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Assessment of Nitrogen and Phosphorus Pathways at the Profile of Over-fertilised Alluvial Soils. Implications for Best Management Practices

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Abstract Contrasting soil profiles (coarse-textured and fine-textured) treated with brilliant blue (BB) dye tracer, inorganic nitrogen (N) and phosphorus (P) concentrations along and between stained preferential flow pathways were examined for an irrigated and overfertilised maize monoculture system at the Mediterranean central Chile. The PO4-P concentrations were 2- to 10-fold higher in areas with BB than in areas without BB below 0.5-m soil depth in both soils. This elevated concentration was attributed to transport through cracks in fine-textured soil and finger flow in coarse-textured soil. The highest PO4-P value (13 mg kg^{-1}) was found in areas with BB at the fine-textured soil. There were no significant differences in inorganic N concentration between areas with and without BB for both soils, which suggest that the effects of preferential flow are less important for inorganic N forms. There was a strong significant ($p < 0.01$) positive correlation between PO4-P and NH4-N concentrations in the fine-textured soil, and the amounts retained were clearly proportional to the clay content. Strategies for reducing N and P losses must be placed on good agronomic management of irrigated maize cropping system including accurate calculation of N and P fertiliser rates and establishment of suitable mitigation measures such as cover cropping.

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1 Introduction

As an insurance policy against low crops yield, commonly, farmer apply fertiliser amounts exceeding the crop requirements (Sattari et al. 2012; Lassaletta et al. 2014; Zhang et al. 2015), causing environmental concerns (eutrophication by anthropogenic activities) if additionally poor irrigation systems design combined with wrong timing and method of fertiliser application are applied. Processes like leaching (Quemada et al. 2013; Salazar et al. 2014; Stutter 2015; Simeonova et al. 2017) and surface runoff (Armstrong et al. 2011; Panagopoulos et al. 2011; Weld et al. 2001; Tomer et al. 2016) generate groundwater and surface water bodies contamination, being nitrate leaching rates higher than those of phosphates particularly in coarse-textured soils with low water retention capacity (Darwish et al. 2011; Salazar et al. 2009). However, considering that a single atom of phosphorus (P) supports the production of as much phytomass as 106 atoms of carbon and 16 atoms of nitrogen (N), relatively low additions of this nutrient can cause eutrophication.

Although P leaching has been shown to be low, even in sandy soils (Neumann et al. 2012), it has been determined that high P fertiliser and manure application rates can reduce the P sorption capacity of the soil. On the other hand, P transport from agricultural lands to water bodies has been mainly attributed to surface runoff, but it is now known that preferential flow processes also favour P transport (De Jonge et al. 2004). Akhtar et al. (2003) noted that variation in flow rate and soil structure were related to elevated concentrations of inorganic P in drainage water after surface P fertiliser applications. King et al. (2015) showed that inorganic P losses can be substantial in sandy soils due to low sorption affinity, but elevated P losses from clayey soils are also possible due to the development of preferential flow (PF) paths (Delgado et al. 2006). Jarvis (2007), broadly speaking, points out that PF should dramatically increase leaching losses of otherwise non-leachable compounds strongly sorbed, such as P, although it will have less effect on highly mobile solutes, such as nitrate.

Most maize (*Zea mays* L.) production in Chile is cultivated under irrigation and monoculture systems at the Mediterranean central zone of the country, obtaining the highest yields in the world. Indeed, some producers at O'Higgins Region report up to 16 Mg ha^{-1}, but average maize yield is 12.3 Mg ha^{-1} (FAS 2013, 2016). Recently, several studies have reported that the zonal macronutrient balances indicate a high risk of N and P non-point source pollution (Corradini et al. 2015; Nájera et al. 2015; Salazar et al. 2015; Salazar et al. 2017). Although there are evidence that connects the surface water pollution (Golembeski 2004; Pizarro et al. 2010) with its source(s), few studies have been carried out in non-point source pollution and evaluation of mitigation measures in central Chile (Ribbe et al. 2008; Tapia and Villavicencio 2007; Fuentes et al. 2015).

Dye tracer experiments allow qualitative pictures to illustrate the preferential flows in soils, which combined with laboratory analyses and in situ irrigation experiments, providing better understanding of hydrodynamic aspect of flow processes in soil. Therefore, here we present the results of a field study carried out on a coarse-textured soil and a fine-textured soil in central Chile (O'Higgins Region), where tracer tests were performed with brilliant blue (BB) dye and the staining patterns analysed to assess whether the solutes move along certain pathways, while bypassing a fraction of the porous matrix. Therefore, we hypothesise that in a clay soil, the solute leaching is mainly associated to PF paths that can be characterised in areas with (stained) BB, whereas in a sandy soil, the solute leaching is mainly associated to matrix flow paths that can be characterised in area without (unstained) BB. Then, the main objective of the study was to examine differences between soil types and solutes (inorganic N and P) concentrations along and between BB-stained flow pathways to suggest best management practices in a very intensive and environmentally concerning maize production zone.

2 Material and Methods

2.1 Study Area and Soil Sampling

The study was conducted between 2012 and 2013 at two experimental sites under a maize-fallow cropping system, with conventional tillage (mouldboard ploughing) during the last 10 years and irrigated by furrows. Located at the longitudinal central valley of Chile, within O'Higgins Region and commune of Pichidegua (Fig. 1), sites are locally named San Luis (34°22′S, 71°25′O, 124 m asl) and El Caleuche (34°25′ S, 71°21′O, 136 m asl). A semi-arid Mediterranean climate, hot and dry summers and relatively cold winters with most rain falling until spring season (Pizarro et al. 2012) characterise both sites.

During the study period, 472-90-90 (San Luis site) and 447-75-75 (El Caleuche site) fertiliser units (N-P_2O_5-K_2O) by hectare were applied, with only nitrogenous materials (urea and commercial compound fertiliser) partitioned at sowing and at V4 plant growth stage (side dressing). Respective yields obtained (April 2013) by site were 15 and 12 Mg ha^{-1}.

Soil at the San Luis site (*coarse-textured* hereafter) is positioned within a nearly flat alluvial terrace and corresponds to a Typic Haploxerepts (*Cambisols*), with sandy loam textural class, moderately deep, with excessive drainage and occasionally flooded. On the other hand, soil at the El Caleuche site (*fine-textured* hereafter) is classified as a Typic Duraqualf (*Planosol*), with silty loam textural class and imperfect drainage, because of a Cqm horizon occurring between 50 and 100 cm depth (Casanova et al. 2013). After morphological description (Schoeneberger et al. 2012), soil samples were collected from the genetic horizons for a general physical and chemical characterisation, following standard methodologies defined for Chilean soils (Sadzawka et al. 2006; Sandoval et al. 2012). Soil texture was determined using Bouyoucos method, bulk density (Db) with cylinders and water retention constants (33 and 1500 kPa) in pressure devices to obtain the water

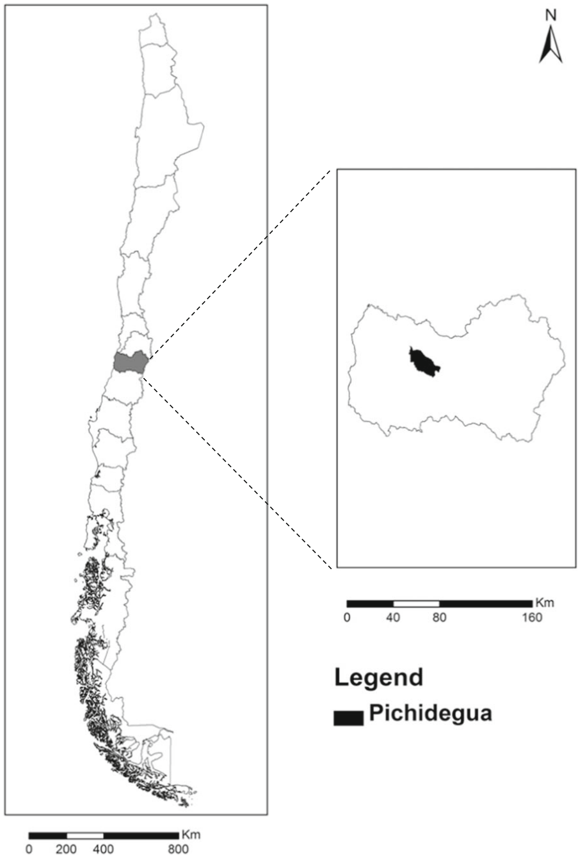

Fig. 1 Location of the Pichidegua commune (black coloured). O'Higgins Region, central Chile

holding capacity (WHC). Soil organic matter contents were determined by wet digestion method (Walkley-Black), while soil pH in a 1:2.5 ratio (soil:water) and cation exchange capacity (CEC) with NH_4OAc percolation at pH 7.0 were determined. Finally, steady-state soil infiltration rate was measured using two concentric rings to estimate saturated hydraulic conductivity (Ks) at field level.

2.2 Preferential Flow Pattern Assessment with Dye Tracer

During summer season (mean maximum temperature > 30 °C), under soil water contents near to wilting point (irrigation stopped during January 2013 and last rainfall event occurring in November 2012) and before maize harvesting (last week of March 2013), an assessment of preferential flow (PF) patterns was carried out for both soils according to Fuentes et al. (2014) procedure.

A volume of blue brilliant (BB) dye tracer solution (2.2 g L^{-1}) was calculated according to Nielsen et al. (2010) to reach saturation at 100 cm soil depth considering the Db, WHC and Ks of the soils, resulting in water heads of approximately 15.7 and 27.5 cm for the *coarse-textured* and *fine-textured* soil, respectively. The volume of BB was applied in a surficial metal square frame of 1.5 m × 1.5 m and after 24–48 h pits were excavated at the centre of the BB-treated area to expose vertical soil profiles until 1 m depth, where stained and unstained areas were sampled.

Under natural daylight conditions and without direct radiation, the soil profiles were photographed and white reflection panels were mounted on three sides of the pits to balance and compensate differences in illumination by diffuse light. Rulers were attached to the profiles to clip and correct the images geometrically and to assess the physical distribution of stained sectors (Weiler and Flühler 2004; Alaoui and Goetz 2008). A Sony DSLR-A100 camera, with a setting to obtain raw images with dimensions of 3872 × 2592 pixels, was used at *fine-textured* soil. The *coarse-textured* soil was photographed using a Nikon D40 camera at 300 × 300-ppp resolution, obtaining images of 2000 × 3008 pixels. The final dimensions of the *fine-textured* soil image were 3769 × 2319 pixels, corresponding to a size of 130 × 80 cm^2 (a resolution of 0.345 × 0.345 mm^2 per pixel), while the final dimensions of the *coarse-textured* soil image were 1733 × 2000 pixels, corresponding to a size of 150 × 130 cm^2 (a resolution of 0.750 × 0.750 mm^2 per pixel).

2.3 Image Analysis

Digital images were cropped to the same pixel size in a general purpose image processing software (®GIMP, version 2), using geometrical correction and maximisation of (blue, green and cyan) colours, followed by subtraction of background colour. Unstained and stained pixels were converted to white and black, respectively, and a median filter of 1 cm was applied.

The vertical flows and dye patterns were analysed (®Matlab software) following the Weiler and Flühler (2004) procedure. Categorising into one of three flow types, according to stained path width (SPW), as: SPW_{20}: < 20 mm; $SPW_{20–200}$: 20–200 mm; SPW_{200}: > 200 mm), two flow types were defined (heterogeneous or homogeneous matrix flow) pursuant to observed geometrical pattern. This was achieved accounting the continuous stained pixels that met the width criteria of the categories above and estimating their distribution per depth, considering that the image and pixel dimensions are known. In addition, diagrams of stained pixels (volume density) related to soil depth were obtained, while concentration categories were neglected.

2.4 Solute Concentration Measurement

Once PF pathways were identified, a putty knife was used to collect soil samples (~ 20 g) from seven stained (PF pathways) and seven unstained (soil matrix) areas of 100 cm^2 below 0.5 m soil depth on a selected wall of the pit, in vertical transects (stained and unstained areas) of each soil profile.

The concentrations of nitrate (NO_3-N) and ammonium (NH_4-N) in each soil sample were determined by KCl extraction and steam distillation and the phosphate (PO_4-P) concentration was analysed by the Olsen method (Sadzawka et al. 2006). Additionally, soil reference samples (10 g, $n = 3$) were used to check whether application of BB could interfere when colorimetric P-Olsen method is used, adding 25 mL of a BB solution (2.2 g L^{-1}) or 25 mL of distilled water (controls). After oven-drying (105 °C), those soil samples were analysed for PO_4-P.

2.5 Statistical Analysis

Paired Student's *t* tests ($p > 0.05$) were conducted using INFOSTAT software to compare solute concentrations between stained and unstained soil areas. Pearson correlation coefficient (r) with a significance level of 0.01 ($n = 14$) was used to detect eventual relationships among PO_4-P, NO_3-N and NH_4-N concentrations in each soil type.

3 Results and Discussion

Physical, chemical and morphological properties of each soil profile (Table 1) confirmed the contrasting conditions under this assessment. According to Landon (2013), moderately high (2.4 cm h^{-1}) and low (1.1 cm h^{-1}) K_s for the *coarse-textured* and *fine-textured* soil were obtained, respectively.

In the *coarse-textured* soil, a homogeneous matrix flow type was found (Fig. 2), where the stained pattern was uniform and there was a high concentration of dye tracer in the upper 55 cm, which can be explained by a well internal drainage and a rapid permeability determined by the moderately high K_s, low WHC (low clay and SOM contents), weak structure and non-compacted soil condition (Table 1). Nevertheless, between 55 and 68 cm soil depth, a macropore flow with strong matrix interaction was observed (stained pattern decrease abruptly and almost disappear below 68 cm), obeying to the fact that B_{w1} and B_{w2} horizons show higher clay contents (less deep percolation).

Only partial homogeneous matrix flow type was found at the Ap horizon of the *fine-textured* soil (Fig. 3) with stain coverage decreasing as the flow changed to a macropore flow pattern (through shrinkage cracks) below ~ 8 cm. The thin vertical stained path width (SPW) observed can be explained by the Bt horizons (low K_s, high WHC and strong structure) resting above silica cemented (Cqm) horizon, determining restricted soil internal drainage conditions.

Clear differences in SPW between studied soils were detected, with the SPW_{200} category widespread through the entire sandy vertical profile (particularly in the arable layer), whereas in the *fine-textured* soil, it was confined to the top layer. Thus, higher sand contents and the pore arrangement promoted a matrix flow type and predominance of SPW_{200} as explained by Fuentes et al. (2015). This difference between soils demonstrated that the solution flow through the *fine-textured* soil interacted to a lesser degree with the soil matrix than in the *coarse-textured* soil. There is a well-known effect of texture on mass exchange, where clayey soils are more prone to PF development due to structure-forming processes such as swelling/shrinking in response to wetting/drying (Coppola et al. 2015; Warsta et al. 2013).

3.1 Solute Concentration Measurements

Table 2 shows the inorganic nitrogen (NH_4-N and NO_3-N) and phosphate (PO_4-P) concentrations in areas with (stained) and without (unstained) BB below 0.5 m soil depth in the studied sites. No significant differences ($p > 0.05$) in inorganic N concentration were observed between both type of areas (stained or unstained) or soils, denoting that the effects of PF should in principle be less dramatic for a mobile solute like nitrate (Clothier et al. 2008; Jarvis 2007).

The previous test (with and without BB application) to reference soil samples allowed to check that dye tracer it does not interfere with Olsen-P determination,

Table 1 General physical and chemical properties of the studied alluvial soils at central Chile

Soil horizon (depth, cm)	SOM %	pH –	CEC $cmol_c kg^{-1}$	Db $Mg\ m^{-3}$	WHC	Clay	Silt	Sand	$Tc_{(soil\ structure)}$
					%	%	%	%	
	Coarse-textured soil (Typic Haploxerept/*Cambisol*)								
$Ap_{(0–15)}$	1.47	6.93	9.65	1.35	11.91	10.0	44.3	45.7	$l_{(weak\ med.\ subang.\ blocks)}$
$A_{2(15–39)}$	1.24	6.90	10.64	1.36	9.11	8.0	34.2	57.8	$sil_{(weak\ med.\ subang.\ blocks)}$
$Bw_{1(39–73)}$	1.18	6.90	10.15	1.32	6.27	16.1	14.1	69.8	$sil_{(weak\ med.\ subang.\ blocks)}$
$Bw_{2(73–103)}$	1.35	6.80	10.94	1.31	28.18	18.1	46.3	35.6	$l_{(weak\ med.\ subang.\ blocks)}$
$C_{(103–132)}$	0.44	7.27	10.49	1.46	0.19	6.0	2.0	92.0	$s_{(massive)}$
$Cg_{(132–155)}$	0.71	7.29	10.94	1.31	5.10	16.1	2.0	81.9	$ls_{(massive)}$
	Fine-textured soil (Typic Duraqualf/*Planosol*)								
$Ap_{(0–9)}$	3.03	7.21	14.80	1.36	20.47	34.5	34.1	31.4	$cl_{(mod.\ med.\ subang.\ blocks)}$
$A_{2(9–22)}$	3.42	6.85	10.93	1.17	19.87	34.6	36.3	29.1	$cl_{(strong\ med.\ subang.\ blocks)}$
$AB_{(22–35)}$	6.52	6.42	17.06	1.13	17.63	28.3	28.0	43.7	$cl_{(strong\ fine\ subang.\ blocks)}$
$Bt_{1(35–51)}$	6.27	6.38	17.90	1.01	16.70	26.4	40.6	33.0	$cl_{(strong\ fine\ subang.\ blocks)}$
$Bt_{2(51–75)}$	4.87	6.82	17.61	1.20	25.61	30.3	46.6	23.1	$cl_{(mod.\ med.\ subang.\ blocks)}$
$C_{(75–96)}$	4.95	5.94	14.89	1.05	24.66	24.4	49.2	26.4	$sl_{(massive)}$
$2Cqm_{(96–115)}$	–	–	–	–	19.90	22.0	23.7	54.3	$scl_{(massive)}$

SOM soil organic matter, *Db* bulk density, *WHC* water holding capacity (mass-based calculation), *Tc* textural class: *l* loam, *sl* sandy loam, *ls* loamy sand, *s* sand, *cl* clay loam, *sil* silty loam, *scl* sandy clay loam; soil structure: *mod.* moderate, *med.* medium, *subang.* sub angular

because there were no significant ($p > 0.05$) differences in the measured P concentrations. However, at the pit walls, there was a significantly ($p < 0.05$) higher PO_4-P concentration in stained areas than in unstained areas (45% in the *coarse-textured* soil and 92% in the *fine-textured* soil). The highest PO_4-P concentrations in stained areas occur at the *fine-textured* soil.

There was a strong significant ($p < 0.01$) positive correlation between PO_4-P and NH_4-N concentrations in the *fine-textured* soil (Table 3), and the amounts retained were clearly proportional to the clay content, with also the highest NH_4-N concentrations in stained areas of this soil. Both PO_4-P and NH_4-N ions are considered to be immobile in soils, but our findings suggest that they can move downwards, mainly through PF pathways such as cracks. Instead, the poor correlation between NO_3-N and PO_4-P concentrations was related to the fact that NO_3-N can move downwards either using PF or matrix flow pathways.

"The importance of site-specific soil properties for risk assessments of P loss has been demonstrated by Djodjic et al. (2004). It is important to note that conventional mineral fertilizers are more likely to be exported than either organic fertilizers or slow-release mineral fertilizers during a rainy event because of their high mobility (Liu et al. 2012)." Conventional P management at both studied agricultural soils here consists in annual and surficial band-applied compound fertiliser during maize sowing. Ignoring mass balances, which denote at levels exceeding maize uptake, build-up of P in the topsoil (0–20 cm) is favoured reaching values such 25 mg kg^{-1} (*coarse-textured* soil) and 77 mg kg^{-1} (*fine-textured* soil). Furthermore, if the capacity of the topsoil to adsorb further P can become limited, mainly inorganic P surplus (Elliott et al. 2002) will be prone to losses by leaching. Although diffusion has been identified as the main process for P movement in soils, diffusion coefficient of inorganic P in soil is relatively low compared to that other nutrients ($\sim 0.1–5.\ 10^{-13}\ m^2\ s^{-1}$) and cannot explain the downward mechanism of P transfer from topsoil to subsurface horizons. Therefore, increases in P concentrations in areas with BB below 0.5 m soil depth may be explained by preferential pathways, where P transport bypasses (area without BB) the subsoil matrix (Kleinman et al. 2003). In particular, the *fine-textured soils* are susceptible to drying cracks, which can allow water to percolate through fractures and P transport to the subsoil may occur rapidly due to PF pathways, bypassing the P sorption capacity of the upper soil layers (Djodjic et al. 2004). Our results suggest that in areas with BB, where mass flow carries P forms through fractures, the PO_4-P form can move below 0.5 m soil depth.

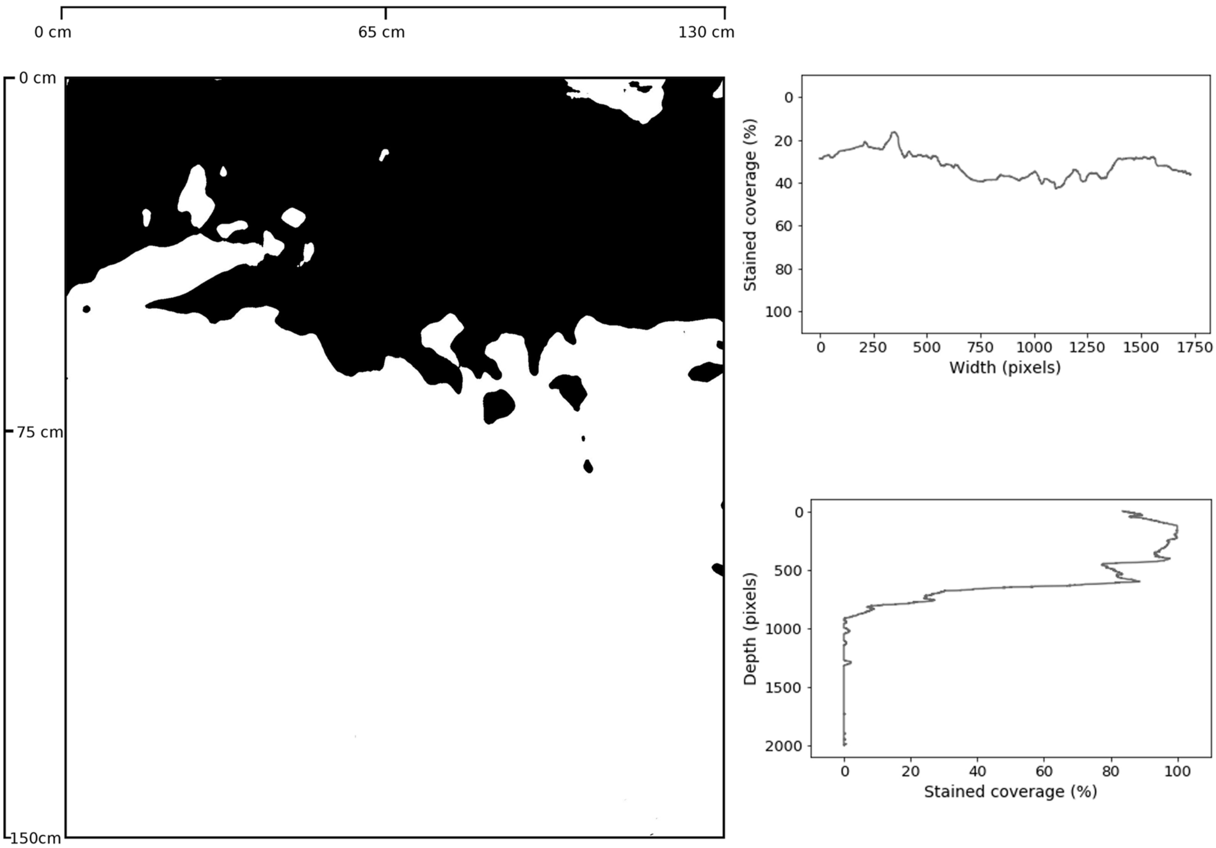

Fig. 2 Preferential flows at the *coarse-textured soil* (Typic Haploxerept/*Cambisol*) with blue brilliant dye tracer. Left panel, stained profile; upper right, horizontal stained coverage pattern; lower right, vertical stained coverage pattern

The higher PO_4-P concentration in areas with BB than in areas without are clearly denoting a matrix flow domain at *coarse-textured* soils, where greater interaction between soil particles and percolating water results in low P leaching (Toor and Sims 2015). Although this soil is well drained and permeable, there are some textural discontinuities in the profile resulting in less permeable horizon overlying a more permeable horizon (Table 1), then it is possible that PO_4-P may be moved in areas with BB influenced by wetting front instability due to the textural or hydraulic conductivity discontinuity (Salazar et al. 2011). In the same way, it is possible for a stable horizontal wetting front to move downwards without breaking into fingers, but it may break into finger flow if it encounters a less permeable layer overlying a more permeable layer (Hendrickx and Flury 2001). At the textural interface between the fine and the coarse soil layers, finger flow formation results from hysteresis in the water retention function and, once fingers are established, causes them to recur along the same pathways during subsequent rain events (Ritsema et al. 1998). In finger flow, the movement of P forms is induced by infiltration flow instability, where fingers facilitate recharge flow and transport of the contaminant to groundwater (Glass et al. 1989; Kung 1990; Salazar et al. 2011). Koopmans et al. (2007) have also reported on sandy soils low PO_4-P sorption capacity in topsoil facilitating relocation of PO_4-P to 0.5 m depth, indicating strong downward movement of this P form. Thus, in order to efficiently retain P within the soil matrix and reduce P leaching to groundwater, Pang et al. (2016) recommend periodically disturbing soil PF paths by tillage and applying a low irrigation rate.

Preferential flow was enhanced in the *fine-textured* soil, considering the macropore flow pattern favoured by the typical crack formation at this soils (Pathak et al. 2011). The PO_4-P concentration in the BB preferential flow zone (12.7 mg kg^{-1}) compared with the soil matrix (1.0 mg kg^{-1}) confirmed the risks of nutrient leaching reported by Nájera

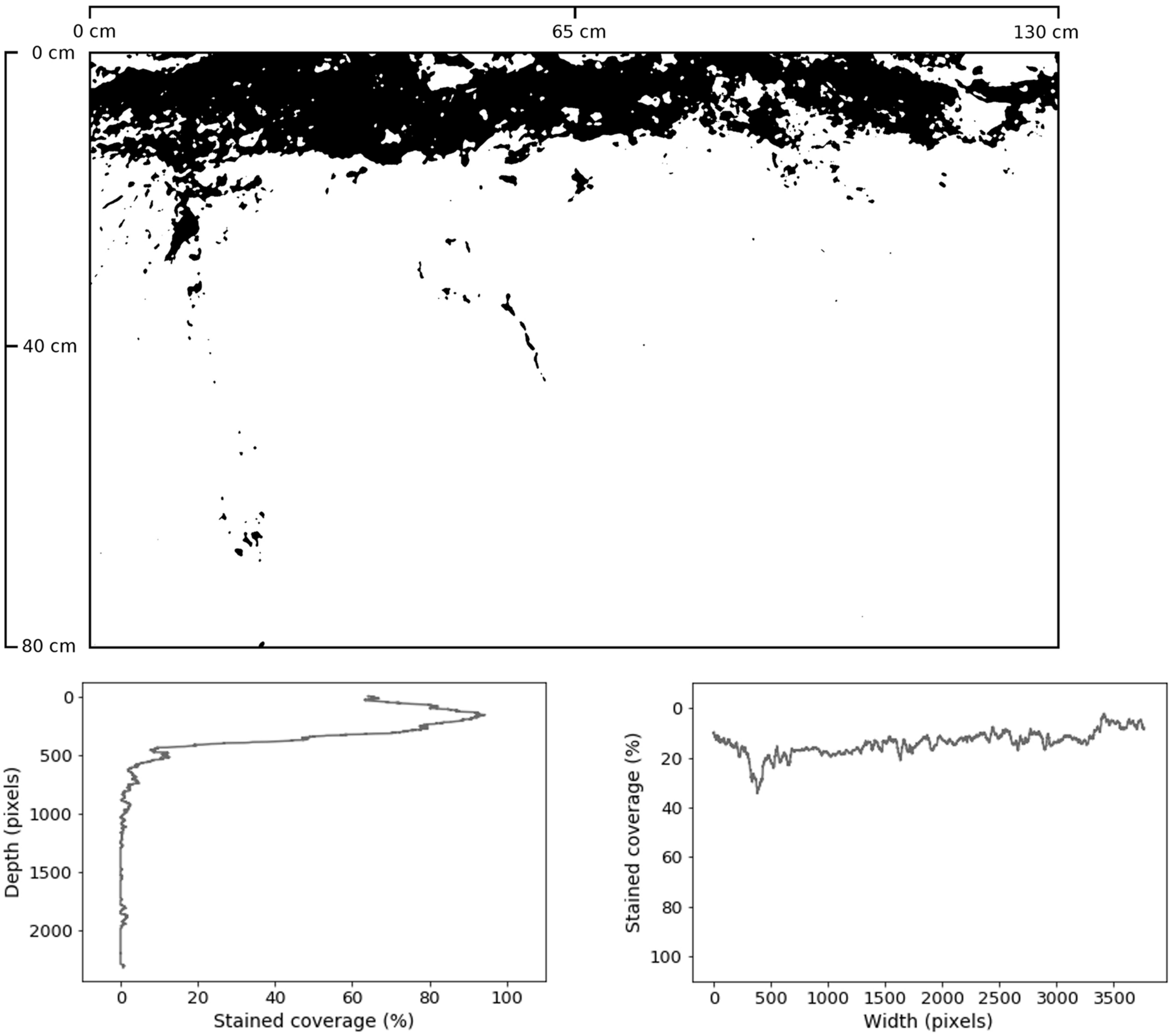

Fig. 3 Preferential flows at the *fine-textured soil* ((Typic Duraqualf/*Planosol*) with blue brilliant dye tracer. Upper panel, stained profile; lower left, horizontal stained coverage pattern; lower right, vertical stained coverage pattern

et al. (2015) in the same area of the study. Nevertheless, the results can vary widely depending on management system, climate conditions, point in the season (Schwen et al. 2011) and the spatial variability of soils (Zeng et al. 2013). Therefore, it is necessary to continue studying and monitoring PF processes. The correlation between PO_4-P and NH_4-N concentrations in the *fine-textured soil* confirms that ion retention increases as soil clay content increases.

Our results suggest that the movement of PO_4-P below 50 cm depth in soil is mainly by preferential flow. Thus, in both sandy and clayey soil, the concentration of soil P below 50 cm soil depth should be higher in a stained (PF pathways) than in an unstained (soil matrix) area, independent of the soil depth. In addition, the relatively large standard deviations in PO_4-P concentration that we found in stained areas (see Table 2) may represent pulses of P that are moving down in the soil.

3.2 Best Management Practices

This field study confirmed that PO_4-P moves along certain pathways, while bypassing a fraction of the porous matrix, whereas that NO_3-N can move downwards either using preferential flow or matrix flow pathways, which indicated a risk of N and P non-point source pollution. In the maize-fallow cropping system, the excessive N and P rates in addition to the continued use of N and P fertilisers

Table 2 Inorganic nitrogen (N) and phosphorus (P) concentrations in areas with (stained) and without (unstained) blue brilliant dye tracer in the studied alluvial soils

Soils/area types	NH_4-N	NO_3-N	PO_4-P
	mg kg^{-1}		
Coarse-textured soil			
Stained	7.6 ± 2.5a	6.0 ± 1.0a	9.4 ± 3.0a
Unstained	5.1 ± 1.7a	6.3 ± 0.7a	5.2 ± 0.6b
Fine-textured soil			
Stained	24.6 ± 4.5a	12.3 ± 5.4a	12.7 ± 8.2a
Unstained	19.1 ± 2.5a	10.2 ± 3.5a	1.0 ± 0.6b

Means (±standard deviation) with different lowercase letter in a column are significantly different (*t* test, $p < 0.05$)

greater than crop needs could produce excessive residual N levels and a build-up of P in soil. This excessive N and P enrichment in soils can increase the potential for losses of N and P to surface water by matrix and preferential flows, respectively, in irrigated maize fields in the Mediterranean zone of Chile (Salazar et al. 2011; Corradini et al. 2015). Najera et al. (2015) carried out a survey in irrigated maize fields in the O'Higgins Region; they found that most of the farmers over-fertilised with N and P, where over-fertilisation amount ranged from 60 to 360 kg N ha^{-1} year^{-1} and from 10 to 120 kg P_2O_5 ha^{-1} year^{-1}. Therefore, great emphasis must be placed on accurate calculation of N and P fertiliser rates, considering the importance of mass balance, in terms of nutrient inputs versus nutrient removal (Maguire et al. 2009).

In addition, these fields are fallow during the autumn-winter season, when intensive precipitation events occur, increasing the risk of movement of residual N and P by matrix and preferential flows. Salazar et al. (2011) noted the importance of antecedent soil moisture status in governing the pathway of subsurface movement of P forms through the soil. They also suggest that preferential flow may occur particularly during autumnal rewetting after intensive precipitation. Similarly, Simard et al. (2000) found that preferential flow was most important following storm events after a period of drought. In addition, Dils and Heathwaite (1999) noted that soil drying during summer months increases the likelihood of preferential flow particularly as the soil wets up in autumn.

Table 3 Correlation coefficients of Pearson for solute concentrations in alluvial soils at central Chile

Soil type	PO_4-P	NO_3-N	NH_4-N
Coarse-textured soil			
NH_4-N	− 0.19	− 0.43	–
NO_3-N	0.11	–	
PO_4-P	–		
Fine-textured soil			
NH_4-N	0,74**	0.43	–
NO_3-N	0.45	–	
PO_4-P	–		

**Significant at $p = 0.01$ ($n = 14$)

Therefore, replacing bare fallow with cover crops, in maize cropping systems, may reduce P preferential flow during autumn-winter period. Recently, Salazar et al. (2017) noted that in a maize-cover crop rotation in central Chile, the transpiration of the cover crop reducing percolation and consequently solute leaching. Similarly, the establishment of cover crops during the intercropping period of maize (replacing bare fallows) in other Mediterranean zones has been proposed to counteract the negative impacts of N leaching or diffuse pollution from irrigated maize fields (Salmerón et al. 2011; Gabriel and Quemada 2011).

Although Teles et al. (2017) reported that the use of cover crops increased crop dry matter accumulation and recycled a large amount of P to the soil surface; they added that the cover crops have relatively little effect on soil P availability and reduced only the moderately labile inorganic P and the nonlabile organic P fractions. It is important to note that P leaching decreased with increasing cover crop growth (Honegger and Kalita 2015). However, there are still many gaps in our understanding of the significance of cover crops in the P removal processes. Similarly, Aronsson et al. (2016) highlighted that more knowledge is required about the effect of cover crops on P losses, particularly the effect of species with different partitioning between shoot and root biomass and the effects of cover systems with harvesting of biomass.

4 Conclusions

At coarse-textured (~ 10% clay) and fine-textured (~ 30% clay) alluvial soils of central Chile, where brilliant blue (BB) tracer dye was added and the stained preferential flow pathways were examined, significantly ($p < 0.05$) higher PO_4-P concentrations were found in areas with BB than in areas without below 0.5-m soil depth. The elevated concentration of P in the stained areas can be due to transport through cracks and finger flow in the coarse-textured and fine-textured soil, respectively. The highest PO_4-P concentrations were found in stained areas of fine-textured soil. In both soil types, there were no significant ($p > 0.05$) differences in inorganic N concentrations between areas with and without BB, which suggests that the effects of preferential flow are less important for these inorganic forms.

This field study confirmed that PO_4-P moves along certain pathways, while bypassing a fraction of the porous matrix. Therefore, great emphasis must be placed on good agronomic management of maize cropping system including accurate calculation of N and P fertiliser rates and establishment of suitable mitigation measures such as cover cropping.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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