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# CHAPTER 3.

# Belowground Dynamics of Intercropping Wheat and Pea in a Dryland Cropping System

## 3.1 ABSTRACT

The Plant Root Simulator (PRS$^{TM}$)-probes (Western Ag Innovations Inc., Saskatoon, SK, Canada) are an emerging tool for the study of *in-situ* nutrient supply rates. PRS$^{TM}$-probes have not been used extensively in Pacific Northwest dryland cropping systems. The objectives of this study were to 1) evaluate soil nutrient supply rates for intercropping treatments and addition of N fertilizer in relation to agronomic performance; 2) determine optimum sampling times for observing differences in nutrient supply rates; and 3) compare nutrient supply rates in root exclusion cylinders to supply rates adjacent to plant rows. PRS$^{TM}$-probes were used within established agronomic trials at Pendleton, OR, where N fertilizer and pea inter-seeding with wheat were the treatments. Differences in nutrient supply rates were observed in connection with N fertilizer application. Few or no differences were observed for intercropping treatments. PRS$^{TM}$-probes identified an increase in N supply associated with the observed grain yield response to N fertilizer. Also, PRS$^{TM}$-probes did not detect a difference in N supply for intercropping where no grain yield response was observed. For most nutrients, the supply rates were greater earlier in the measurement period (April), associated with higher soil moisture. Most nutrient supply rates were not affected by the PRS$^{TM}$-probe placements (in-row or within root exclusion cylinders) during this period. PRS$^{TM}$ nutrient supply measurements were related to plant response to N fertilizer and intercropping treatments in a one-year field experiment. Most relevant nutrient data were obtained during April. PRS$^{TM}$-probe placements inside a root exclusion cylinder did not appear to be essential for nutrient measurements in this dryland cropping system.

## 3.2 INTRODUCTION

Cereal-legume intercropping systems can increase the efficiency of resource utilization and can reduce nitrogen fertilizer requirements (Sullivan, 2003; Tilman et al., 2002; Crews and Peoples, 2005). In a dryland agricultural system, interspecies competition for water is a major concern and can result in the suppression of growth and yield responses by less competitive species (Szumigalski and Van Acker, 2005). Therefore, growing winter pea (*Pisum sativum*) with winter wheat (*Triticum aestivum*) simultaneously in the same rows can negatively affect wheat yield by scavenging water prior to wheat grain development.

Preliminary research showed that intercropping wheat with pea in North Central Oregon (Pendleton and Moro, 2004-05, OR) resulted in a grain yield increase (Machado and Tuck, 2005, unpublished data). In that preliminary study, grain yield increased 470 kg/ha in Pendleton and 1278 kg/ha in Moro when wheat was intercropped with peas.

Rotations or intercropping with legumes bring a natural source of N into agricultural soils. By determining the optimal wheat-pea ratio and synthetic N rate for wheat-pea mixtures, this knowledge can be used to develop a wheat-pea cropping system that relies less on artificial N and more on natural fixed N (Machado and Tuck, 2005 unpublished data). Additionally, legume crops acidify their rhizosphere by producing and excreting more organic acids as compared to cereals. This acidification of the rhizosphere can enhance P solubility (Li et al., 2007) and other nutrients that become more bioavailable with changing soil pH.

An additional factor to take into account is soil tillage and crop residue, which influence soil nutrient availability. Previous studies have confirmed that direct-seed (DS) management increases soil microbial biomass in agricultural soils as compared to conventional tillage (CT) (Doran, 1987; Granatstein et al., 1987; Carter, 1991). The large amount of soil disturbance of CT accelerates carbon loss and promotes nitrogen mineralization (Stewart and Bettany, 1982). Therefore it is important to understand how soil nutrients are affected by intercropping wheat with pea crops under both conventional and direct-seed management conditions. Presently there is an interest in the dryland Pacific Northwest wheat production to adopt direct-seeding practices**.**

The focus of this one-year research study was the belowground nutrient supply dynamic of wheat-pea mixtures. The objectives of this study were to 1) evaluate soil nutrient supply rates for intercropping treatments and N fertilizer addition in relation to agronomic performance (grain yield); 2) determine optimum sampling times for observing differences in nutrient supply rates; and 3) compare nutrient supply rates in root exclusion cylinders to supply rates adjacent to the plant rows.

## 3.3 METHODS AND MATERIALS

### 3.3.1 Site Location and Soil

This field experiment was conducted at the Columbia Basin Agricultural Research Center (CBARC), Pendleton, Oregon (Umatilla County) (45.7ºN, 118.6ºW; elevation 438 m) in 2006-2007. The field site was conventionally tilled until the initiation of the experiment in the fall of 2005.

The soil type is a Walla Walla silt loam, classified as coarse-silty, mixed, super-active, mesic Typic Haploxeroll. The Walla Walla series consists of deep and very deep, well-drained soils formed in loess on hills (slopes are 0 - 20%) at elevations of 400 to 500 meters. The soil at CBARC receives 70% of its precipitation during the winter months from September to February. Wheat is seeded in the fall (September/October) and harvested in the following July/August. The mean annual precipitation is approximately 406 mm (12 to 15 inches).

### 3.3.2 Experimental Design and Treatments

Experimental design was a randomized complete block design with two, non-replicated systems: direct-seeding (DS) and conventional tillage (CT). The size of each system was 55 by 43 m. Each system had 6 different treatments plots, including a control, replicated 3 times (Table 3.1).

‘Stephens’ soft white winter wheat (*Triticum aestivum*) and ‘Spector’ winter pea (*Pisum sativum*) were seeded together on October 25, 2006 with a Fabro drill. Seeding depth for both crops was approximately 2.5 cm with a band of fertilizer (urea: 46-0-0) placed 7 cm deep and 2.5 cm to the side of the seed. Rhizobium-inoculated pea seeds were used. Seeding rate for winter wheat was 270 seeds/m$^2$ for all treatments, whereas pea seeding rates were: zero for 0% pea, 37.5 seeds/m$^2$ for 50% pea, and 75 seeds/m$^2$ for 100% pea.

Table 3.1. Treatments for direct-seed (DS) and conventional tillage (CT) systems. The 6 treatment plots consist of 3 different pea seeding rates (0, 50, and 100%) and 2 different rates of synthetic N application (0 and 45 kg ha$^{-1}$).

| **Treatments** | **% Wheat** | **% Pea** | **kg ha$^{-1}$ N** |
|---|---|---|---|
| 1 | 100 | 0 | 0 |
| 2 | 100 | 0 | 45 |
| 3 | 100 | 50 | 0 |
| 4 | 100 | 50 | 45 |
| 5 | 100 | 100 | 0 |
| 6 | 100 | 100 | 45 |

### 3.3.3 Soil Measurements

Soil temperature was measured *in-situ* from March 28 to June 20 at a depth of 10 to 15 cm, using a Dallas semiconductor DS 1920 temperature iButtonÂ® (computer chip enclosed in a 16 mm thick stainless steel can). One 15-cm deep soil core from each treatment plot was taken every two weeks at the time of PRS$^{TM}$-probes exchange to determine gravimetric water content and baseline soil properties for each treatment combination. Every four weeks during the field experiment, three separate sub-samples from the main soil sample were used for soil microbial biomass carbon (MBC) determination by the $CHCl_3$ (chloroform)-fumigation extraction method (Horwath and Paul, 1994). Another three separate sub-samples were extracted with 100 mL of 0.5M $K_2SO_4$, shaken for 30 min on a rotary shaker at 350 rpm and filtered through a Whatman no. 1 filter. The filtrate was analyzed for soil $NO_3^-$–N and $NH_4^+$–N using a Lachat Quick Chem 4200 analyzer (Milwaukee, WI). All soil analyses were done at the USDA-ARS National Forage, Seed, Cereal Research Unit, Corvallis, OR.

### 3.3.4 Plant Biomass and Wheat Yield

A one-meter length of row was sampled for wheat biomass at the physiological maturity of wheat, one week before harvest in July, 2007 from each plot across both systems (DS and CT). The wheat was harvested during the second week of July with a plot-sized combine to determine wheat yield. Peas where not harvested in this experiment.

### 3.3.5 Ion-Exchange Membrane

Plant Root Simulator (PRS$^{TM}$)-probes (Western Ag Innovations Inc., Saskatoon, Saskatchewan, Canada) (Figure 3.1) treated with $NaHCO_3$ were used to measure soil nutrient flux in the field. A PRS$^{TM}$-probe is designed as either cation or anion- exchange resin membrane enclosed in a plastic holding device, creating a probe (Figure 3.1). Nutrient supply rates were expressed as µg of nutrient adsorbed per 10 cm$^2$ of ion-exchange surface area over 2-weeks (i.e., µg/10cm$^2$/2wks). Nutrient accumulation on the ion-exchange membrane during the burial period can be considered as an estimate of the potential nutrient supply rate to an absorbing surface such as a plant root (Gibson et al., 1985; Casals et al., 1995; Huang and Schoenau, 1996b). Anion exchange membranes were used to obtain quantities of $NO_3^-$, $HPO_4^{2-}$ or $H_2PO_4^-$, $SO_4^{2-}$, and $BO_3^-$. The cation exchange resin adsorbed $NH_4^+$, $K^+$, $Ca^{2+}$, and $Mg^{2+}$ from soil solution. Supply rates of micronutrients, $Mn^{2+}$, $Fe^{2+}$, $Cu^{2+}$, and $Zn^{2+}$, were also measured. Therefore, a chelating pre-treatment with EDTA of the anion exchange membrane was employed, in addition to $NaHCO_3$. The chelating agent adsorbed to the anion exchange membrane forms complexes with these metal ions.

Figure 3.1 A PRS$^{TM}$-probe pair consists of one cation (orange) and one anion (purple) PRS$^{TM}$ -probe.

The PRS$^{TM}$-probe sampling events started on March 28, 2007, which included six, 2-week sampling periods. The sampling period began at the jointing/tillering stage and continued to the fully matured wheat growth stage. PRS$^{TM}$-probes were vertically inserted into the soil to a depth of 15 cm to measure nutrient flux *in-situ* with minimal disturbance. In each treatment plot, 2 PRS$^{TM}$-probe pairs were installed. Each PRS$^{TM}$-probe pair was buried in the field next to the seeding row, approximately 10 cm apart from each other (Figure 3.2).

Root competition is a potential problem, since roots can be stronger sink for nutrients than the PRS$^{TM}$-probes (WAII, 2006). Therefore, another 2 PRS$^{TM}$-probe pairs were buried (~ 4 cm apart) in the center of two separate root exclusion cylinders (REC) that were installed in the mid row of each treatment plot (Figure 3.2). By using the REC, competition for nutrients by

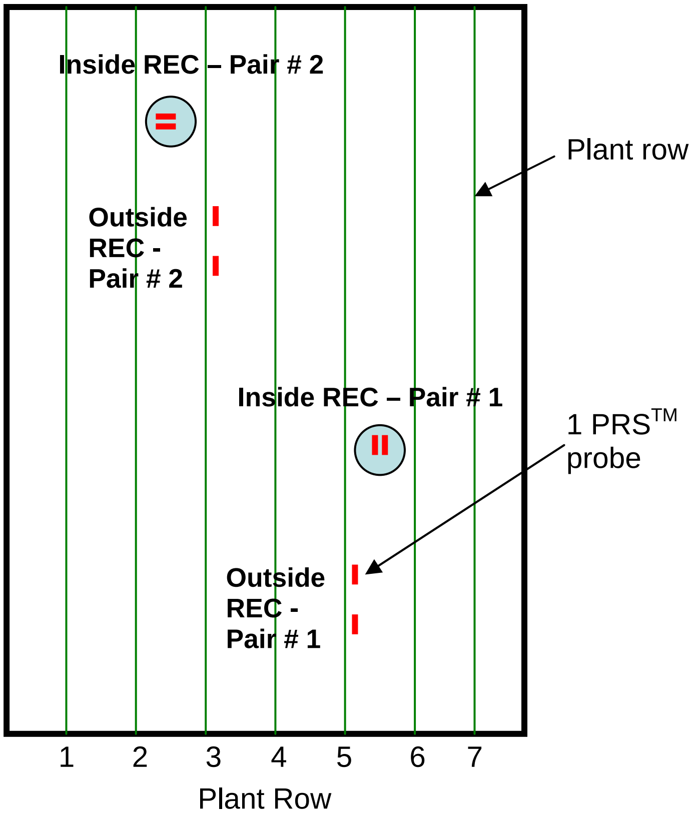

Figure 3.2 Diagram of treatment plot showing PRS$^{TM}$-probe placements. Outside the root exclusion cylinders (REC) PRS$^{TM}$ -probes were inserted into the soil next to the plant rows; PRS$^{TM}$-probes inside the REC were placed in the mid-row between plant rows.

plant roots is prevented and the net nutrient supply rate (total nutrient supply from soil) can be measured rather than the surplus of nutrient supply rate. The RECs were made from 10 cm diameter PVC-pipes cut to a length of 15 cm (WAII, 2006).

All buried PRS$^{TM}$-probes were exchanged biweekly with 'fresh' PRS$^{TM}$-probes into the same soil slots (sampling occurred at the same soil slots). The buried PRS$^{TM}$-probes were removed and placed in polyethylene bags, transported on ice to the lab and stored in a refrigerator until cleaning. The PRS $^{M}$-probes were rinsed with deionized water and scrubbed clean under running water to remove adhering soil. After cleaning, the PRS$^{TM}$-probes were stored in clean polyethylene bags in the refrigerator until shipment to Western Ag Innovations for analysis.

Twelve nutrient ions were measured with the PRS$^{TM}$-probes and extracted with 0.5N HCl simultaneously with one 1-hr extraction. The two PRS$^{TM}$-probe pairs (per plot) inside the REC were eluted together and the same was done for the two PRS$^{TM}$-probe pairs (per plot) outside the REC. The analysis for levels of nitrate ($NO_3^-$ -N) and ammonium ($NH_4^+$-N) was done via automated colorimetry (FIA Lab 2600). Other nutrients ($PO_4^{2-}$, $SO_4^{2-}$-S, $BO_3^-$-B, $K^+$, $Ca^{2+}$, $Mg^{2+}$, $Fe^{2+}$, $Mn^{2+}$, $Cu^{2+}$, and $Zn^{2+}$) in the eluate were measured by an inductively coupled plasma spectrophotometer (IRIS Intrepid II XSO, Thermo Scientific) (WAII, 2006).

### 3.3.6 Statistical Analyses

Statistical analyses were done using analysis of variance (ANOVA) with random component - Date; to test for statistically significant differences (p-value ≤ 0.05) among treatments within each system (DS and CT) for each nutrient supply rate over time. Statistical analyses for the nutrient supply rates were done using SAS System version 7. Four different ANOVAS with random component: Date, were done as follows:

1. DS experiment including root exclusion cylinders (REC) nutrient supply rate
2. DS experiment including outside REC nutrient supply rate
3. CT experiment including root exclusion cylinders (REC) nutrient supply rate
4. CT experiment including outside REC nutrient supply rate

Four separate ANOVAs were employed because nutrient supply rates measured outside the REC and inside REC are two different measurements of nutrient availability and have to by analyzed individually. For each of the ANOVAs, the independent variables were: pea rates (0, 50, 100) and N-fertilizer (0, 45 N- kg ha$^{-1}$). Soil nutrients were the dependent variables. The data: Inorganic N ($NO_3^-$–N and $NH_4^+$–N), $PO_4^{2-}$, $SO_4^{2-}$, $Fe^{2+}$, $Mn^{2+}$, $Cu^{2+}$, $Zn^{2+}$ was log transformed to improve random distribution in order to satisfy ANOVA assumptions. Results are presented using untransformed data.

Statistical analyses for soil nitrate-N, microbial biomass carbon, plant biomass, and wheat yield were obtained using ANOVA in JMP 4 (SAS Institute, Inc. version 4.0.4) to test for significant differences (p-value ≤ 0.05) among treatments within each cropping system, direct-seed (DS) or conventional till (CT).

## 3.4 RESULTS AND DISCUSSION

Data collection was done during one season. The data are presented in different ways to address the study objectives. First, soil measurement responses to treatments are discussed in relation to grain yield. Second, temporal aspects of 11 nutrient supply rates are presented to determine optimum sampling times for observing differences in nutrient supply rates among treatments. Lastly, nutrient supply rate measurements are compared to PRS$^{TM}$-probes placements inside vs. outside the root exclusion cylinders.

### 3.4.1 Soil Measurement Response to N fertilizer and Intercropping Treatments in Relation to Agronomic Performance

In the CT system, the N fertilized treatments significantly increased grain yields (p-value 0.0001), by around 300 to 600 kg ha$^{-1}$, compared to the non-fertilized treatments (Table 3.2). In the DS system, N fertilized treatments did not significantly affect grain yields (p-value 0.059) compared to the other treatments. Wheat yield was not significantly (p-value > 0.05) affected by the different pea seeding rates in either cropping system.

Mean wheat biomass and MBC were not affected (p-value > 0.05) by N fertilization or intercropping treatments in both CT and DS systems (Table 3.2). Significant effects were measured for soil nitrate (mg $NO_3$-N/kg soil) in fertilized treatments. DS (p-value 0.024) and CT (p-value 0.044) systems had twice as much soil nitrate concentration in fertilized treatments compared to non-fertilized treatments (Table 3.2). There were no statistical differences were observed in N fertilized treatments for soil ammonium-N (mg $NH_4$-N/kg soil) (data not shown). Soil $NO_3$-N and $NH_4$-N concentrations were not affected by pea seeding rates in either cropping system.

Similar to the standard soil test for soil nitrate-N, PRS$^{TM}$-probes measured a significant N fertilizer effect on inorganic N supply availability during the experiment (Table 3.3). The two soil tests identified an increase in N supply associated with the observed grain yield responses to N fertilization. Generally, PRS$^{TM}$-probes detected more significant differences in nutrient supply rates with N fertilization addition for the main macro nutrients N, P, and K compared to the pea intercropping treatments. PRS$^{TM}$-probes detected fewer significant effects with no consistent trends in the intercrop wheat-pea treatments (Table 3.3).

Table 3.2 Effect of N fertilizers and pea intercrop treatments on mean grain yield, wheat biomass, microbial biomass C (MBC), and soil nitrate-N. All treatments were seeded at same rate for wheat.

| **Seeding Rate % Pea** | **Urea - N kg ha$^{-1}$** | **DS** | **CT** |
|---|---|---|---|
| | | **Grain yield, kg ha$^{-1}$** | |
| 0 | 0 | 1553 | 1677 |
| 0 | 45 | 2458 | 2107 |
| 50 | 0 | 1517 | 1464 |
| 50 | 45 | 2198 | 2128 |
| 100 | 0 | 1789 | 1768 |
| 100 | 45 | 1904 | 2060 |
| Significance (ANOVA) (n=3) | | | |
| N fertilizer | | NS | ** |
| Pea rate | | NS | NS |
| | | **Wheat biomass, g m$^{-1}$** | |
| 0 | 0 | 553 | 560 |
| 0 | 45 | 710 | 577 |
| 50 | 0 | 427 | 447 |
| 50 | 45 | 623 | 510 |
| 100 | 0 | 560 | 430 |
| 100 | 45 | 650 | 517 |
| Significance (ANOVA) (n=3) | | | |
| N fertilizer | | NS | NS |
| Pea rate | | NS | NS |
| | | **Microbial biomass C, µg g$^{-1}$** | |
| 0 | 0 | 138 | 117 |
| 0 | 45 | 166 | 140 |
| 50 | 0 | 185 | 164 |
| 50 | 45 | 131 | 147 |
| 100 | 0 | 145 | 152 |
| 100 | 45 | 205 | 194 |
| Significance (ANOVA) (n=15) | | | |
| N fertilizer | | NS | NS |
| Pea rate | | NS | NS |
| | | **Soil nitrate-N, mg kg$^{-1}$** | |
| 0 | 0 | 2 | 2.7 |
| 0 | 45 | 4.6 | 5.4 |
| 50 | 0 | 1.6 | 1 |
| 50 | 45 | 3.9 | 4.9 |
| 100 | 0 | 1.8 | 1.4 |
| 100 | 45 | 4 | 3.1 |
| Significance (ANOVA) (n=15) | | | |
| N fertilizer | | * | * |
| Pea rate | | NS | NS |

Significance level: 0.01, 0.05, NS = **, *, or NS

Table 3.3 Effect of N fertilizers and pea intercrop treatments on mean PRS$^{TM}$-probe nutrient supply rates inside and outside the root exclusion cylinders. All treatments were seeded at same rate for wheat.

| **PRS$^{TM}$--probes placement** | **Seeding Rate % Pea** | **Urea - N kg ha$^{-1}$** | **DS** | **CT** |
|---|---|---|---|---|
| | | | **$NH_4^+$ -N + $NO_3^-$-N, µg/10cm$^2$/12wks** | |
| **In - REC** | 0 | 0 | 114 | 88 |
| | 0 | 45 | 100 | 85 |
| | 50 | 0 | 93 | 37 |
| | 50 | 45 | 111 | 91 |
| | 100 | 0 | 86 | 52 |
| | 100 | 45 | 157 | 93 |
| | Significance (ANOVA) (n=18) | | | |
| | N fertilizer | | * | NS |
| | Pea rate | | NS | NS |
| **Outside - REC** | 0 | 0 | 47 | 23 |
| | 0 | 45 | 82 | 69 |
| | 50 | 0 | 54 | 13 |
| | 50 | 45 | 84 | 48 |
| | 100 | 0 | 22 | 14 |
| | 100 | 45 | 87 | 42 |
| | Significance (ANOVA) (n=18) | | | |
| | N fertilizer | | * | ** |
| | Pea rate | | * | NS |
| | | | **P, µg/10cm$^2$/12wks** | |
| **In - REC** | 0 | 0 | 2.7 | 2.1 |
| | 0 | 45 | 2.2 | 1.7 |
| | 50 | 0 | 2.8 | 2.5 |
| | 50 | 45 | 2.5 | 1.8 |
| | 100 | 0 | 2.3 | 2 |
| | 100 | 45 | 2.3 | 1.9 |
| | Significance (ANOVA) (n=18) | | | |
| | N fertilizer | | NS | * |
| | Pea rate | | NS | NS |
| **Outside - REC** | 0 | 0 | 3.1 | 3.2 |
| | 0 | 45 | 2.6 | 1.9 |
| | 50 | 0 | 3.4 | 2.5 |
| | 50 | 45 | 2.4 | 2 |
| | 100 | 0 | 3.3 | 2.4 |
| | 100 | 45 | 3.3 | 1.9 |
| | Significance (ANOVA) (n=18) | | | |
| | N fertilizer | | NS | ** |
| | Pea rate | | NS | NS |
| | | | **K, µg/10cm$^2$/12wks** | |
| **In - REC** | 0 | 0 | 275 | 220 |
| | 0 | 45 | 220 | 208 |
| | 50 | 0 | 262 | 210 |
| | 50 | 45 | 251 | 202 |
| | 100 | 0 | 307 | 243 |
| | 100 | 45 | 279 | 195 |
| | Significance (ANOVA) (n=18) | | | |
| | N fertilizer | | * | ** |

| | | | | |
|---|---|---|---|---|
| | Pea rate | | * | NS |
| **Outside - REC** | 0 | 0 | 308 | 228 |
| | 0 | 45 | 229 | 166 |
| | 50 | 0 | 299 | 191 |
| | 50 | 45 | 226 | 137 |
| | 100 | 0 | 302 | 211 |
| | 100 | 45 | 270 | 157 |
| | Significance (ANOVA) (n=18) | | | |
| | Fert N rate | | ** | ** |
| | Pea rate | | NS | * |

Significance level: 0.01, 0.05, NS = **, *, or NS

### 3.4.2 Optimum Sampling Time for Observing Differences in Nutrient Supply Rates

The temporal aspects of 11 nutrient supply rates are discussed for observing differences among treatments. This section focuses on nutrient supply rates outside the root exclusion cylinder (REC) for reasons that are addressed in the next section. For nutrients supply fluxes of total inorganic N, P, S, Mn, Fe, Zn, and Cu the supply rates were generally greater during the first four weeks (April) compared to the later sampling dates (Table 3.4). This was associated with higher soil moisture and biological activity (i.e., MBC) early in the growing season (Table 3.5). Whereas the nutrient supply rates of K, Mg, Ca, and B stayed relatively constant during the experiment (Table 3.4), and were less affected by soil moisture and biological factors (Table 3.5). Drohan et al. (2005) found similar results for relative constant supply rates for basic cations at low soil moisture in the Mojave Desert, USA. Despite of low soil moisture (2.2 - 4.8%) to a depth of 25 cm PRS$^{TM}$-probes were able to continuously adsorb Ca and Mg over three months (Drohan et al., 2005).

Table 3.4 Mean nutrient supply rates from PRS$^{TM}$-probes at each 2-week exchange.

| **Exchange Date** | **Inorganic N** | **P** | **K** | **S** | **Mg** | **Mn** | **Ca** | **Fe** | **Zn** | **Cu** | **B** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ---------------------------------------μg/10cm$^2$/2wks------------------------------------ | | | | | | | | | | |
| **14-Apr** | 236 | 5 | 240 | 9 | 289 | 16 | 1066 | 15 | 0.4 | 0.5 | 0.8 |
| **28-Apr** | 69 | 2 | 198 | 5 | 176 | 4 | 557 | 7 | 0.6 | 0.2 | 0.8 |
| **12-May** | 60 | 3 | 276 | 3 | 261 | 3 | 865 | 7 | 0.3 | 0.1 | 1.4 |
| **26-May** | 15 | 1 | 202 | 1 | 183 | 1 | 567 | 3 | 0.4 | 0.0 | 1.8 |
| **9-Jun** | 17 | 2 | 235 | 3 | 198 | 3 | 642 | 3 | 0.2 | 0.1 | 1.0 |
| **23-Jun** | 22 | 2 | 252 | 1 | 212 | 2 | 706 | 3 | 0.4 | 0.1 | 0.8 |

Table 3.5 Mean gravimetric soil water content and soil microbial biomass carbon (MBC).

| Sample Date | Soil Water % | MBC µg C/g soil |
|---|---|---|
| 28-Mar | 25 | 234 |
| 14-Apr | 20 | 156 |
| 12-May | 12 | 187 |
| 9-Jun | 7 | 107 |
| 23-Jun | 6 | 100 |

Soil temperature remained below 20˚C until mid-May and did not rise above 30˚C during the time of the experiment was employed (Figure 3.3). The mean monthly soil temperatures were approximately 11, 17, and 21˚C in April, May, and June respectively. It appears that soil temperature was not as an important factor influencing ion diffusion and microbial activity (i.e., MBC) as soil moisture content. Soil temperature affects diffusion of nutrients in the soil, but does so indirectly (Barber, 1995; Yang et al., 1991a). Cool soil temperature generally 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 temperature, however, in temperate regions, the microorganisms with a prominent role in nutrient cycling are mesophilic (Sylvia et al., 2005). The temperature range of maximum mesophilic activity and therefore optimum nutrient cycling in soils of temperate regions ranges between 15 and 35˚C. Soil temperature in this study did not rise to 15˚C until the end of April beginning of May (Figure 3.3). For that reason, soil temperature influenced ion diffusion rates and biological activity less compared to soil water content. Nutrient supply fluxes and MBC correlated with soil moisture (Tables 3.4 and 3.5).

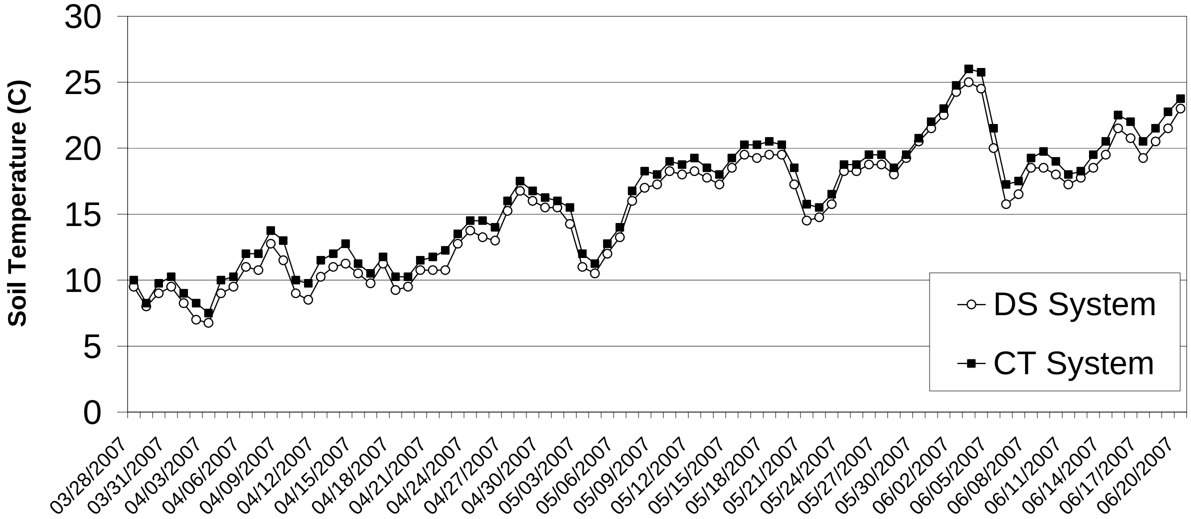

Figure 3.3 Soil temperatures for direct-seed (DS) and conventional till (CT) systems.

PRS$^{TM}$-probes were most sensitive in detecting N fertilizer treatment differences during the early period (April). The mean inorganic N ($NH_4^+$-N + $NO_3^-$-N) in both DS and CT systems was significantly higher (p-value 0.028 and 0.001, respectively), by about 50 times, in the N fertilized treatments compared to non-fertilized treatments (Figure 3.4). Treatment differences for inorganic N supply rates were observed in April but not later in the growing season.

In the CT system, P supply rates were significantly lower (p-value <0.05), by about one fold, in N fertilized treatments compared to non-fertilized treatments (Figure 3.5). No significant N fertilizer effect on P supply rate was observed in the DS system (data not shown). The supply rate of P was not affected by the different pea seeding rates in either tillage system. Treatment differences for P supply rates were observed in April but not later in the growing season.

The mean K supply rate in the DS and the CT system, was significantly lower, 60 and 40% respectively, in the N fertilizer treatments compared to non- fertilized treatments (p-value 0.001 for both systems) (Figure 3.6). The timing for measuring treatment differences in K supply rate was not as important as compared to inorganic N and P supply rates. Early measurements for inorganic N and P were important to observe treatments differences but not for K supply rates (Figures 3.4, 3.5 and 3.6).

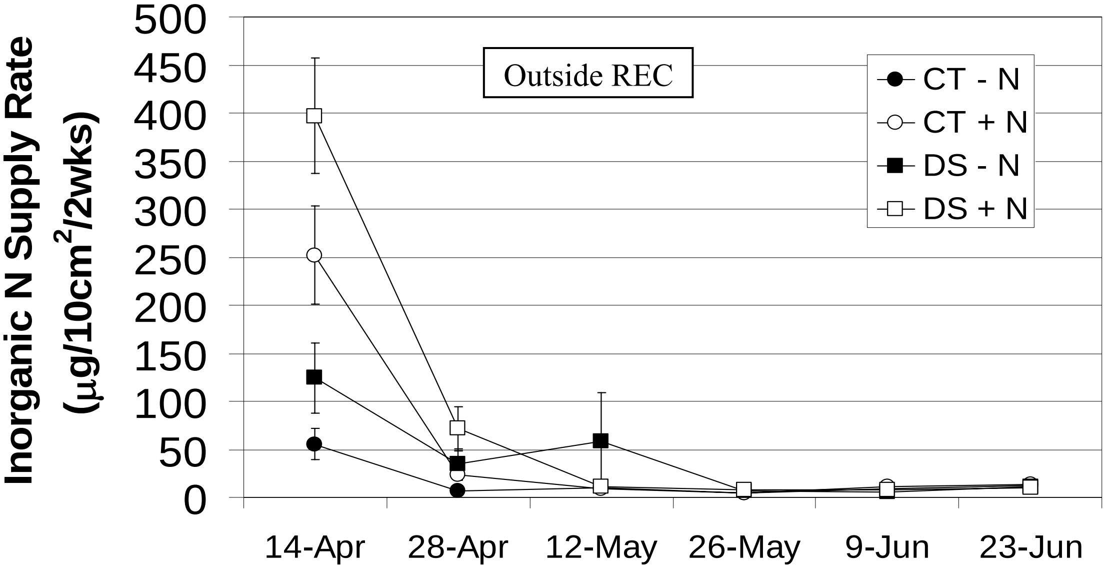

Figure 3.4 Supply rate of inorganic nitrogen from PRS$^{TM}$-probes at each 2-week exchange, measured in N fertilized (+ N) and unfertilized (- N) treatments for both direct-seed (DS) and conventional tillage (CT) systems. N fertilized treatments were greater (p-value < 0.05; n=9) than non-fertilized treatments.

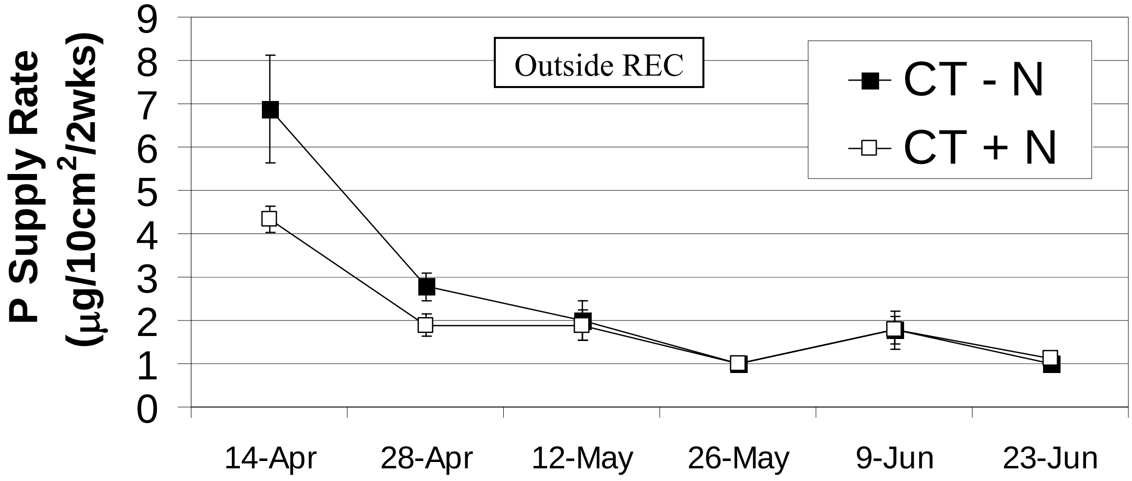

Figure 3.5 Supply rate of P from PRS$^{TM}$-probes at each 2-week exchange, in the conventional till (CT) system in N fertilized (+ N) and unfertilized (- N) treatments. The supply rate of P was less (p-value < 0.05; n=9) in N fertilized compared to unfertilized treatments.

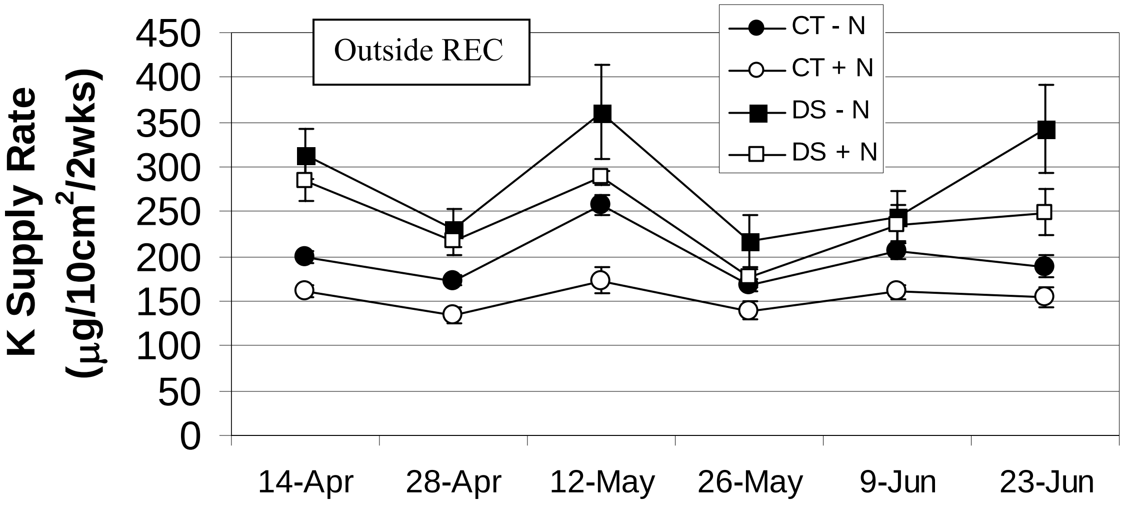

Figure 3.6 Supply rate of potassium from PRS$^{TM}$-probes at each 2-week exchange, measured in N fertilized (+ N) and unfertilized (- N) treatments for both direct-seed (DS) and conventional tillage (CT) systems. The supply rate of K over time was lower (p-value 0.05; n=9) in N fertilized compared to unfertilized treatments.

### 3.4.3 Nutrient Supply Comparisons of Root Exclusion Cylinder to Supply Rates Next to Plant Row

Most nutrient supply rates were not affected by the PRS$^{TM}$-probe placements, in row (next to plant rows) or in root exclusion cylinders (REC), during the early measurement periods (Table 3.6). When nutrient fluxes were greatest and were associated with higher soil moisture and MBC early in the growing season (April) (Table 3.4 and 3.5). Table 3.6 shows the overall mean nutrient supply rates for the first two 2-week exchange periods inside versus outside the REC. Table 3.6 indicated that the dominant nitrogen species was nitrate-N and was the largest fraction of the inorganic N ($NO_3^-$-N + $NH_4^+$-N) supply rate in both DS and CT systems.

In both DS and CT systems, P supply rate was significantly higher ($p$-value $< 0.05$) outside the REC compared to inside the REC (Table 3.6). The wide range of inorganic and organic acids produced by microorganisms and plants can act as chelating agents resulting in the

Table 3.6 Mean PRS$^{TM}$-probe nutrient supply rates, for the first two 2-week exchange periods, differences observed for inside vs. outside the root exclusion cylinders (REC) in DS and CT systems.

**DS System**

| | **Inside REC** | | **Outside REC** | |
|---|---|---|---|---|
| Nutrient ion | Mean supply rate µg/10cm$^2$/4wks | SE | Mean supply rate µg/10cm$^2$/4wks | SE |
| Inorganic N | 216 | 23 | 157 | 30 |
| $NO_3^-$-N | 207 | 23 | 148 | 30 |
| $NH_4^+$-N | 9 | 1 | 9 | 1 |
| $PO_4^{2-}$ | 3 | 0 | 5 ** | 0 |
| $K^+$ | 235 | 12 | 274 * | 16 |
| $SO_4^{2-}$-S | 9 * | 2 | 5 | 0 |
| $Ca^{2+}$ | 815 ** | 54 | 613 | 43 |
| $Mg^{2+}$ | 234 * | 13 | 193 | 11 |
| $Mn^{2+}$ | 12 | 2 | 12 | 2 |
| $Fe^{2+}$ | 14 ** | 1 | 10 | 1 |
| $Cu^{2+}$ | 0.4 | 0.1 | 0.3 | 0.1 |
| $Zn^{2+}$ | 0.4 | 0.1 | 0.4 | 0.1 |
| $BO_3^-$ | 0.6 | 0.1 | 0.6 | 0.1 |

**CT System**

| | **Inside REC** | | **Outside REC** | |
|---|---|---|---|---|
| Nutrient ion | Mean supply rate µg/10cm$^2$/4wks | SE | Mean supply rate µg/10cm$^2$/4wks | SE |
| Inorganic N | 152 | 28 | 85 | 21 |
| $NO_3^-$-N | 146 | 28 | 77 | 21 |
| $NH_4^+$-N | 6 | 1 | 7 | 1 |
| $PO_4^{2-}$ | 3 | 0 | 4 * | 0 |
| $K^+$ | 186 | 5 | 181 | 16 |
| $SO_4^{2-}$-S | 9 ** | 2 | 4 | 1 |
| $Ca^{2+}$ | 934 | 50 | 884 | 90 |
| $Mg^{2+}$ | 250 | 9 | 253 | 23 |
| $Mn^{2+}$ | 9 | 2 | 8 | 2 |
| $Fe^{2+}$ | 12 | 2 | 8 | 1 |
| $Cu^{2+}$ | 0.4 | 0.1 | 0.3 | 0.0 |
| $Zn^{2+}$ | 0.6 | 0.1 | 0.5 | 0.1 |
| $BO_3^-$-B | 1.1 | 0.1 | 0.9 | 0.1 |

Significance level (ANOVA): 0.01, 0.05 = **, * (n=36) release of orthophosphate into the soil solution (Li et al., 2007, Sylvia et al., 2005; Brady and Weil, 2002; Barber, 1995; Marschner, 1997). This acidification effect of the rhizosphere could explain the higher P supply rate to the PRS$^{TM}$-probes, which are buried next to the plants roots outside the REC.

Regardless of the PRS$^{TM}$-probe placements inside or outside the REC, the PRS$^{TM}$-probes measured nutrient supply rate differences in N fertilizer treatments. These trends are shown in Table 3.3; the different PRS$^{TM}$-probe placements did not alter the direction of N fertilizer effect on N, P, and K fluxes. That is, in N fertilized treatments, inorganic N supply rates were higher compared to zero N fertilizer. For P and K supply rates in N fertilized treatments were generally lower compared to zero N fertilizer. These trends appear regardless whether measurements were taken in or outside the REC (Table 3.3).

The approach of burying PRS$^{TM}$-probes *in-situ* both inside and outside of the REC can provide a more complete picture of the soil nutrient supply dynamics. The difference between ion fluxes inside and outside of REC can be used as an index of plant nutrient uptake (Huang and Schoenau, 1997). In this study, if this approach of estimating the index of plant nutrient uptake would have been taken, it could not be applied to P and K supply rates in the DS system and to P supply rate in the CT system. Because these ion fluxes were greater outside compared to inside the REC (Table 3.6). Therefore, a negative value would be obtained as an index of plant nutrient uptake.

## 3.5 CONCLUSION

The anticipated result of this field study was to gain a better understanding of a wide variety of soil macro-and micronutrient supply rates and their responses to intercropping treatments, application of N fertilizer, and grain yield in a dryland agricultural system. PRS$^{TM}$-probe measurements of nutrient supply rates were related to agronomic performance (grain yield) affected by N fertilizer and intercropping treatments in this one-year field experiment. Furthermore, the study provides insight on the optimum sampling times for observing treatment differences in nutrient supply rates and whether PRS$^{TM}$-probe placements (in row or in root exclusion cylinders) affected nutrient supply dynamics.

Wheat yield, in the CT system, was significantly higher in N fertilized (p-value < 0.05) compared to non-fertilized treatments where urea fertilizer was applied. There were no significant differences in wheat yield among the intercropping treatments in either the DS or the CT systems. In treatments that received N fertilizers, in both DS and CT systems, the PRS$^{TM}$-probes identified an increase in N supply associated with observed grain yield response to added fertilizer N. The PRS$^{TM}$-probe measurements provided similar results as the traditional soil test for inorganic N with added N fertilizer. Few or no differences were observed for intercropping treatments. Therefore, PRS$^{TM}$-probes did not detect a difference in nutrient supply for intercropping treatments where no grain yield response was recorded.

In this study, PRS$^{TM}$-probes were most successful in measuring greater nutrient supply rates earlier in the observation period (April), at a time that was associated with higher soil moisture. Differences between N fertilizer treatments were found early in the observation period and suggest that early measurements were more useful in relation to estimating wheat yield response. Lastly, PRS$^{TM}$-probe placements (in row or in root exclusion cylinders) did not affect the supply rates of most nutrients during the early sampling (April) when nutrient fluxes were greatest and measured values were related to grain yield. This indicates that different PRS$^{TM}$-probe placements may not be essential for nutrient measurements in this dryland cropping system.

This study shows that the fluxes of soil nutrient ions depend on soil moisture and biological factors. Since soil moisture and MBC decreased over the growing season, so did nutrient supply rates. Low soil moisture may have impaired the rate of decomposition, microbial growth, and diffusion of ions. Therefore, future PRS$^{TM}$-probe samplings should be conducted earlier in the growing season (e.g., in February or beginning of March) or based on gravimetric water content more than 15% to get greatest sensitivity in detecting treatment differences in this dryland agriculture system. Measurements could be omitted after the middle of May when gravimetric water content is less than 15- 10%. In addition, PRS$^{TM}$-probe monitoring may not be ideally suited for identifying pea-wheat nutrient interactions in this dryland cropping system because peas do not produce much biomass (i.e., root growth) until later in the season (May) after most of the topsoil has dried out.

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