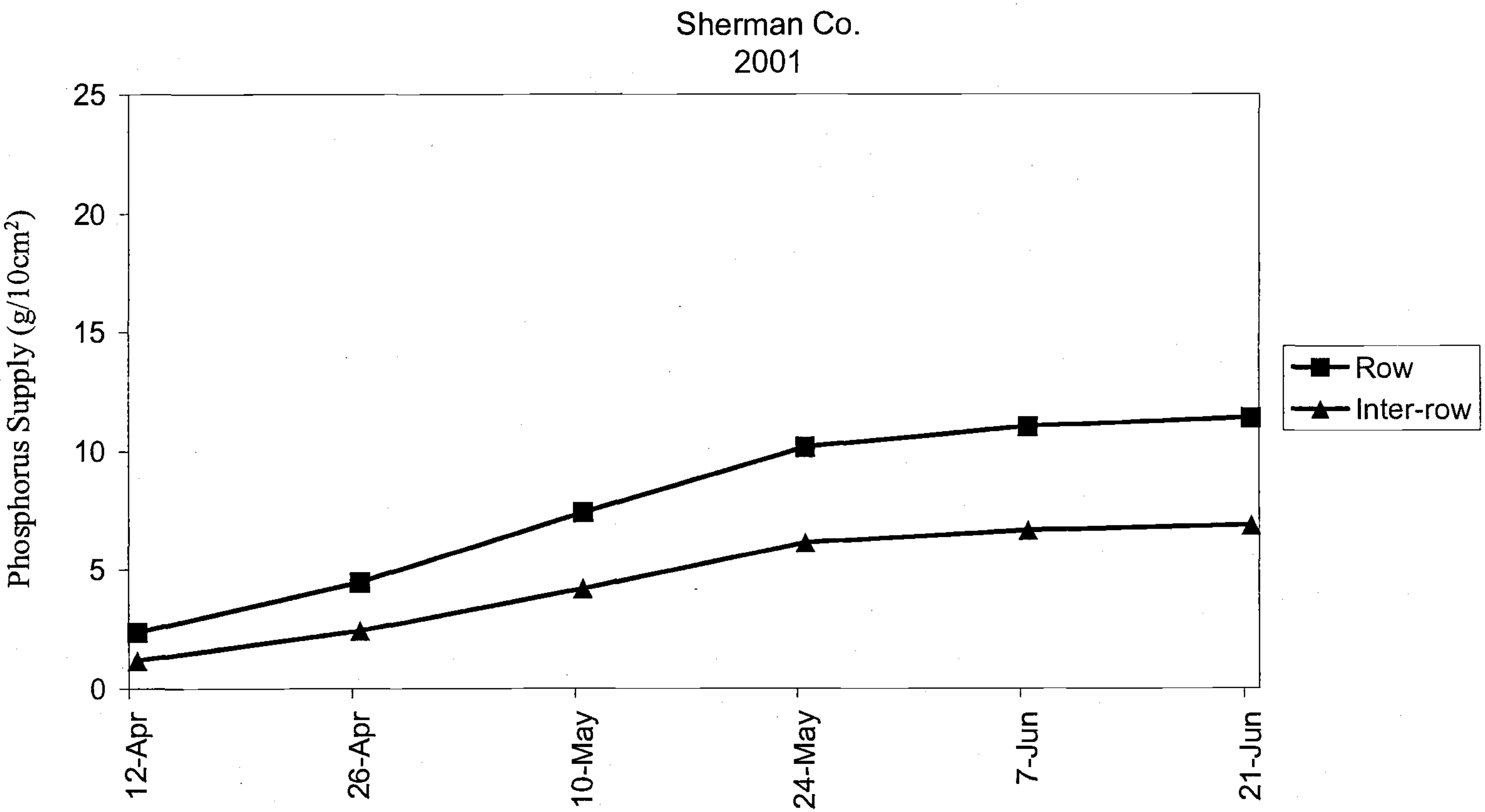


Fig. 3.12 Cumulative P supply rate during the first 10 weeks of spring wheat growth at the Sherman site in 2001. Two PRS Probes, one in the wheat row and one in the inter-row, were buried for consecutive two week intervals. The supply rate of P in the row is not significantly greater than the supply rate of P in the inter-row (probability level = 0.05).

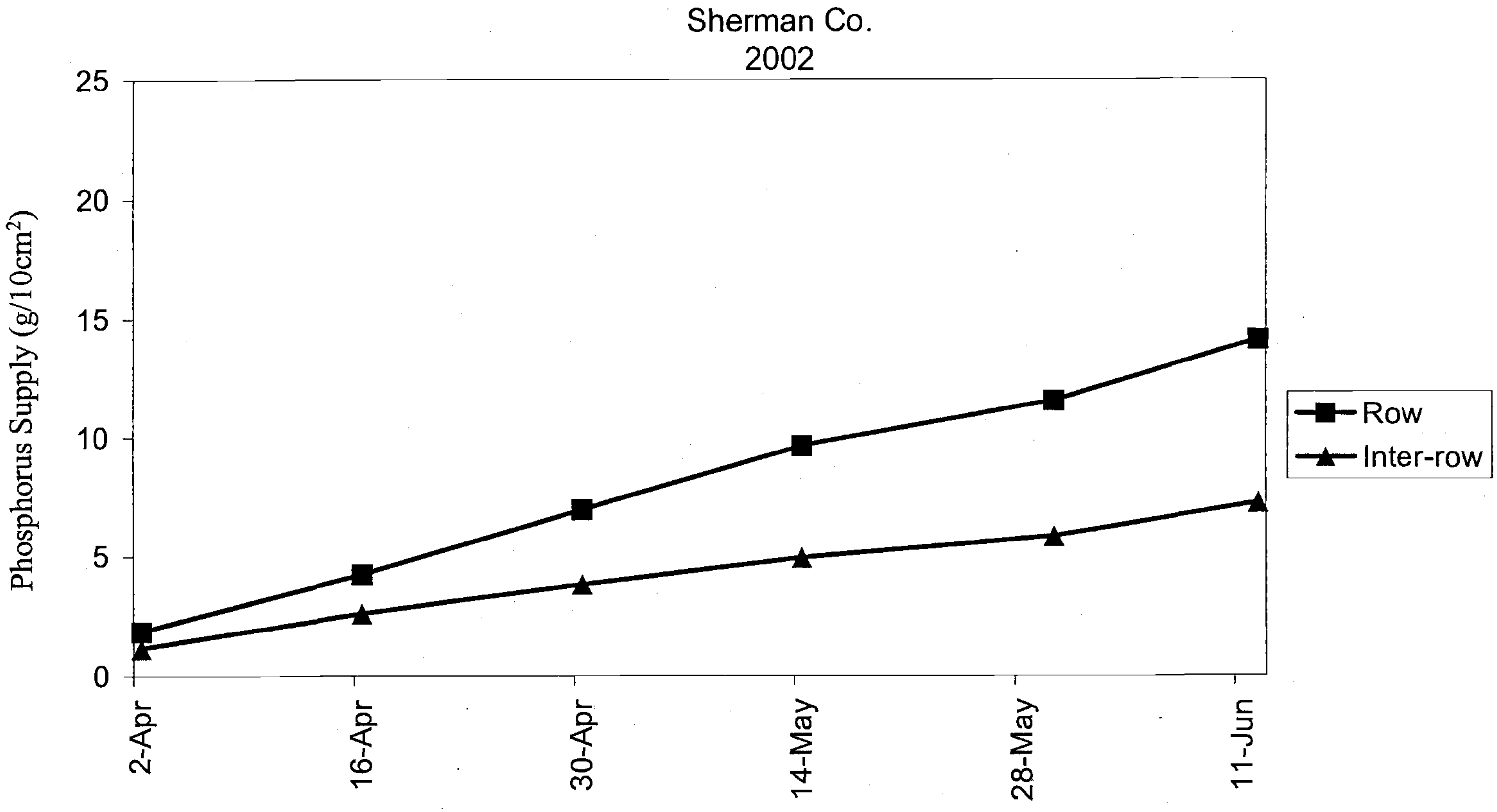


Fig. 3.13 Cumulative P supply rate during the first 10 weeks of spring wheat growth at the Sherman site in 2002. Two PRS Probes, one in the wheat row and one in the inter-row, were buried for consecutive two week intervals. The supply rate of P in the row is not significantly greater than the supply rate of P in the inter-row (probability level = 0.05).

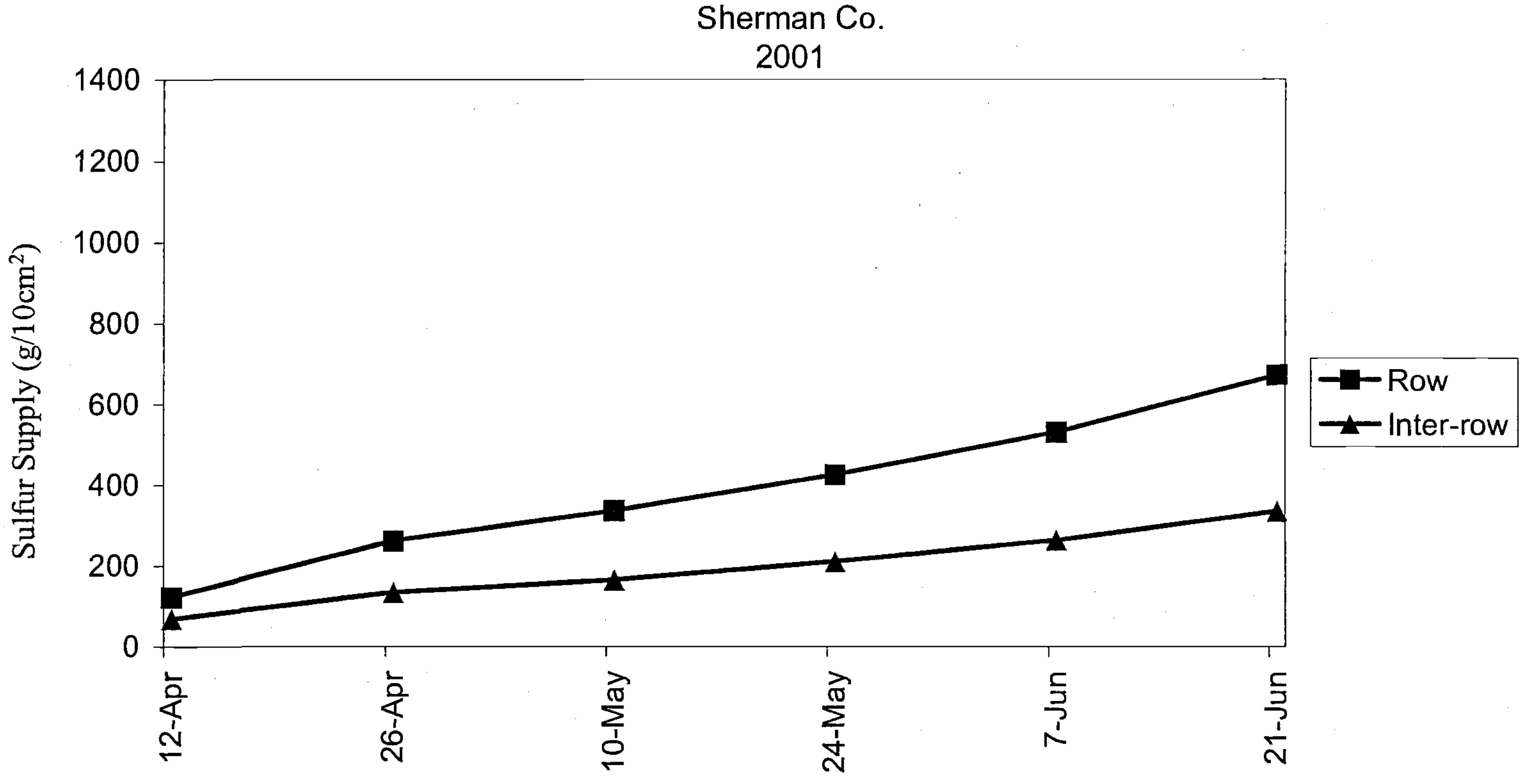


Fig. 3.14 Cumulative S supply rate during the first 10 weeks of spring wheat growth at the Sherman site in 2001. Two PRS Probes, one in the wheat row and one in the inter-row, were buried for consecutive two week intervals. The supply rate of S in the row is not significantly greater than the supply rate of S in the inter-row (probability level = 0.05).

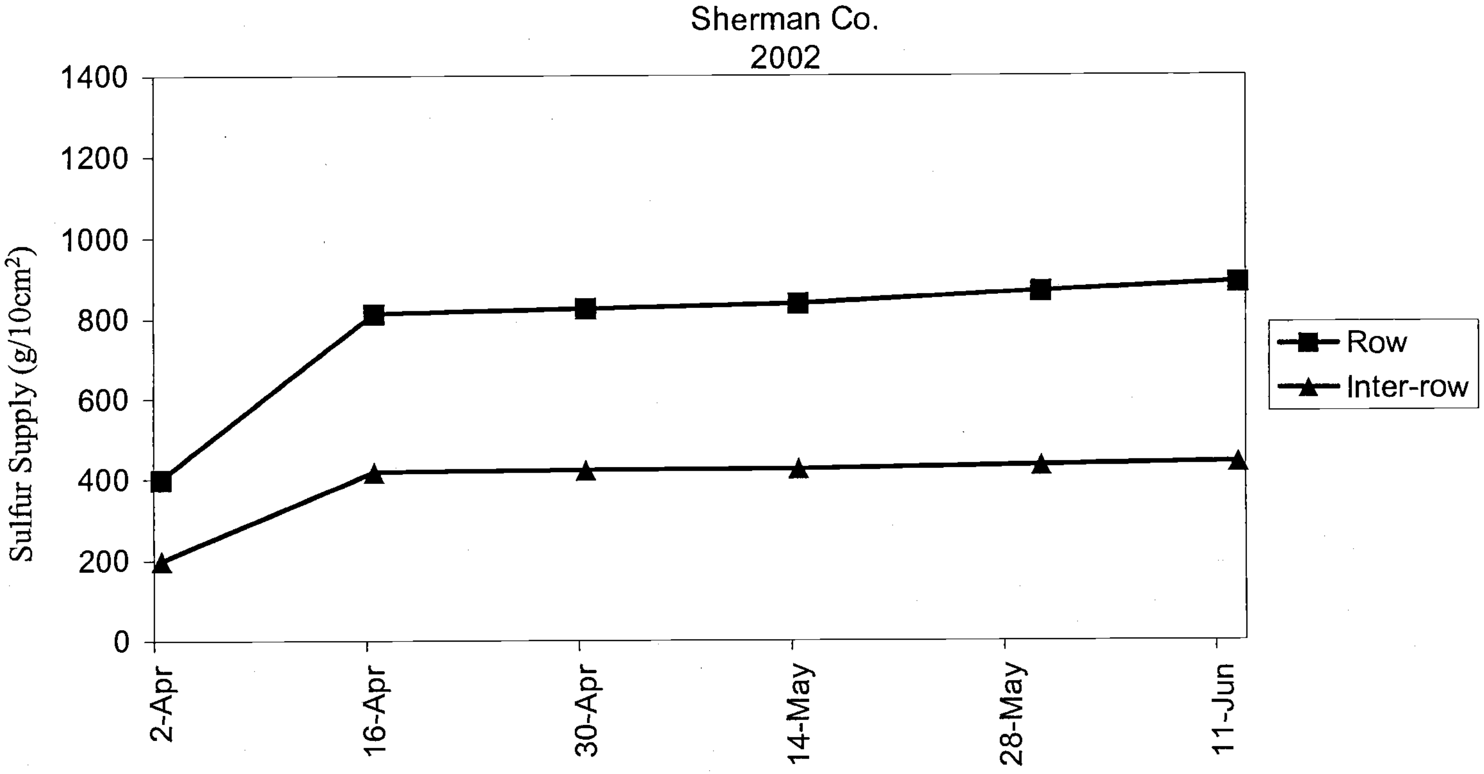


Fig. 3.15 Cumulative S supply rate during the first 10 weeks of spring wheat growth at the Sherman site in 2002. Two PRS Probes, one in the wheat row and one in the inter-row, were buried for consecutive two week intervals. The supply rate of S in the row is significantly greater than the supply rate of S in the inter-row (probability level = 0.05).

therefore, S mineralized from the S fertilizer may have been restricted to movement by diffusion. The steady increase in S supply over time in 2001 may reflect the slow diffusion of S through the soil (Fig. 3.14). Greater soil moisture content in 2002 may have been sufficient for mass flow of water to carry S through the soil. The plateau in the 2002 supply rate curves may indicate S immobilization resulting from increased soil microorganism activity as soil temperature warmed (Fig. 3.15).

Like five-leaf tissue concentration of P and S, the quantity of P and S in soil post-harvest was often in the sufficient range for optimum yield. Across treatments and sites, P ranged from 11 ppm to 34 ppm and S ranged from 3 ppm to 8 ppm. Fertilizer recommendations for spring wheat call for zero P application when Olsen-P is over 14 ppm and zero S application when DTPA-extractable S is over 4 ppm (Mahler and Guy, 1998). Post-harvest, standard soil tests indicated only two statistically significant differences in P or S among treatments. At the Morrow site in 2001, the mean Olsen-P measured in the P treatment was 14% less than the mean P measured in the S and control treatments (Table 3.6). At the Sherman site in 2002, mean DTPA-extractable S measured in the S + P treatment was 24% less than the mean S measured in the S and P treatments (Table 3.6).

It is puzzling that post-harvest soil tests measured almost no differences in soil P and S content between fertilizer treatments. If low soil moisture prevented wheat uptake of P and S, the nutrients should have remained in the soil. The nutrients were not leached out of the soil because precipitation was not sufficient to cause leaching of even the mobile nutrient, SO_4^{2-} (Brady and Weil, 1999). Deficient N in the soil may be a possible explanation as to why the chemical soil tests did not reveal significant differences in P

Table 3.6 Mean soil P and S sampled post-harvest. Olsen-P was tested from samples from the surface 30.5cm of each plot and DTPA-extractable S was tested on samples from the surface down to 122cm. Different letters within each treatment column by year and site indicate significantly different treatment effects (probability level = 0.05).

			P		S					
Year	Site	Treatment	Surface 30.5cm	SE	Surface 30.5cm	SE	30.5 - 61cm	SE	61 - 91.5 cm	SE
2001	Gilliam Co.	S + P	19.3a	0.1	6.5	1.1	6.3	0.4	9.8	0.6
		S	22.3b	0.9	8.2	1.0	4.8	0.1	8.7	0.9
		P	18.8a	0.7	5.6	0.3	4.7	0.7	11.0	2.1
		N control	21.1b	0.3	5.6	0.5	6.6	0.5	9.3	1.4
	Sherman Co.	S + P	26.8	0.8	4.1	0.3	2.9	0.3	3.3	0.5
		S	25.5	0.7	2.7	0.7	2.4	0.2	2.5	0.6
		P	26.3	0.8	2.8	0.4	2.4	0.4	1.9	0.3
		N control	27.9	0.4	2.6	0.3	2.1	0.5	1.8	0.6
	Umatilla Co.	S + P	13.9	1.9	6.7	0.9	5.4	0.4	6.6	1.0
		S	12.3	1.0	6.8	0.2	5.2	0.3	6.4	0.5
		P	11.6	0.4	6.0	0.5	4.9	0.3	5.1	0.2
		N control	19.1	7.1	5.3	0.3	4.8	0.5	5.1	0.3
	Wasco Co.	S + P	28.1	1.7	5.5	0.7	3.4	0.4	5.1	0.6
		S	31.3	0.8	6.1	0.8	3.7	0.5	4.7	0.8
		P	29.4	2.2	4.1	0.5	3.9	0.6	3.4	0.7
		N control	29.9	0.5	5.7	0.3	5.0	0.9	3.9	0.6
2002	Morrow Co.	S + P	15.3	1.7	23.0	7.8	13.0	0.5	mn	mn
		S	13.3	0.6	26.7	11.0	39.3	24.3	mn	mn
		P	16.3	3.9	16.7	1.5	17.8	3.1	mn	mn
		N control	13.0	1.4	26.1	7.3	42.4	28.2	mn	mn
	Sherman Co.	S + P	31.0	2.5	6.4a	0.2	7.0	0.3	7.0	0.4
		S	34.0	0.7	8.6b	1.2	7.5	0.5	6.7	0.4
		P	30.0	1.1	7.1b	0.5	6.6	0.3	7.2	0.7
		N control	28.5	0.5	6.3a	0.2	7.3	0.3	6.7	0.7
	Umatilla Co.	S + P	26.3	2.5	4.6	0.4	4.9	0.4	5.5	0.3
		S	23.3	3.1	5.3	0.8	5.0	0.6	5.4	0.7
		P	21.3	2.0	4.3	0.5	4.6	0.4	4.4	0.3
		N control	19.8	1.4	4.9	0.7	5.3	0.6	5.6	0.6
	Wasco Co.	S + P	28.3	0.8	4.7	0.4	5.3	0.4	6.0	0.4
		S	28.0	0.7	5.8	1.0	5.5	0.7	6.6	0.1
		P	27.8	1.8	4.4	0.2	4.7	0.3	5.4	0.3
		N control	28.8	1.0	4.7	0.2	5.2	0.5	6.2	0.5

and S from the various fertilizer treatments. If N was limiting, S and P mineralization from the soil would be halted when low N supplies curbed microorganism activity. It is possible that N was limiting to the same degree in each treatment and the S and P levels in the soil were immobilized to the same level.

3.5 CONCLUSION

Fertilizing with P and S following years in which HRS wheat yields are negatively affected by drought may be unnecessary. When wheat fields have been fertilized in drought years as they would normally in average precipitation years, sufficient residual P and S may remain in the dryland fields in NC Oregon for maximum yield. Therefore, growers should consider plant tissue concentration of nutrients and predicted annual precipitation before fertilizing with P and S.

MAP and $(NH_4)_2SO_4$ fertilizers may not mineralize rapidly when added to soil low in moisture content and temperature. Despite banding fertilizers near the seed, mineralization and diffusion of nutrients may be restricted to such an extent that HRS wheat may not access fertilizer by the five-leaf growth stage.

The dissimilar processes by which P and S moves through soil low in moisture content are reflected in cumulative supply rate curves. In 2001 when soil was drier, S movement through the soil may have been controlled by diffusion, while in 2002, when soil was slightly more moist, S appeared to move through the soil by mass flow.

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CHAPTER 4.
CONCLUSION

Anion exchange membranes did not measure plant available P and S in soil with low water content and cool temperatures in NC Oregon. In dry and cool soil conditions, nutrient acquisition is achieved by plant root growth and the ability of the plant to create a water potential gradient at the root surface. Due to the inability of AEM to grow or to create a water potential gradient, *in situ* use of AEMs should not replace standard, chemical soil extractant soil tests in less than ideal soil conditions.

The spring wheat growing seasons in which this study was conducted, 2001 and 2002, were the third and fourth consecutive years of drought in NC Oregon. Due to successive years of low wheat yields caused by the drought, sufficient residual P and S for maximum yield potential existed in the soil of all four sites in this study in 2001 and 2002. Therefore, spring wheat growers in the dryland region of NC Oregon need not fertilize with P nor S following three to four years of drought.

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