Spatial distribution of soil fertility at Winchmore Research Station

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For the Fertiliser Association of New Zealand

Executive Summary

The Winchmore phosphorus (P) fertiliser trial was initiated in 1952 and is the longest-running replicated grazed pasture experiment in the world. The initial objective of this trial was to determine the pasture response to different rates of single superphosphate fertiliser (SSP) under border dyke irrigation. In 2018, irrigation management was changed to centre pivot spray irrigation. Irrigation and fertilisation are critical management practices to maintain plant productivity of grazed pastures in New Zealand. However, flood irrigation along with excess SSP fertiliser applications can cause redistribution and accumulation of P and S in soils, along with risks of nutrient leaching below the active root system of pastures. Changes in irrigation management can have a significant effect on the distribution of soil nutrients as well as their risk of losses by runoff and leaching. Therefore, assessing the three-dimensional distribution of soil chemical characteristics and nutrient available pools before conversion to centre pivot irrigation is crucial as a baseline for understanding the effect of changed irrigation management on soil nutrient distribution at the Winchmore fertiliser trial.

Across and down the border strip distribution of Olsen P, soil pH, sulphate sulphur (S), and extractable organic sulphur were investigated in three treatments (control, 188, and 376 kg SSP $ha^{-1}yr^{-1}$) and two soil depths (0-75 and 75-175mm) at the Winchmore fertiliser trial. Moreover, the same parameters were investigated for down border strip effect in the 5 treatments (control, 188, 250, and 376 kg SSP $ha^{-1}yr^{-1}$ and 175 Sechura rock phosphate $ha^{-1}yr^{-1}$) present at the Winchmore fertiliser trial at four different soil depths (0-75, 75-150,150-300, and 300-500mm). Comparison between Olsen P in three treatments (control, 188, and 376 kg SSP $ha^{-1}yr^{-1}$) at the Winchmore fertiliser trial and two treatments (dryland and 20% irrigation) from the Winchmore irrigation trial (unpublished data) was carried out to determine across and down the border strip effects on Olsen P in the topsoil (0-75mm).

Results showed that Olsen P, soil pH, and extractable organic sulphur were significantly higher in the border crutches compared to the strip of the plot. Increases of these soil parameters in the border crutches were ascribed to sheep grazing behaviour and irrigation, causing an accumulation of plant residues and animal excreta in these areas compared to the strip. Across P treatments and soil depths, no down border strip effect was observed for all the parameters measured, suggesting that flood irrigation had no impact on down strip fertility distribution. In general, soil pH was lower under fertilised treatments compared to the control and increased with increasing soil depth. Olsen P concentrations were significantly higher under fertilised treatments compared to the control and increased with increasing P rates, especially in the topsoil (0-75mm). Superphosphate fertilisation increased sulphate sulphur concentrations compared to the control, but differences between fertilised treatments were not significant. A similar pattern was observed for extractable organic sulphur concentrations. Olsen P concentrations were significantly higher under fertilised treatments in the subsoil, especially in the 376 SSP treatment, and higher accumulation at depth was observed from the border crutches. Sulphur, either as sulphate or organic form, was accumulating to depth regardless of P rates and forms. Accumulation at depth of S and P was attributed to leaching due to the stony nature of the Lismore soil present at the Winchmore research site and its low adsorption capacity for P and S along with the higher accumulation of nutrients, especially in the border crutches. Fertilised and non-irrigated treatment (dryland) exhibited lower accumulation of Olsen P in the border crutches compared to fertilised and irrigated treatments (188 SSP, 250 SSP, 376 SSP), while irrigation had no impact on down border strip distribution of bioavailable P regardless of P treatment.

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Acknowledgement

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Introduction

Superphosphate fertiliser has been integral to the development of the New Zealand agricultural industry due to the importance of both sulphur (S) and phosphorus (P) for plant growth. Legumes (clovers), in particular, have high requirements of S and P due to their critical roles in the nitrogen fixation process. The impact of superphosphate and various application rates has been studied for many years at the Winchmore Research Station. Over the period from 1949 to 1952, two long-term trial sites were established to analyse the effects of varying rates of superphosphate under constant irrigation levels (the Winchmore fertiliser trial) and varying levels of irrigation under constant rates of superphosphate application (the Winchmore irrigation trial), both of which were managed under sheep grazing (Rickard and Moss, 2012).

After 66 years, the Winchmore fertiliser trial has been subject to a vast amount of testing covering a wide range of topics (Cousins and McDowell, 2012). Some of which include; the accumulation and distribution of phosphorus in the soil profile, the effects of long term fertiliser applications on the quantities of organic carbon, the effects of long-term superphosphate applications on phosphorus fractions in the soil and how management practices affect soil carbon storage (Condron and Goh 1989; Nguyen and Goh 1992a; Condron et al. 2012; Wakelin et al. 2017). Typically, the trial site has been irrigated through border dyke irrigation for more than 65 years (Rickard and Moss, 2012). This can move nutrients around the site due to the large volumes of water applied. The trial site has been converted from border dyke irrigation to centre pivot irrigation in September 2018. To determine how changes in irrigation management influence spatial soil fertility across the plots, an assessment of soil fertility distribution across and down the border strip is critical to be undertaken before this change occurs.

Under grazed pastures, the distribution of soil fertility can be affected by many factors, including animal grazing behaviour, rainfall and irrigation (runoff/leaching), nutrient application and topography, among other factors. Soil fertility has been shown to build up in the border crutches due to animal camping behaviour; however, there was much less variation down the length of the plot (Williams and Haynes 1992; Saville et al. 1997). Grazing animals cause the movement of nutrients due to the concentration of nutrients under urine and dung patches (Williams and Haynes 1990). In a study conducted on merino sheep grazing flat land, Hilder (1966) found that about one-third of the total dung was deposited on less than 5% of the total area of the field. Animals only use a small amount of the nutrients they ingest, with 60-95% of ingested nutrients returned to the pasture in urine and dung (Haynes and Williams 1993). Therefore, losses of nutrients from these small areas where nutrients accumulate are expected (Hilder 1966).

Loss from the soil profile due to overland flow or leaching are also known causes of nutrient loss. Nutrient loss due to overland flow is typically by sediment loss (erosion) when occurring on steeper typography or bare soils. In soils taken from the Winchmore fertiliser trial and subjected to artificial rainfall, McDowell et al. (2003) found that P in overland flow depended on P rates and the form of P applied. However, there is little information on the nutrient movement caused by the overland flow of pasture covered soils. It is expected that the flow of the water over land will have some impact on the movement of nutrients through dung floatation and soil erosion under grazed pastures (Williams and Haynes 1992; Saville et al. 1997; Carey et al. 2004). Where these animal excreta and sediments deposit, a build-up of nutrients is expected. Unpublished data from the Winchmore irrigation trial showed non-significant evidence of down border fertility distribution. Therefore, irrigation was believed to have little to no impact on soil fertility distribution, with the majority of the distribution being attributed towards grazing (Dudler-Guela 2001, Unpublished data).

This document reports on analysis of soil test results from soil samples collected in autumn and December of 2018 from the Winchmore fertiliser trial, and archived samples. Analysis results from soil samples taken from the Winchmore irrigation trial in May 2001 were also used.

Methods

1. Trial Site

Winchmore Research Station is located 10 kilometres inland of Ashburton, mid- Canterbury, New Zealand, on Lismore stony silt loam soil. Winchmore has a mean annual rainfall of 728 mm spread relatively evenly throughout the year. During the years of 1949 – 1952, two long-term trial sites were established to analyse the effects of varying rates of superphosphate (0, 188, 376 kg SSP $ha^{-1}yr^{-1}$) under constant irrigation levels and varying rates of irrigation under constant levels of superphosphate application (250 kg SSP $ha^{-1}yr^{-1}$) both under sheep grazing.

History of the trial

In the winter of 1948, the area was ploughed out of brown top, and after a summer fallow was bordered, and then green feed was sown in the autumn of 1949. Again, after winter ploughing, the site was summer fallowed and then sown into pasture. The pasture mix was as shown in Table 1. Five T ha^{-1} lime was applied over this period, half with the green feed crop and half at the time of pasture sowing. Superphosphate was also applied at the rate of 375 kg ha^{-1}, 125 kg ha^{-1} with green feed sowing and 250 kg ha^{-1} at the time of pasture sowing. The trial started in 1952, at that time, the pasture was perennial ryegrass and white clover dominant. Throughout the trial, treatments that have received superphosphate applications have remained ryegrass and white clover dominant (Rickard and Moss 2012). The trial was irrigated by border dyke irrigation at a rate of 100 mm when the gravimetric soil moisture content of the top 100mm reached about 15% until 1996 when it changed to irrigation at 20% gravimetric soil moisture content in the top 100mm of the soil. In 2018, the irrigation method was changed from border dyke irrigation to spray (pivot) irrigation. This occurred to keep the trial relevant to on farm practice. During the change to pivot irrigation, minimal disturbance of the trial occurred with all new fences going back on the same line as the old ones, the borders remaining. The only major difference is that there is now one small area where one wheel passes through the trial. Also, during the conversion period, the plots were not grazed due to having fence work done. The plots were mowed once to ensure the pasture quality was maintained and to keep the trial as similar to a grazed pasture as possible during that time.

Table 1. Pasture mix sown at Winchmore, February 1950 (taken from Rickard and Moss (2012)).

Species	Sowing rate (kg ha^{-1})
Perennial ryegrass (*Lolium perenne*)	17
Short rotation ryegrass (*Lolium multiflorum*)	17
Cocksfoot (*Dactylis glomerata*)	6
Timothy (*Phleum pratense*)	6
Crested Dogstail (*Cynosurns cristatus*)	1
White clover (*Trifolium repens*)	2
Subterranean clover (*Trifolium subterranean*)	2
Red clover (*Trifolium pratense*)	2

2. Treatment and trial design

The Winchmore fertiliser trial was designed to evaluate the effects of five different superphosphate treatments on pasture production under grazing, namely, 1, 2, 3, 4 and 5 corresponding to the application of 0, 188, 376, 376, and 564 kg SSP $ha^{-1}yr^{-1}$. Treatments 4 and 5 were discontinued in 1958 to measure their residual effects until 1980. After 1980, they were replaced by two new treatments, namely 250 kg SSP $ha^{-1}yr^{-1}$ and 175 kg Sechura RPR $ha^{-1}yr^{-1}$ + elemental sulphur, which have been carried out since then. There were four repetitions of each treatment in a randomised block design, with each plot being one border in the previous border dyke irrigation system separately fenced (Smith et al. 2012). Each treatment has had the same rate (100 mm) of irrigation application, initially applied when gravimetric soil moisture reached 15%. However, this changed to 20% in 1996 (Rickard and Moss 2012). Each treatment was grazed by separate mobs of sheep, which rotated between replicates. All plots in one block of treatments were grazed at the same time. To remove the possibility of nutrient transfer, sheep are emptied out for 24 hrs prior to moving on to the trial. Plots were grazed to provide 80% annual removal by 1 year ewes (hogget's) (Rickard and Moss 2012). The number of animals grazing each treatment varied depending on the pasture growth of each treatment. The ewes were sourced from the same main flock every year. The fertiliser was applied in winter by top dressing where the top dresser was set at slightly less than the required amount, and the deficit was applied by hand. This method was used to ensure over applying does not occur (Rickard and Moss 2012).

The irrigation trial was established in 1949 and comprised five irrigation treatments, namely dryland (no irrigation), 3 weekly irrigations during the irrigation season (3w irrigation), irrigation when topsoil reached 10 % of gravimetric soil moisture (10% irrigation), irrigation when topsoil reached 15 % of gravimetric soil moisture (15% irrigation), and irrigation applied when topsoil reached 20 % of gravimetric soil moisture (20% irrigation) (Rickard and Moss 2012). The trial included 5 replicates of each irrigation treatment and 4 replicates of the dryland treatment, with each plot measuring approximately 0.12 ha. All treatments received 250 kg SSP $ha^{-1}yr^{-1}$ in winter. Each treatment has been rotationally grazed by a separate flock of sheep. Lime was applied to the whole trial (Fertiliser + irrigation trials) in 1948 (5 T ha^{-1}) and 1965 (1.9 T ha^{-1}) to maintain soil pH at 5.5–6.0 (Rickard and Moss 2012).

3. Sampling

This report used three data sets. These were collected by Kendal Buchanan (summer school student at AgResearch), Ray Moss and Trevor Knight (AgResearch), and Judith Dudler Guela (exchange student from ETH Zurich at Lincoln University). Samples taken by Kendal Buchanan in December 2018 will be referred to as data set A, Ray Moss and Trevor Knight samples as data set B, and Judith Dudler Guela samples as data set C. In data set A, soil samples were taken at 25 locations on each plot, five across by five down, as shown in Figure 1. At each sample location, 5 cores to 75mm depth were taken and bulked to ensure the sample was representative of that site and to ensure sufficient volume was obtained to enable archiving for later use. A sample from 75mm to 175mm was also taken with the same method at each site and archived for future use. Samples were then sieved through a 2mm sieve and dried at 37 degrees Celsius until dry. Samples were then sent to ARL for soil pH, Olsen P, sulphate sulphur, and extractable organic sulphur testing. Sub-samples were taken to enable this testing, and the remainder of the samples was returned to AgResearch Limited for archiving.

Samples were labelled so that they match (autumn 2018) soil samples taken in Dataset B (as shown in Table 2), where 4 depths and 4 positions down the middle of each plot were sampled. The numbering system they used was incorporated into the numbering system of samples taken in this instance so that the spatial distribution of the two sample collections could be easily related to each other.

Table 2. shows the sample numbering system used in Dataset B. The samples were labelled using their first digit to identify their vertical position within the plot (successive numbers in Table 2.), then the second digit their horizontal position within the plot (1,2,3,4, or 5) and then depth (A, B, C, or D). For example, in the data set A, the first sample taken was 6-1-A and the second (working across the plot) was 6-2-A. The sampling method ensured the middle sample (3) was in the same location as the autumn sampling in Dataset B (the 5 cores were taken around the previous sample locations, which could be easily seen). Five sight poles were set up equidistant apart in the long fence lines of plots 1, 6, 11 and 20. At least 2 sight poles could be used at all times to find the line which gave the position of the middle sample sight horizontally. The remaining 4 points in the horizontal direction from that plot were made at right angles to the fence line (this was, however, not on the line of the site poles due to the plot setup). The crutch samples (samples 1 and 5) were taken at the immediate bottom of the border. The distance between the two crutch samples was then measured, and the middle sample site (3) was halfway between the two crutch points. The off-centre samples (2 and 4) were taken halfway between the midpoint and the crutch points. This was repeated for the 5 locations down the plot (T, IT, M, IB and B or: Top, In-between Top and Middle, Middle, In-between Middle and Bottom, and Bottom). Please note that the longitudinal notations (T, IT, M, IB and B, as shown in Figure 2) were used for data processing in place of the numbers used for sample collection where the location on the plot was being referenced as opposed to overall position. Latitudinal references were 1, 2, 3, 4, 5 from west to east (as shown in Figure 2).

Soil samples in data set B were taken in autumn 2018 from all P treatments present on the Winchmore fertiliser trial and were incorporated into this study. Those were taken from the five P treatments present at the Winchmore fertiliser trial from the centre of each plot at 4 different locations down the plot (T, IT, IB and B) and 4 soil depths (A=0-75, B=0-150, C=150-300, and D=300-500mm). Samples were dried then sieved through a 2mm screen and stored prior to forwarding to the ARL lab during February 2021 to analyse soil pH, Olsen P, sulphate sulphur and extractable organic sulphur.

Soil samples in data set C were taken from the Winchmore irrigation trial in May 2001 and were also used. Those have been sampled from two treatments: the control (dryland) and the 20% irrigated. Samples have been taken from the topsoil (0-75mm) at different locations down the plot (T, IT, M, IB and B) and across the plot (crutch, off-centre, middle). Soil samples have been analysed for Olsen P.

Figure 1: Experimental Design; each orange dot represents one sample point

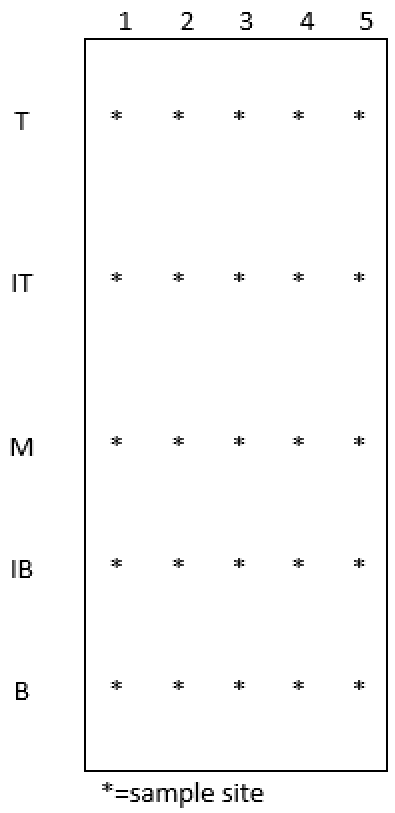

Figure 2: Sampling design and naming reference

Table 2 : Dataset B sample numbering system

Treatment	175	375	c	250	188	c	375	175	250	188	c	188	175	375	250	375	250	175	188	c
Plot number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
sample number in postion on plot	1	6	11	16	21	26	31	36	41	46	51	56	61	66	71	76	81	86	91	96
	2	7	12	17	22	27	32	37	42	47	52	57	62	67	72	77	82	87	92	97
	3	8	13	18	23	28	33	38	43	48	53	58	63	68	73	78	83	88	93	98
	4	9	14	19	24	29	34	39	44	49	54	59	64	69	74	79	84	89	94	99
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100

4. Soil analyses

Soil samples were analysed for soil pH, Olsen P, sulphate sulphur, and extractable organic sulphur at ARL laboratory in data sets A and B and for Olsen P in data set C. Soil pH was carried out at the standard ratio of 1:2.5 soil/water after mixing and equilibration for 1-4 hours (Blakemore et al. 1987). Olsen P was determined by extracting air-dried soil with 0.5M $NaHCO_3$, adjusted to pH 8.5 for 30 minutes at soil/solution ratio of 1:20 (Watanabe and Olsen 1965). Sulphate sulphur was extracted with 0.02M KH_2PO_4 for 30 min at a soil/solution ratio of 1:10. Sulphate in the extract was determined by ion chromatography (Watkinson and Kear 1994). Extractable organic sulphur was calculated by subtracting sulphate sulphur from total extractable sulphur. Total extractable sulphur was determined by extracting with 0.02M potassium dihydrogen phosphate (KH_2PO_4) at a 1:10 soil/solution ratio (v/v) for 30 minutes. Total extractable sulphur in the extract was determined by ion chromatography (Watkinson and Kear 1996).

5. Statistical analysis

Soil pH, sulphate sulphur, and extractable organic sulphur were log-transformed to carry out statistical analyses. Although Olsen P concentrations were log-transformed, they were still not normally distributed; thus, non-parametric tests were used to statistically analyse this parameter. Data set A was subjected to a three-way analysis of variance (ANOVA) to test the effect of P treatment, down the border strip effect, across the border the strip effect and their interactions at each soil depth (0-75 and 75-175mm). Data set B was subjected to three-way ANOVA to test the effect of P treatment, down the border strip effect, soil depth, and their interactions. In the presence of a significant effect, one-way ANOVA was performed followed by Tukey post-hoc test to separate group means. For Olsen P, Kruskal Wallis test (non-parametric test) was performed, followed by Dunn's-Benferroni post-hoc test to separate group means. To compare data sets A and C, Olsen P was subjected to a non-parametric test (Friedman's test) to test the across and down the border strip effects. In the presence of a significant effect, Kruskal Wallis test was performed, followed by Dunn's-Benferroni post-hoc test to separate group means. The level of significance was set at 5% probability.

Results

1. Data set A

Olsen P:

Phosphorus applications significantly increased Olsen P concentrations compared to the control at both soil depths (Tables 3 and 4). Regardless of soil depths and P treatments, concentrations of Olsen P were significantly higher in the border crutches (east and west) compared to the strip. In the 0-75mm depth, Olsen P concentrations increased by 1.92, 3.65, and 1.8-fold in the border crutches compared to the strip in the control, 188 SSP, and 376 SSP treatments, respectively (Figure 3). Whereas, in the 75 -175mm depth, Olsen P concentrations increased by 1.36, 4.09, and 3.18-fold in the border crutches compared to the strip in the control, 188 SSP and 376 SSP treatments, respectively. Irrespective of soil depths, no down plot effect was observed for Olsen P concentrations, except for the 188 SSP treatment in the 75-175mm soil depth. Olsen P concentrations decreased with increasing soil depth irrespective of P treatment.

Soil pH:

In general, the control showed significantly higher soil pH compared to the fertilised treatments (188 SSP and 376 SSP), especially in the topsoil (0-75mm) and across the plot. There was no evidence for increased acidification with increasing superphosphate rate. Soil pH was significantly higher in border crutches (east and west) compared to the strip regardless of P treatment (Figure 4). This trend was only significant in the topsoil (0-75mm) (Table 3 and figure 4). In the 0-75mm depth, an increase by 0.16, 0.28, and 0.2 unit was observed between the border crutches and the strip in the control, 188 SSP, and 376 SSP treatments, respectively. Soil pH increased with increasing soil depth regardless of P treatments.

Sulphate sulphur:

In both soil depths (0-75 and 75-175mm), sulphate sulphur concentrations were significantly higher in fertilised treatments compared to the control across and down the plot (Tables 3 and 4 and figure 5). In the 0-75mm soil depth, although means of sulphate sulphur concentrations in 376 SSP were higher than 188 SSP treatment (average of 2.6 mg S kg^{-1}), differences were not statistically significant between the two treatments. Concentrations of sulphate sulphur decreased with depth, as did the differences between means of 188 SSP and 376 SSP treatments. In the 75-175mm depth, a significant across and down plot effect was observed for 188 SSP treatment, where higher concentrations of sulphate sulphur were observed in the west border crutch and the top of the plot. Sulphate sulphur concentrations decreased with increasing soil depth irrespective of P treatment.

Extractable organic sulphur:

Extractable organic sulphur concentrations were significantly higher in the fertilised treatments compared to the control, however differences between 188 SSP and 376 SSP were not significant. This trend was observed across and down the plot irrespective of soil depth (Tables 3 and 4 and figure 6). Concentrations of extractable organic sulphur were significantly higher in the border crutches (east and west) compared to the strip regardless of P treatments, except for 376 SSP in the 75-175mm depth. No down plot effect was observed for Extractable organic sulphur concentrations in both 0-75mm and 75-175mm depths. Extractable organic sulphur concentrations decreased with depth irrespective of P treatments. In the 0-75mm depth, extractable organic sulphur concentrations increased by 1.2-, 1,19-, and 1.24-fold in the border crutches compared to the strip in the control, 188 SSP, and 376 SSP, respectively. On the other hand, in the 75-175mm depth, Extractable organic sulphur concentrations increased by 1.16-, 1,12, and 1.07-fold in the border crutches compared to the strip in the control, 188 SSP, and 376 SSP, respectively. Extractable organic sulphur concentrations decreased with increasing soil depth irrespective of P treatment.

Table 3. Analysis of variance (*P*-values) for the effect of phosphorus treatment (PT), down border strip (DBS) and across border strip (ABS) on Olsen P, soil pH, sulphate sulphur and extractable organic sulphur taken from the control, 188 SSP and 376 SSP treatments at 0-75mm soil depth.

	Olsen P	**Soil pH**	**Sulphate sulphur**	**Extractable organic sulphur**
P Treatment (PT)	<0.001	<0.001	<0.001	<0.001
Down border strip (DBS)	ns	0.001	ns	0.023
Across border strip (ABS)	<0.001	<0.001	0.010	<0.001
PT * DBS	-	ns	ns	ns
PT* ABS	-	0.002	ns	ns
DBS * ABS	-	ns	ns	ns

Table 4. Analysis of variance (*P*-values) for the effect of phosphorus treatment (PT), down border strip (DBS), and across border strip (ABS) on Olsen P, soil pH, sulphate sulphur, and extractable organic sulphur taken from the control, 188 SSP and 376 SSP treatments at 75-175mm soil depth.

	Olsen P	Soil pH	Sulphate sulphur	Extractable organic sulphur
P Treatment (PT)	<0.001	<0.001	<0.001	<0.001
Down border strip (DBS)	ns	ns	ns	ns
Across border strip (ABS)	<0.001	ns	0.005	<0.001
PT * DBS	-	ns	ns	ns
PT* ABS	-	ns	ns	ns
DBS * ABS	-	ns	ns	ns

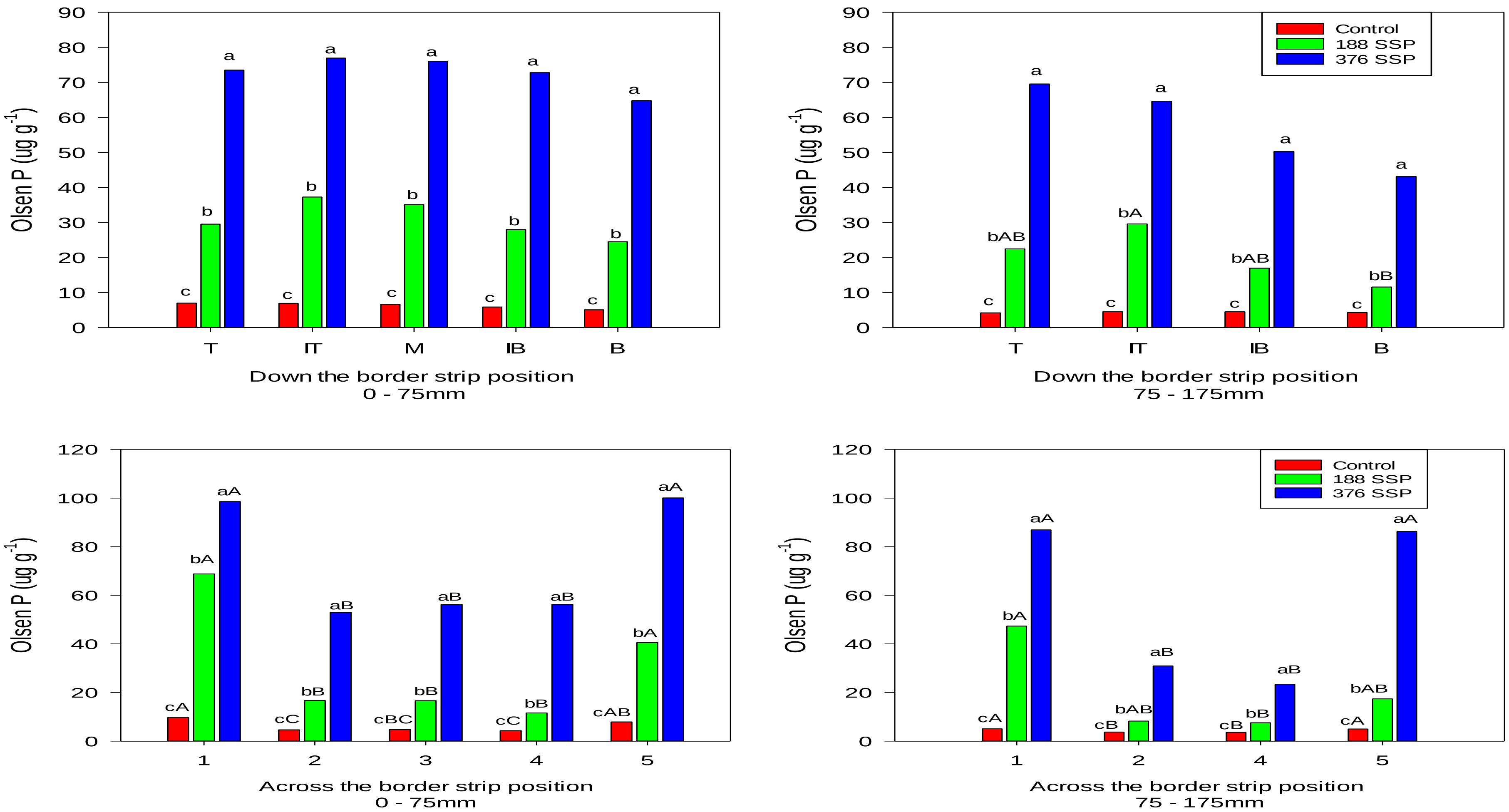

Figure 3: Across (top) and down (bottom) the border strip distribution of Olsen P in soil samples taken from 0-75mm (left) and 75-175mm (right) under the control, 188 SSP, and 376 SSP treatments. Different lowercase letters indicate significant differences (*P* < 0.05) between P treatments for a given across or down the border strip position, while different uppercase letters indicate significant differences (*P* < 0.05) between across or down the border strip positions for a given P treatment.

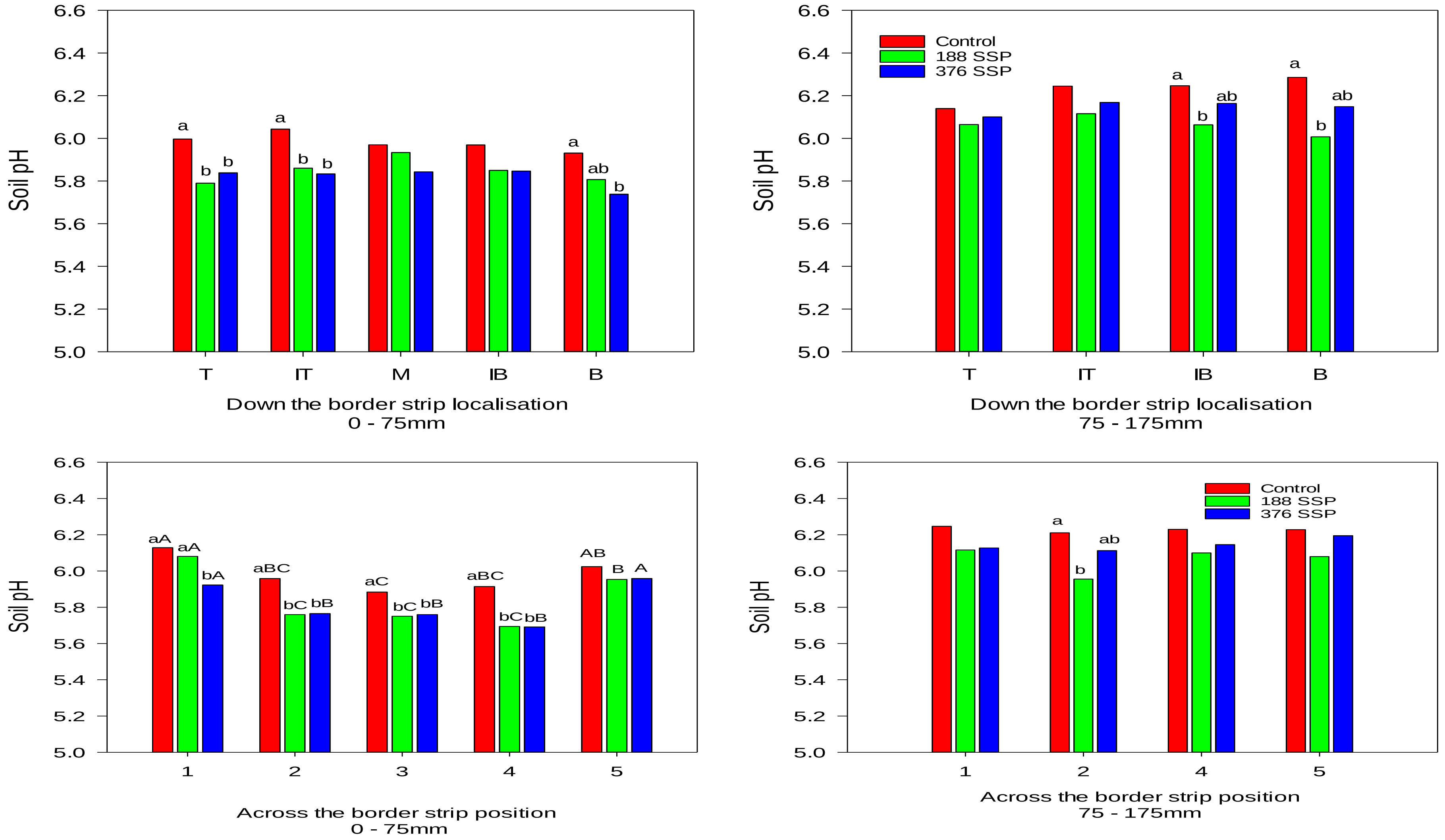

Figure 4: Across (top) and down (bottom) the border strip distribution of soil pH in soil samples taken from 0-75mm (left) and 75-175mm (right) under the control, 188 SSP, and 376 SSP treatments. Different lowercase letters indicate significant differences ($P < 0.05$) between P treatments for a given across or down the border strip position, while different uppercase letters indicate significant differences ($P < 0.05$) between across or down the border strip positions for a given P treatment.

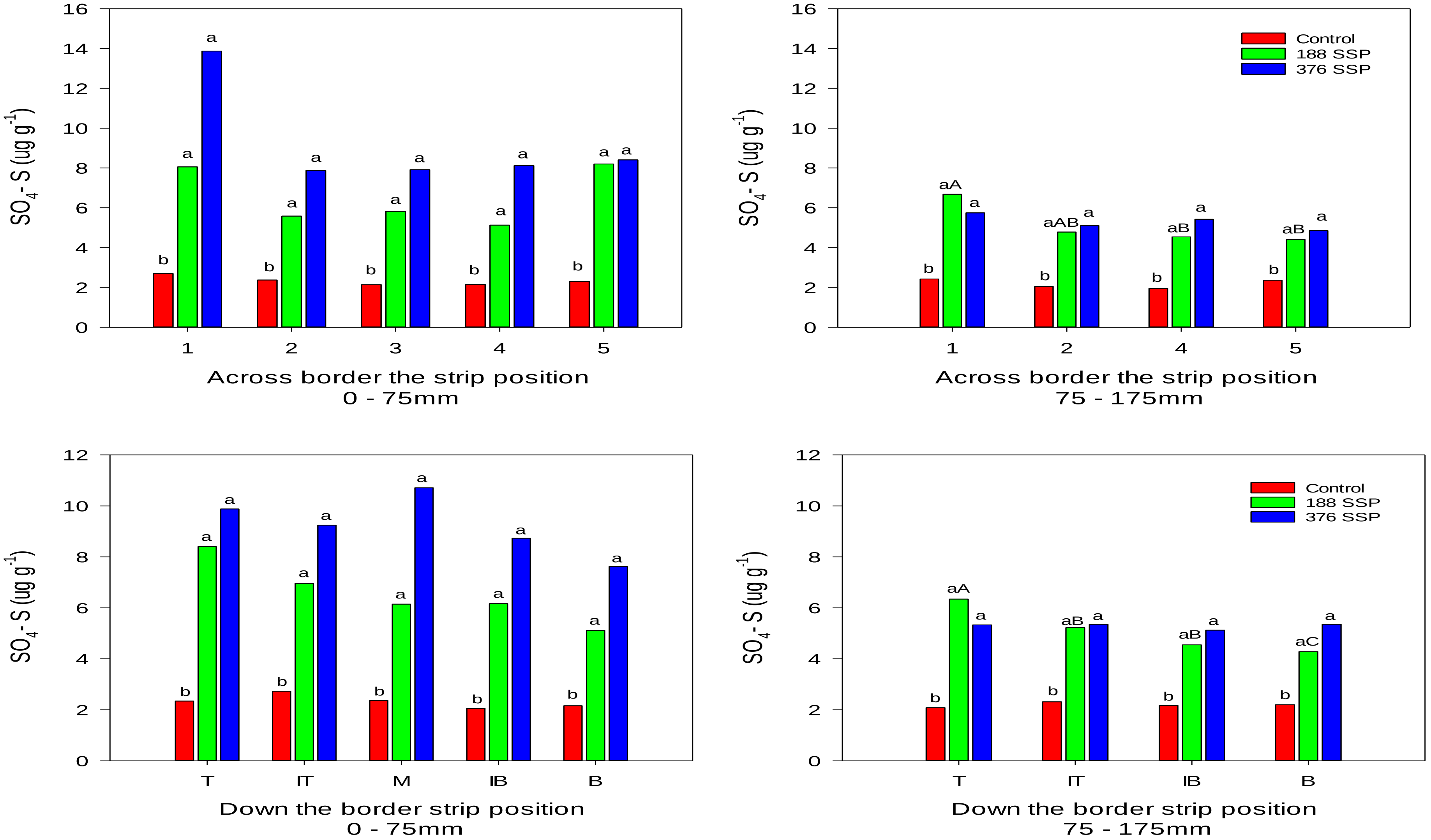

Figure 5: Across (top) and down (bottom) the border strip distribution of sulphate sulphur in soil samples taken from 0-75mm (left) and 75-175mm (right) under the control, 188 SSP, and 376 SSP treatments. Different lowercase letters indicate significant differences ($P < 0.05$) between P treatments for a given across or down the border strip position, while different uppercase letters indicate significant differences ($P < 0.05$) between across or down the border strip positions for a given P treatment.

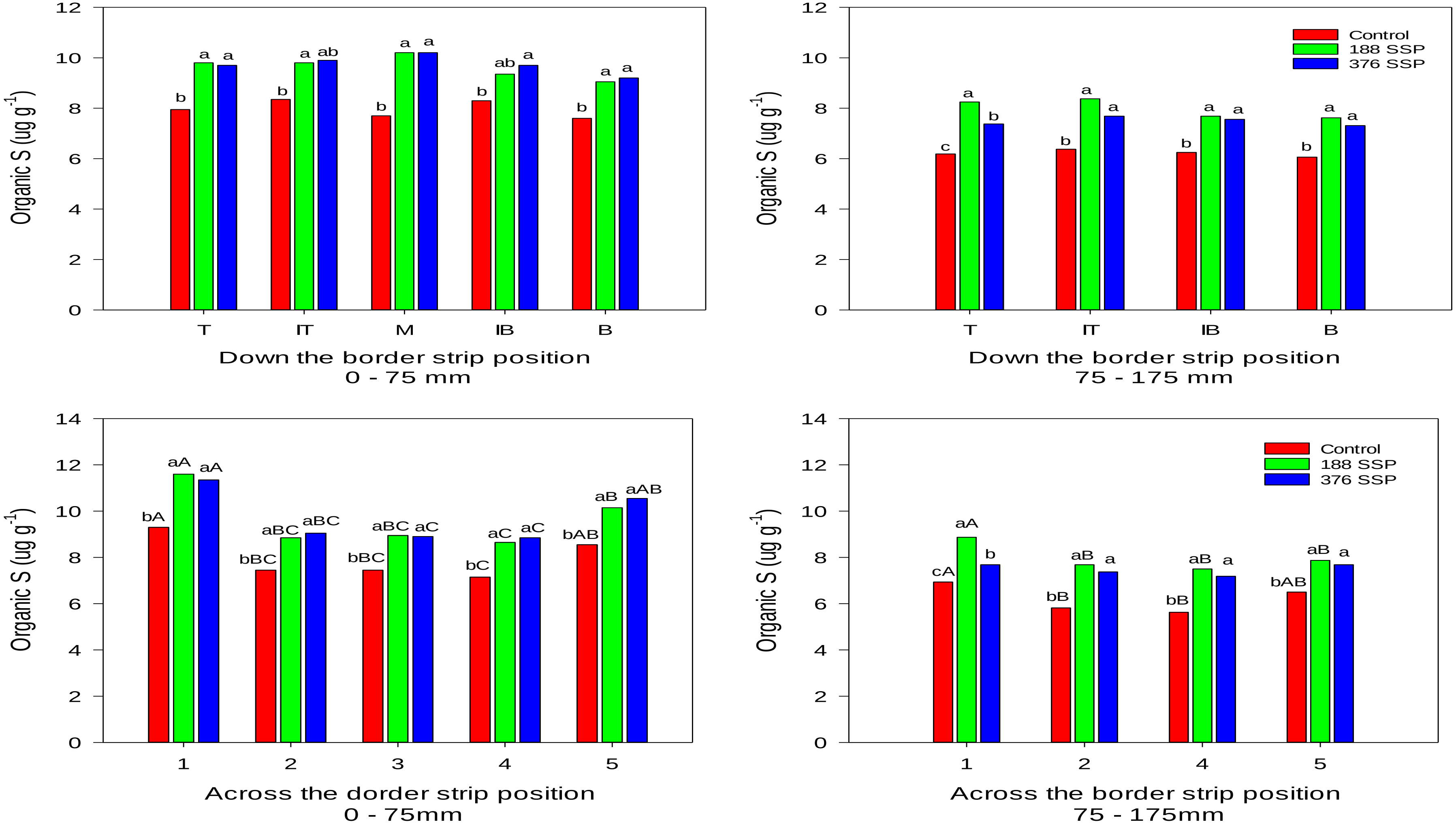

Figure 6: Across (top) and down (bottom) the border strip distribution of extractable organic sulphur P in soil samples taken from 0-75mm (left) and 75-175mm (right) under the control, 188 SSP, and 376 SSP treatments. Different lowercase letters indicate significant differences (*P* < 0.05) between P treatments for a given across or down the border strip position, while different uppercase letters indicate significant differences (*P* < 0.05) between across or down the border strip positions for a given P treatment.

2. Data set B

Olsen P:

Phosphorus fertilised treatments showed significantly higher concentrations of Olsen P compared to the control in the 0-75mm soil depth (Figure 7). In fact, in the topsoil, the 376 SSP treatment showed the highest Olsen P concentration, followed by 175 SRPR, 250 SSP, 188 SSP, and the control. In the 75-150mm soil depth, significant differences persisted in Olsen P concentrations between the control and the fertilised treatments. However, below 150mm soil depth, Olsen P concentrations were only significantly higher under the 376 SSP treatment compared to other P treatments. Regardless of soil depth, no down the plot effect was observed for Olsen P concentrations (Table 5 and figure 7). Olsen P concentrations decreased with increasing soil depth regardless of P treatments.

Soil pH:

In general, soil pH in the control was significantly higher than fertilised treatments regardless of soil depth. There was no evidence for increased acidification with increasing fertiliser rate and there was no difference between the RPR/elemental S and superphosphate treatments (Figure 8). No down the plot effect was observed for soil pH across soil depths and P treatments, except for 188 SSP in the 0-75mm depth (Figure 8). Soil pH increased with depth regardless of P treatments.

Sulphate sulphur:

In the 0-75 and 75-150mm soil depths, sulphate sulphur concentrations were similar down the plot and across P treatments, while below 150mm soil depth, fertilised treatments showed significantly higher concentrations of sulphate sulphur compared to the control (Figure 9). Although means of sulphate sulphur concentrations in the 376 SSP treatment were higher compared to other treatments and tended to increase from top to bottom of the plot, differences were not significant (Table 5 and figure 9). Sulphate sulphur concentrations decreased with depth irrespective of P treatment.

Extractable organic sulphur:

In 0-75mm depth, extractable organic sulphur concentrations showed no significant differences down the plot and across P treatments (Figure 10). In 75-150mm depth, fertilised treatments had significantly higher concentrations of Extractable organic sulphur compared to the control, but again differences between fertilised treatments were not statistically significant. From 150mm soil depth, extractable organic sulphur concentrations were significantly higher in the fertilised treatments compared to the control in the top half of the plot (Figure 10). Extractable organic sulphur concentrations decreased with depth regardless of P treatments.

Table 5. Analysis of variance (*P*-values) for the effect of phosphorus treatment (PT), soil depth (SD), and down border strip (DBS) on Olsen P, soil pH, sulphate sulphur, and Extractable organic sulphur taken from the control, 188 SSP, 250 SSP,175 SRPR, and 376 SSP treatments.

	Olsen P	Soil pH	Sulphate sulphur	Extractable organic sulphur
P treatment (PT)	<0.001	<0.001	<0.001	<0.001
Soil depth (SD)	<0.001	<0.001	<0.001	<0.001
Down border strip (DBS)	ns	0.001	ns	0.001
P * SD	-	ns	<0.001	ns
PT * DBS	-	0.009	ns	ns
SD * DBS	-	ns	ns	ns

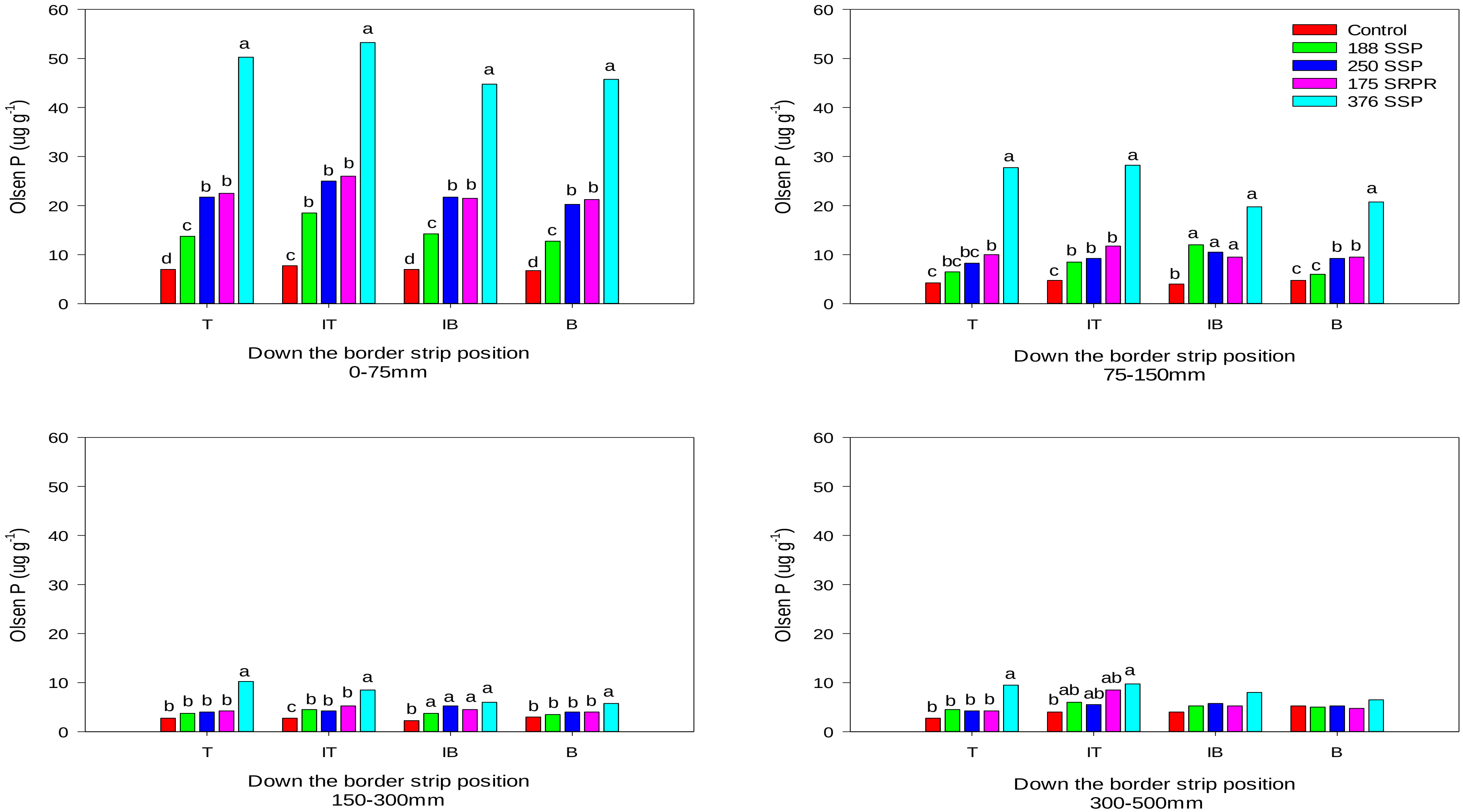

Figure 7: Down the border strip distribution of Olsen P in soil samples taken from different soil depths under the control, 188 SSP, 250 SSP, 175 SRPR, and 376 SSP treatments. Different lowercase letters indicate significant differences ($P < 0.05$) between P treatments for a given down the border strip position.

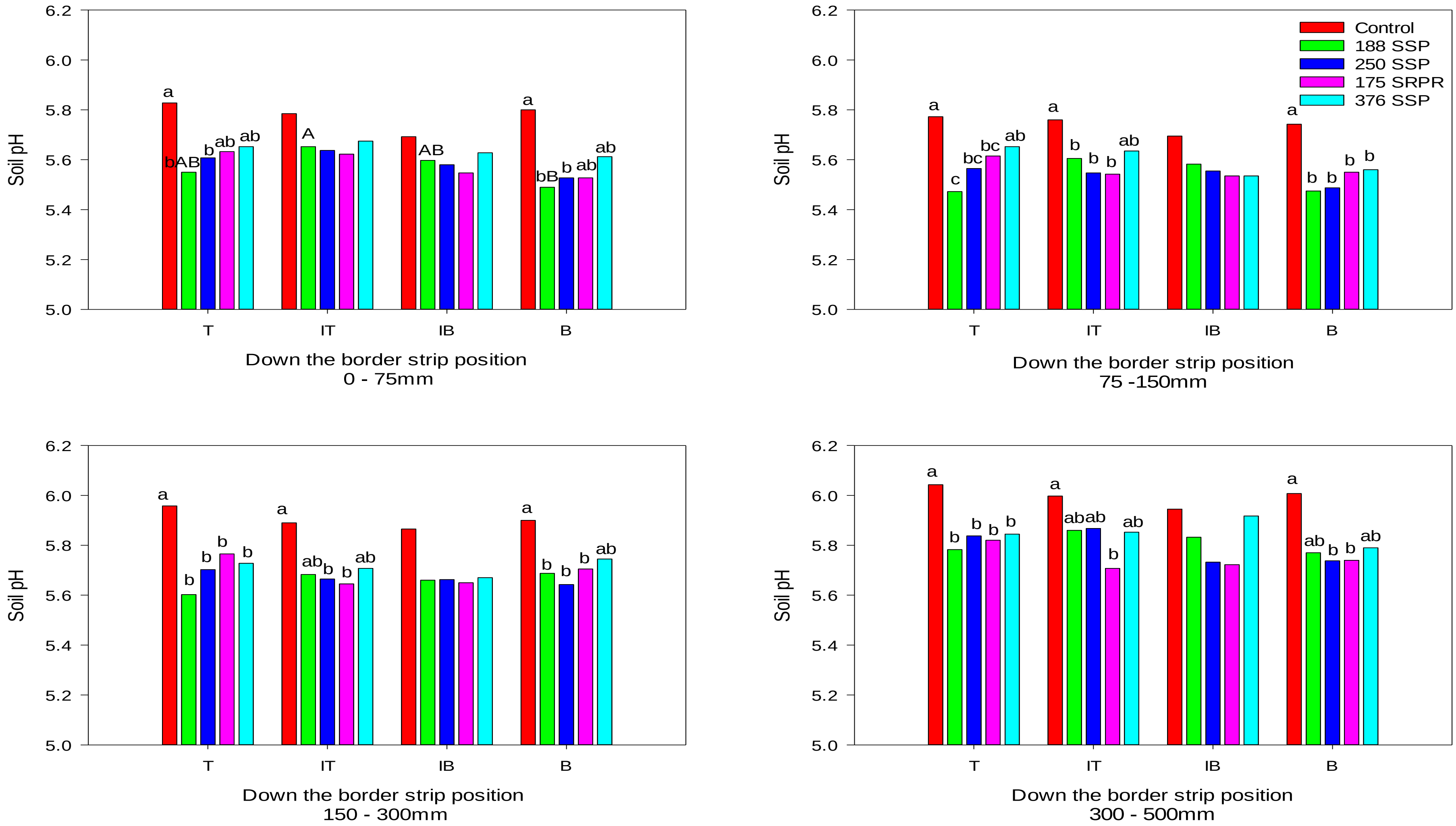

Figure 8: Down the border strip distribution of soil pH in soil samples taken from different soil depths under the control, 188 SSP, 250 SSP, 175 SRPR, and 376 SSP treatments. Different lowercase letters indicate significant differences (*P* < 0.05) between P treatments for a given down the border strip position.

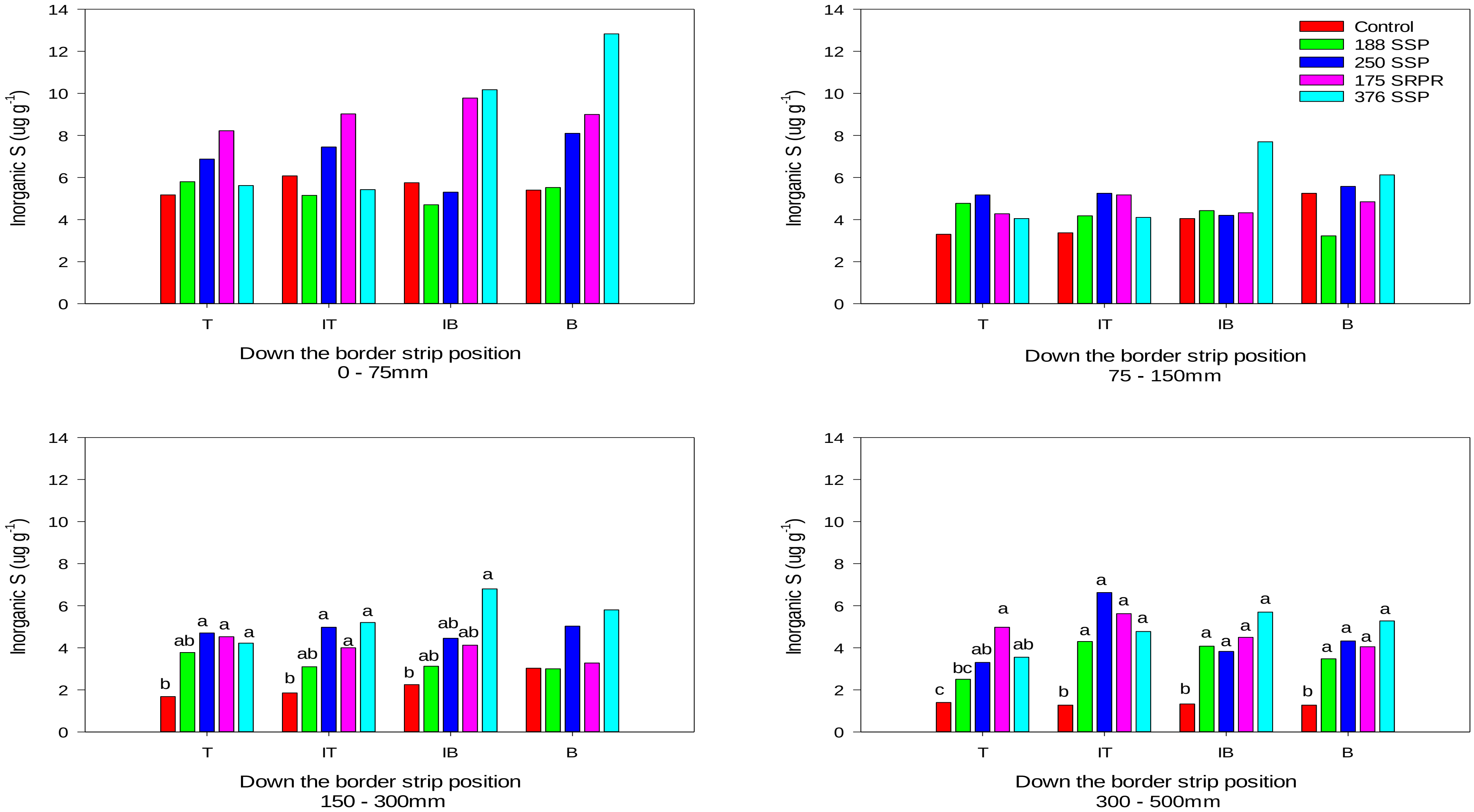

Figure 9: Down the border strip distribution of sulphate sulphur in soil samples taken from different soil depths under the control, 188 SSP, 250 SSP, 175 SRPR, and 376 SSP treatments. Different lowercase letters indicate significant differences ($P < 0.05$) between P treatments for a given down the border strip position, while different uppercase letters indicate significant differences ($P < 0.05$) between down the border strip positions for a given P treatment.

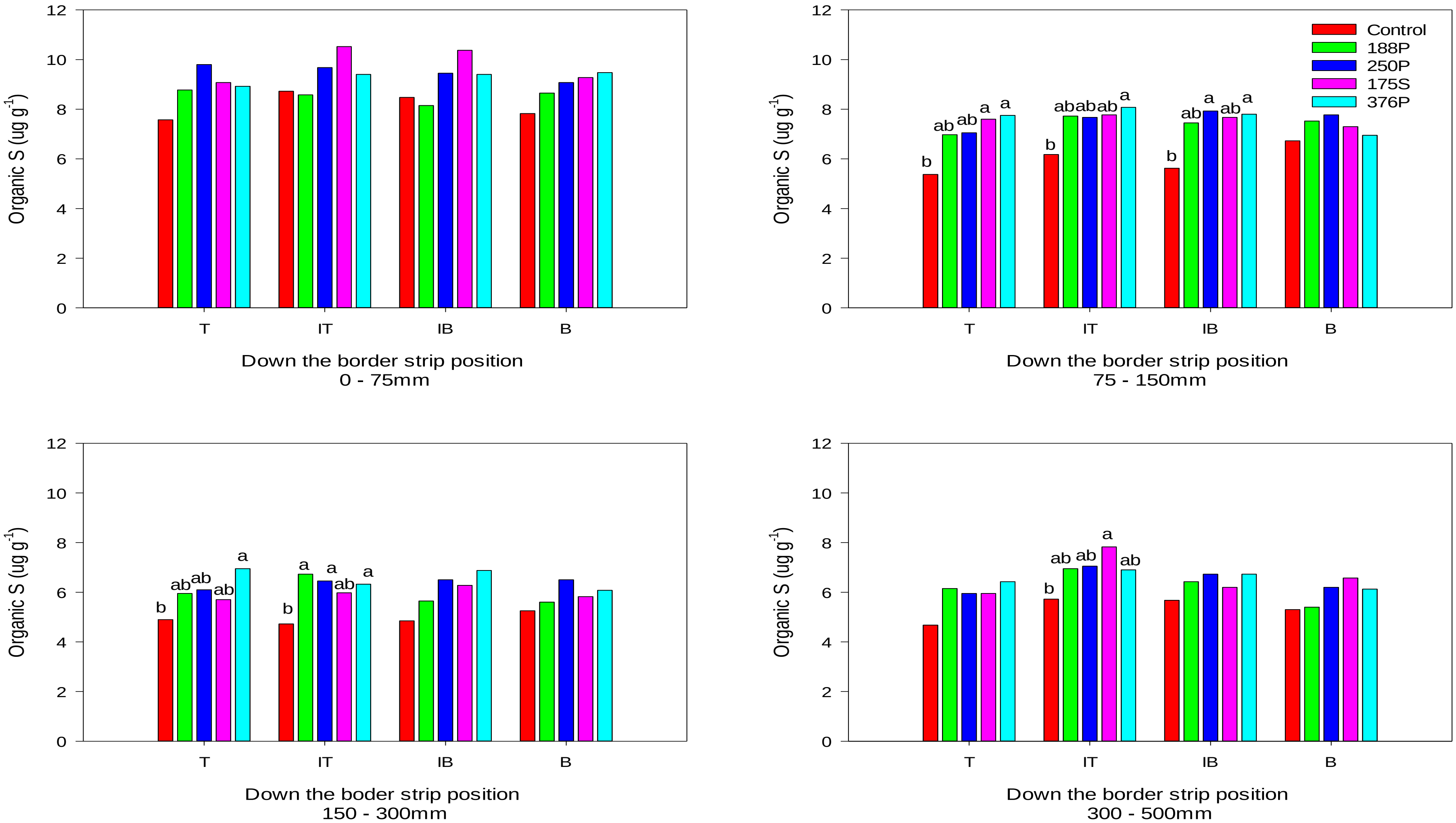

Figure 10: Down the border strip distribution of extractable organic sulphur in soil samples taken from different soil depths under the control, 188 SSP, 250 SSP, 175 SRPR, and 376 SSP treatments. Different lowercase letters indicate significant differences ($P < 0.05$) between P treatments for a given down the border strip position.

Comparison between data set A and C:

Olsen P:

Phosphorus fertilised and non-irrigated (dryland) as well as P fertilised and irrigated (188 SSP, 250 SSP, and 376 SSP) showed significantly higher Olsen P concentrations in the border crutch compared to the off-centre and the middle of the strip (Figure 11). Olsen P concentrations increased in the border crutch compared to the strip by factors of 1.9, 3.5, 1.8, 3.28, and 1.5 for the control, 188 SSP, 376 SSP, 250 SSP, and dryland, respectively. No evidence of down the plot effect was found in both irrigated and non-irrigated fertilised treatments (Figure 11).

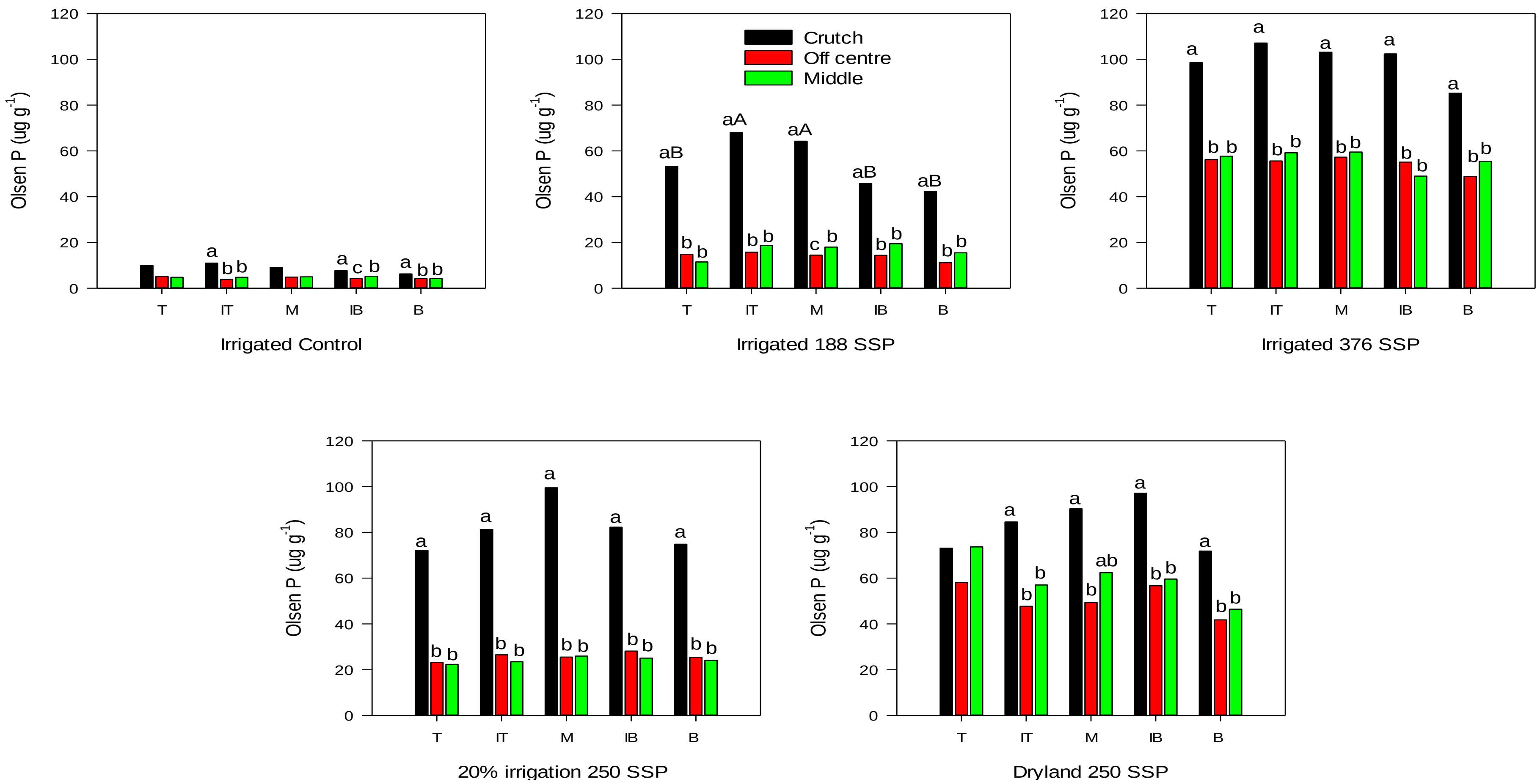

Figure 11: Across and down the border strip distribution of Olsen P in soil samples taken from 0-75mm soil depth of three treatments from the Winchmore fertiliser trial (control, 188 SSP, 376 SSP) and two treatments from the Winchmore irrigation trial (dryland 250 SSP and 20% irrigation 250 SSP). Different lowercase letters indicate significant differences (*P* < 0.05) between across the border strip positions for a given down the border strip position.

Discussion

1. *Olsen P*

The results of this study showed that P applications (188 SSP and 376 SSP) significantly increased Olsen P concentrations compared to the control in the topsoil (0-75mm) and the subsoil up to 175mm. Results also revealed that despite P fertilisers being evenly applied in the plots, there was a significant variation in P availability across the plots, with significantly higher concentrations of Olsen P in the border crutches compared to the strip. This trend has been observed across the control, the P treatments (188 SSP and 376 SSP) and soil depths (0-75 and 75-175mm). Past studies conducted on the topic have attributed this variation to stock behaviour and irrigation (Williams and Haynes 1992; Saville et al. 1997). Sheep graze the entire plot but camp along the crutch of the border. Sheep have been found to deposit approximately one-third of excreta in less than 5% of the paddock (depending on topography and management intensity), that area being their camping sites (Hilder 1966). Therefore, dung and urine accumulate in these areas. Animals only utilise a small amount of the nutrients ingested, and of those, 60 to 95% are excreted (Haynes and Williams 1999). The majority of excreted phosphorus is in the dung (Haynes and Williams 1993), which explains the higher Olsen P values present in the border crutches compared to the strip of the plot. Under border dyke irrigation, the deposit of dung in border crutches has been observed after irrigation events, especially when dung is dry (Saville et al. 1997). Having higher and greater plant biomass, border crutches can catch and accumulate higher quantities of dung, thereby increasing Olsen P concentrations compared to the strip.

Previous studies combining data of pasture production and bioavailable P have pointed out that Olsen P under the 376 SSP treatment was considerably above the agronomic optimum, which may increase P leaching (Nguyen and Goh 1992b; Edmeades et al. 2006). The stony and free-draining nature of the soil at Winchmore research station can increase P transfer to depth, especially when P applications exceed plant P demand (Toor et al. 2004; Tian et al. 2017). Lismore soil has been described as having a small P and S retention capacities (Nguyen et al. 1989; Tian et al. 2019) and P retention values of this soil were estimated to be less than 30% in the 0-150 soil depth (Carrick et al. 2013). Results from data set B confirmed that higher leaching of P was occurring in the 376 SSP treatments to a depth of 500mm, where 376 SSP had significantly higher Olsen P concentrations compared to all other fertilised treatments. Phosphorus leaching could also occur in areas where P has built up, such as border crutches. In fact, in the 75-175mm soil depth, Olsen P concentrations were significantly higher in border crutches compared to the control regardless of fertilised treatments (188 SSP and 376 SSP). This indicated higher leaching of P to depth under this irrigated pasture system, especially from the border crutches. It is important to note that some of the movement of P to 75-175mm soil depth under fertilised treatments could be ascribed to bioturbation via earthworm activity which reflected the higher level of pasture production and plant residues returns under these treatments compared to the unfertilised control (Fraser et al. 1994).

Phosphorus in faeces is present as inorganic and organic P forms. Leaching of P in the border crutches could be ascribed to inorganic P rather than organic P, due to the relatively stable amount of organic P in faeces and its recalcitrance, at least for the short-term (Haynes and Williams 1993). However, recent findings by McDowell et al. (2021) demonstrated that dissolved organic P can be prone to leaching more than inorganic P in low P retention soils. Besides, organic P could become available after mineralisation and leach in the long run, especially in border crutches characterised by high nutrient availability and microbial activity (Haynes and Williams 1999). Toor et al. (2003), investigating a Lismore soil, found that 65% of P losses by leaching were in particulate dissolved P mainly composed of monoester and diesters organic P forms. Further research on the contribution of different inorganic and organic P pools to across the border distribution of bioavailable P and P leaching to depth at the Winchmore fertiliser trial is warranted.

The Winchmore fertiliser trial has been irrigated by border-dyke (flood) irrigation for 66 years, and over this period, it has been noted that dried dung can be seen floating in the irrigation water (Saville et al. 1997). This method of irrigation is expected to cause down plot transfer of nutrients through both the transfer of dung and sediment (Close and Woods 1986). In fact, Saville et al. (1997) found that Olsen P tended to increase in the middle of the plots when investigating one treatment at the Winchmore research station that received an average of 200 kg SSP ha^{-1}. A similar trend was also observed in this study in the 188 and 376 SSP treatments in the 0-75mm soil depth, however no significant down the plot effect was detected. Moreover, in the 75-175mm soil depth, Olsen P concentrations decreased from top to the bottom of the plot in the 376 SSP treatment, suggesting higher P leaching from the top of the plot, but again no significant differences were observed between different locations down the strip in this treatment.

Comparing Olsen P in the border crutch in irrigated and dryland treatments, results showed that the dryland treatment had a lower accumulation of bioavailable P in the border crutch compared to other irrigated and P fertilised treatments. This suggests that the irrigation effect may have partly increased the movement of P from the strip towards the border crutches either directly by enhancing plant biomass and stocking rate and indirectly by movement of dung and sediment, which accumulate plant and animal returns in the border crutches. However, irrigation had no effect on down border fertility distribution for bioavailable P. It is important to mention that, although the 376 SSP treatment had higher Olsen P concentrations compared to the 188 SSP, higher accumulation of Olsen P in the border crutches relative to the strip was found under the 188 SSP compared to the 376 SSP treatment. This pattern was also observed in the 75-175mm soil depth. This result needs further investigation to understand why such higher accumulation occurs under 188 SSP compared to 376 SSP treatment.

2. Soil pH

Phosphorus applications significantly decreased soil pH in the topsoil compared to the control, while differences in soil pH were not significantly different between fertilised treatments. Phosphorus fertilisation, especially in the form of superphosphate, can decrease soil pH (Horsnell 1985); however, not net effect of superphosphate applications in the topsoil has been found under the Winchmore fertiliser trial (Tian et al. 2017; Smith and Moss 2020; Gray and Moss 2021). Moreover, compared to the control, fertilised treatments have been documented to have higher content of white clover (Fraser et al. 2011; Smith et al. 2012; Scott et al. 2012), which can contribute to lowering the soil pH through N_2 fixation process, higher cation uptake, as well as nitrate leaching if the latter occurs (de Klein et al. 1997). Soil acidification can also occur as a result of the dissociation of organic acids. It has been shown in a recent study that white clover released higher amounts of organic anions and exhibited lower soil pH compared to perennial ryegrass (Touhami et al. 2020). The 175 SRPR treatment had similar pH to the superphosphate fertilised treatments due to the acidity from application of elemental sulphur (0.063 kmol H^+ kg^{-1} S), being balanced the alkalinity added by RPR (-0.064 kmol H^+ kg^{-1} P (de Klein et al. 1997).

In the topsoil, soil pH was significantly higher in the border crutches compared to the strip regardless of P treatments (control, 188 SSP and 376 SSP). Previous studies have linked this increase in soil pH to the accumulation of plant residues and animal excreta in border crutches. Higher quantities of faeces and urine are deposited in the border crutches compared to the strip. Most of the calcium ingested by sheep is excreted in faeces as calcium carbonates, which has an alkaline pH between 7 to 8. On the other hand, 60 to 70% of inorganic N is voided in urine as urea, which can result in a short term increase in soil pH after hydrolysis by ureases (Haynes and Williams 1993), but this may then be counteracted by volatilisation of NH_3 or nitrification and nitrate leaching which are acidifying processes. Moreover, plant biomass in the border crutches is higher due to the availability of nutrients as well as the contamination with dung preventing sheep from grazing this part of the plot; thus, plant residues accumulate in these areas. Plant residues, especially derived from white clover, have been found to have an alkaline pH due to the excess uptake of cations by this plant. The content of white clover has been found to be higher under fertilised treatments compared to the control, which may explain the higher increase in soil pH in the border crutches of the fertilised treatments (0.28 and 0.2 units for 188 SSP and 376 SSP, respectively) compared to the control (0.16 unit). The higher total pasture production leading to more dung being excreted and transferred to the crutch position may have also played an important role in increasing soil pH under border crutches relative to the strip under fertilised treatments compared to the control. This disproportionate movement of nutrients (via animals and plant offtake) from the strip to the border crutches is responsible for changes in soil pH across border strip and P treatments.

3. Sulphate sulphur

Along with the increase of bioavailable P, the applications of SSP fertiliser (188 SSP and 376 SSP) have significantly increased the concentrations of sulphate sulphur compared to the control. In the 0-75mm soil depth, means of sulphate sulphur concentrations in 376 SSP were higher compared to 188 SSP treatment, however differences were not statistically significant between the two treatments. This is possibly attributed to the high variability in the values of sulphate sulphur measured in both treatments, along with the sampling being carried out at the end of the growing season, thereby not reflecting the difference in SSP applications. Similar reasons could also explain the absence of significant differences between the control and all fertilised treatments (188 SSP, 250 SSP, 175SRPR, and 376 SSP) in both 0-75mm and 75-150mm in data set B. These results are in line with the findings of Nguyen and Goh (1990) and Edmeades et al. (2005).

Sulphur can be lost by leaching if applications via fertilisers exceed plant requirements (Nguyen et al. 1989; Nguyen and Goh 1990). Previous studies on the same site have shown that 188 SSP treatment supplied an equivalent of 21 kg S ha^{-1}, which was optimum for maintaining an adequate plant S status, however, 376 SSP treatment supplied quantities of S higher than plant requirements (Nguyen et al. 1989), thus representing higher risks for S leaching. Interestingly, the results of this study revealed that, in the subsoil (75-500mm), sulphate sulphur concentrations under all fertilised treatments were significantly higher compared to the control, suggesting S leaching regardless of P rates and forms applied at the Winchmore fertilised trial.

4. Extractable organic sulphur

It has been shown that sulphur intake determines the amount of S excreted by animals in faeces and urine. Therefore, it is assumed that extractable organic sulphur concentrations would be higher in the 376 SSP treatment compared to 188 SSP and the control treatments (Haynes and Williams 1993). The results of this study showed that in the topsoil, Extractable organic sulphur was significantly higher under fertilised treatments (188 SSP and 376 SSP) compared to the control, indicating that P applications caused an accumulation of extractable organic sulphur. However, no significant difference was observed between 188 SSP and 376 SSP treatments despite double the amount of S applied in 376 SSP compared to 188 SSP treatment. Phosphorus applications to pasture systems enhance plant biomass and stocking rates, thereby increasing the amount of plant detritus and animal excreta returned to the soil compared to the control (Nguyen et al. 1989; Nguyen and Goh 1990). Plant biomass and stocking rate were similar in the 188 SSP and 376 SSP treatments, which can explain the similar amounts of extractable organic sulphur in both treatments. On the other hand, lower stocking rate, plant biomass, and microbial activity due to P and S deficiencies could explain the significantly lower extractable organic sulphur in the control in comparison with the fertilised treatments (Nguyen and Goh 1990).

Extractable organic sulphur concentrations showed a significant accumulation in the border crutches compared to the strip regardless of P treatment. Similar to bioavailable P, sheep grazing behaviour and irrigation may have contributed to this result (Nguyen and Goh 1992c). Sheep camp on the border crutches where they excrete dung and urine. Most sulphur voided in faeces is in organic form, while urine contains both inorganic and extractable organic sulphur with a proportion between 50 to 60% of total S. Therefore, border crutches accumulate more extractable organic sulphur than the strip. Moreover, greater pasture biomass has been observed in the camping areas due to higher nutrient availability (derived from accumulated excreta) and contamination with urine preventing sheep from grazing these areas. Therefore, plant detritus can accumulate in these areas and contribute to the extractable organic sulphur pool. Irrigation also can contribute to extractable organic sulphur being accumulated in the border crutches via the movement of dry dung, which is caught in the dense and high plant biomass in the border crutches.

Data set B showed that the concentrations of extractable organic sulphur were not significantly different between the control and fertilised treatments (188 SSP, 250 SSP, 175SRPR, and 376 SSP), which contradicts the data set A. Data set B was based on soil samples taken from the centre of the plot, while data set A were based on soil samples taken from across the plot, including the border crutches. Provided that border crutches have shown significantly higher accumulation of Extractable organic sulphur, this could possibly explain why no significant difference was observed in data set B sourced only from the centre of the plot. However, for more accurate assessment, investigation of the distribution of extractable organic sulphur (and other nutrients) across plots in all five P treatments is needed.

Extractable organic sulphur concentrations were significantly higher in the fertilised treatments (188 SSP and 376 SSP) compared to the control in the 75-175mm soil depth. Similar result was found in the 75-150mm soil depth when comparing the control to all fertilised treatments (188 SSP, 250 SSP, 175SRPR, 376 SSP). This suggests leaching of extractable organic sulphur to depth, especially from the border crutches and regardless of the form and amount of P applied. The stony nature of the Lismore soil present at the Winchmore site and its lower S retention capacity may have promoted S (organic and inorganic) losses to depth, especially from border crutches. These results corroborate the findings of Nguyen and Goh (1990) and Nguyen and Goh (1992b). It is also important to note that some of the S movement to depth, at least the 75-175mm soil depth, could be due to soil bioturbation via earthworms, which are higher in number under fertilised treatments compared to the control (Fraser et al. 1994).

Conclusions

Although applications of SSP were evenly spread on the Winchmore fertiliser trial, a heterogeneous spatial distribution of soil fertility was observed, specifically across the border strip. A similar trend was observed in the unfertilised control. Soil pH, Olsen P, and extractable organic-sulphur were significantly higher in the border crutches compared to the strip. This was attributed to a direct effect of sheep grazing and camping behaviour and an indirect effect of irrigation, together causing an accumulation of plant residues and animal excreta in border crutches compared to the strip. No evidence of down border strip distribution of soil fertility was found. In the topsoil, SSP fertilisation significantly decreased soil pH but significantly increased Olsen P, sulphate-sulphur and extractable organic sulphur compared to the control. While Olsen P increased with increasing P rates, sulphate-sulphur and extractable organic-sulphur were significantly similar between different rates of fertiliser application in the topsoil. In the subsoil, concentrations of Olsen P, sulphate sulphur and extractable organic sulphur were significantly higher in all fertilised treatments compared to the control, especially from border crutches. This indicated that an accumulation of P and S to depth was occurring regardless of P rates and forms. This accumulation to depth of S and P was ascribed to the stony nature of the Lismore soil present at the Winchmore research site and its low adsorption capacity for P and S, along with the build-up of nutrients in the border crutches via grazing animals.

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