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ORIGINAL PAPER

Cover Crop Identity Differently Affects Biomass Productivity as well as Nitrogen and Phosphorus Uptake of Maize (Zea mays L.) in Relation to Soil Type

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Abstract
Cover crop integration in agriculture rotation is associated to multiple agronomic and environmental benefits. However, the effect of cover crop identity on the following cash crop productivity and nutrient uptake is still uncertain, particularly in relation to soil types. We set up an experiment to test the effects of four different cover crop species (Indian mustard, lupine, field pea, and oat) on maize above- and belowground biomass as well as on nitrogen and phosphorus nutrition after incorporation of the cover crop litter in two soil types (clay and sandy soil). We observed that aboveground and belowground biomass of maize was always higher in sandy than clay soil likely due to better soil physical properties. On general, in clay soil, the presence of a preceding cover crop promoted or did not modify the aboveground and the belowground maize productivity compared to bare soil. On the other hand, in sandy soil, the decomposing litter of non-leguminous cover crops decreased maize aboveground productivity whereas any preceding cover crop decreased maize root biomass. The burial of leguminous litter significantly increased the N uptake by maize in both soil types. For what concerns the phosphorus uptake by maize, it appears that due to high phosphorus soil availability, the selected cover crops did not play a major role in improving P uptake, with the only exception of field pea. Our data show that leguminous cover crops improved the N status of maize particularly under conditions of low N fertilization rates.

Keywords Cover crop · Sandy soil · Clay soil · Aboveground biomass · Root biomass · Nutrient uptake

1 Introduction

Increasing crop productivity while reducing energy inputs and lowering environmental impacts has become a primary and major challenge for modern agriculture in order to develop more sustainable agronomic practices. The integration of cover crops (or green manure crops) in agro-ecosystems can be, in this sense, a suitable solution that can provide multiple benefits (Blanco-Canqui et al. 2015). Indeed, it has been shown that the presence of cover crops within the crop rotation can help reducing nitrogen leaching (Nouri et al. 2022), increasing soil organic carbon (Austin et al. 2017; McClelland et al. 2021; Poeplau and Don 2015), suppressing weeds (Osipitian et al. 2019), improving soil microbiome (Kim et al. 2020), and reducing soil erosion (Kaye and Quemada 2017).

Despite the above-listed benefits, the impact of cover crops on the subsequent cash crop productivity and nutrient uptake is still uncertain to such an extent that the most recent meta-analyses on this topic report contrasting effects. For example, Fan et al. (2021) showed an overall positive effect of cover crops on cash crop yield that augmented of c. 10%, even if the effect was dependent on the type of cover crops (leguminous versus non-leguminous), the climatic conditions, and the growing season of cover crops. In the meta-analysis by Marcillo and Miguez (2017), a mixture of cover crop species and legume cover crops increased the cash crop yield by, respectively, 13% and 21%, whereas grass cover crops showed neutral effects. On the other hand, Wang et al. (2021) showed no effect of cover crops on cash crop yield, even if non-leguminous cover crops tended to decrease the yield in interaction with climatic conditions and soil texture. Differently, Abdalla et al. (2019)

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reported an overall decrease of c. 4% of cash crop yield for both leguminous and non-leguminous cover crops with, respectively, a positive and a negative effect on grain nitrogen content in the case of legumes and non-legumes. Finally, Alvarez et al. (2017) and Shackelford et al. (2019) found a decrease of yield when cover crop was a non-leguminous and a significant increase after leguminous cover crop species. Considering the importance that cover crops are gaining in agriculture in many countries (Pe'er et al. 2017; Kebede 2021; Qin et al. 2021), a better understanding of the mechanisms of how cover crop residues, from different species and under different soil types, affect nutrient uptake and biomass productivity of the subsequent a cash crop can help to further expand their use (Lynge et al. 2022).

Improving the nutrient use efficiency of cash crops represents an opportunity not only to increase crop yield, but also to reduce nutrient losses to the environment (Nouri et al. 2022). The concept of critical (nutrient) concentration has been specifically developed since several decades to assess the nutrient status of a crop in order to provide a more precise estimation of when and how much fertilizer a crop requires (Lemaire et al. 2021). The "critical concentration" represents the minimum concentration of a nutrient that is necessary for obtaining the maximum production and it can be calculated as a function of crop biomass, i.e., by means of the so-called nutrient dilution curve. Such a concept has been applied for different cash crops with reference to different nutrients, including nitrogen (N) and phosphorus (P) (e.g., Ata-Ul-Karim 2016; Cadot et al. 2018; Fontana et al. 2021a; Lemaire et al. 2019). Based on the dilution curve, the "nutrition index" is defined as the ratio between the nutrient concentration and the critical nutrient concentration for the actual plant biomass of the crop (Sadras and Lemaire 2014). This index can then be used to assess the excessiveness or deficiency of the specific nutrient in order to monitor the nutritional status and to optimize plant nutrition.

With the main goal to understand if and how cover crops affect the subsequent cash crop growth, we set up a greenhouse experiment to test the specific effect of cover crop identity (i.e., four different species) on maize productivity (above- and belowground biomass) as well as on maize N and P uptake after burial of the cover crop litter in two different soil types (i.e., a clay and a sandy soil). Specifically, we wanted to answer the following questions: (1) how do aboveground and belowground productivity respond to cover crop identity under different soil type? (2) Is the uptake of N and P differently affected by the cover crop identity? (3) On the basis of the N and P nutrient index, does maize manifest any N or P limitation in response to cover crop identity in the two soil types?

2 Material and Methods

2.1 Experimental Design

Four species of cover crops, i.e., oat (*Avena strigosa* Schreb.), Indian mustard (*Brassica juncea* (L.) Czern.), lupine (*Lupinus albus* L.), and field pea (*Pisum sativum* L.), were cultivated during a greenhouse pot experiment (pot diameter 27 cm and pot height 24 cm) at Agroscope-Changins (Nyon, Switzerland) during the period June–July 2018. The cash crop following the cover crop growth was maize (*Zea mays* L.) during the period August–September 2018. These four cover crop species were selected for their expected different legacy effects on the productivity and nutrition of the following cash crop, i.e., the maize. Indeed, lupine and field pea are legumes with the ability to fix atmospheric nitrogen. In addition, significant differences can be found at root level: oat has the highest root length and root area among the studied species (Wendling et al. 2017); lupine is a non-mycorrhizal species forming root clusters (i.e., proteoid roots) capable to mobilize phosphorus that is sparingly soluble (Nuruzzaman et al. 2005); pea is a mycorrhizal species with higher specific root length than lupine (Wamberg et al. 2003); mustard is a non-mycorrhizal species with a pivotal root system known to promote rhizobacteria enhancing phosphorus nutrition (Kumar et al. 2013).

In accordance with previous studies (Fontana et al. 2021b), the cover crop densities were 5, 20, 25, and 7 plants per pot for, respectively, lupine, oat, Indian mustard, and field pea. The aboveground biomass of cover crops was harvested 8 weeks after the sowing in correspondence of the flowering state (Fontana et al. 2021b). A pruning shears was used to chop the fresh aboveground biomass in a bowl. After, 20 g of chopped biomass was subsampled to both determine water content (55 °C for 72 h) and perform the chemical analyses. The soil plus the root biomass of cover crop contained in each pot were thoroughly mixed with the rest of the chopped biomass and then repotted. Five days after repotting, three maize grains were then sown in each pot. The two less vigorous maize plants were removed 5 days after sprouting and their biomass was left on the surface of the pot. Maize plants were harvested after 8 weeks, i.e., during the flowering period. Two weeks after the sowing, the equivalent of 30 kg N ha^{-1} (50% NH_4 and 50% NO_3) was added to each pot. We deliberately provided a lower dose of N fertilization, i.e., 25% of the official recommendation (Sinaj and Richner 2017), because we wanted to test the contribution of preceding cover crops under potentially limiting N availability. Before maize sowing, a cellulose filter was buried in a litterbag at 2 cm depth to estimate its rate of decomposition.

Two different soil types were selected for this experiment, hereafter called clay and sandy soil, with contrasting physico-chemical properties. The sandy soil was collected at the Federal Agricultural Research Station (Agroscope) of Cadenazzo from a grassland. Instead, the clay soil was collected at Agroscope-Changins from a grassland that was not harvested and did not receive any fertilization input during the 3 years preceding our experiment. The amount of clay soil in each pot was of 9.5 kg, whereas the amount of sandy soil was of 9.3 kg (at field capacity). Briefly, the sandy and clay soils were characterized, respectively, by pH 5.8 and 7.8, clay content 62 and 291 g kg^{-1}, sand content 519 and 282 g kg^{-1}, organic carbon concentration (C_{org}) 11 and 19 g kg^{-1}, total nitrogen concentration (N_{tot}) 1.5 and 2.2 g kg^{-1}, available phosphorus concentration (Olsen P-$NaHCO_3$) 50.1 and 29.3 mg kg^{-1}, DTPA-exchangeable iron 116 and 38.6 mg kg^{-1}, DTPA-exchangeable manganese 5.1 and 15.1 mg kg^{-1}, DTPA-exchangeable zinc 5.5 and 0.54 mg kg^{-1}, and cation exchange capacity 67.9 and 143.3 meq kg^{-1}.

During the cover crops and the maize growth, daily air temperature in the greenhouse was maintained between 18 and 25 °C to ensure optimal growth conditions for plant growth. When natural light intensity was lower than 250 W m^{-2}, a light supplement was provided by high-pressure sodium lamps (400 W m^{-2}) from 6 a.m. to 8 p.m. The pots were manually watered to keep optimal soil moisture conditions, i.e., 75–80% of the field capacity. In addition, pots were moved each 3 weeks to avoid potential bias due to greenhouse heterogeneity.

The combination of four cover crop species, two soil types, and four replicates led to a total number of 32 pots. Furthermore, maize was also cultivated on pots of bare soils (three replicates, hereafter simply called "bare soil") that were previously incubated under the same greenhouse conditions but without any cover crop, ultimately bringing the number of pots to 38.

2.2 Nutrient Analyses in Plant Biomass

Aboveground productivity of cover crops as well as aboveground and belowground productivity of maize was measured at the end of the growth period. Subsamples of fresh cover crop biomass as well as maize biomass were oven-dried (55 °C for 72 h) to estimate the water content. Plant biomass was ground using a Retsch rotor mill. Total N was determined by dry combustion using the Dumas method (Masson et al. 2010). Radial ICP-AES (Varian Vista RL Simultaneous or Varian 725 ES Simultaneous) was used to determine total P content after calcination (480 °C for 5 h) and mineralization in hydrofluoric acid (Masson et al. 2010).

2.3 Soil Sampling and Analyses

At the end of cover crop and maize growth, four soil cores (2.5 cm diameter) were collected along the entire depth of each pot, then sieved (2 mm mesh size) and thoroughly mixed. For each soil sample, total N concentration (NF ISO 13878) was measured by means of an elemental analyzer (Thermo Scientific, Flash 2000) and, after extraction with sodium bicarbonate (Na-HCO_3), available P (Olsen-P) (NF ISO 11263) was also measured. In addition, at the end of maize growth, soil ammonium (NH_4) and nitrate (NO_3) concentrations were measured using an automated analyzer (AA3 HR Autoanalyser, Seal Analytical, UK) after extraction of 5 g of fresh soil in 30 mL 1 M KCl. Dissolved inorganic nitrogen (DIN) was estimated by summing up the ammonium and nitrate concentrations.

2.4 Statistical Analyses and Calculations

Aboveground nutrient uptake is here defined as the amount of nutrient (N or P) that is stocked in maize aboveground biomass (mg pot^{-1}) and simply calculated by multiplying the aboveground biomass by the correspondent nutrient concentration. The nitrogen nutrition index (NNI) was obtained as the ratio between the actual maize nitrogen concentration (%N) and the critical nitrogen concentration (%N_c). The N_c was calculated using the plant biomass according to Du et al. (2020) using the following equation: $N_c = 26.126 \times W^{-0.292}$ where W is the maize aboveground biomass. Similarly, the phosphorus nutrition index (PNI) was calculated as the ratio between the actual phosphorus concentration in maize biomass (%P) and the critical phosphorus concentration (%P_c). The P_c was calculated according to Cadot et al. (2018) using the following equation: $P_c = 3.49 \times W^{-0.19}$ where W is the maize aboveground biomass. For NNI and PNI >1, the maize status for, respectively, nitrogen and phosphorus can be considered non-limiting, whereas the NNI and PNI < 1 suggest a correspondent nutrient deficiency. The relative response of N uptake in response to the different cover crop species in clay and sandy soil was calculated as the ln-transformed ratio between the value in presence of cover crop and the correspondent value in bare soil.

Data were subjected to statistical analysis using the software TIBCO Statistica (version 13.5). In particular, a two-way analysis of variance (ANOVA) was initially applied to assess any significant interaction between soil type and cover crop identity. Because our primary interest is the role of cover crop identity on maize growing in a clay and in a sandy soil, a one-way ANOVA separately for each soil type was applied and multiple comparison analyses were performed using the Fisher LSD post hoc test for any significant effect of cover crop identity.

3 Results

The two-way analysis of variance showed a significant effect of soil type and cover crop identity on above- and belowground biomass as well as on the uptake of N and P by maize after 8 weeks of growth (Table S1). A significant interaction between soil type and cover crop identity was also observed for biomass productivity and N uptake, but not for P uptake by maize (Table S1). In particular, the post hoc LSD Fisher test outlined as field pea residues in sandy soil and lupine residues in sandy soil were associated with the highest maize aboveground and belowground productivity as well as N uptake (Tables 1 and 2). In the light of the interaction between soil type and cover crop identity, the analysis of the results has been then performed separately for each soil type.

3.1 Aboveground and Belowground Biomass

The aboveground biomass of maize was, overall, between 1.2 and 2.7 times greater in sandy than clay soil when a preceding cover crop was cultivated and its litter was buried (Table 1 and Fig. S1). In bare soils, i.e., in soil without a preceding cover crop cultivation and without litter burial, aboveground biomass of maize was, on average, 4.3 times still greater in sandy soil compared to clay soil (Table 1 and Fig. S1).

Similarly to the aboveground biomass, the belowground biomass of maize roots was higher in sandy soil for all the cover crop treatments, with the only exception of oat treatment (Table 1 and Fig. S2). In bare soils, belowground biomass of maize roots was still significantly greater, i.e., 6.6 times, in sandy soil compared to clay soil (Table 1 and Fig. S2).

In order to test the effect of the preceding cover crop species on maize productivity, we compared the aboveground and belowground biomass in soil previously cultivated with the cover crop to the corresponding biomass in bare soil (Table 1). In clay soil, the presence of oat and field pea increased the aboveground biomass of maize, with no effect associated to lupine and Indian mustard presence. In sandy soil, the presence of oat and Indian mustard reduced the aboveground biomass of maize with no effect associated to field pea and lupine presence (Table 1). The comparison of cover crop treatments showed that, in clay soil, field pea significantly increased aboveground maize productivity

Table 1 Mean (± SD, $n = 4$) aboveground and belowground biomass (g pot^{-1}) of maize (*Z. mays*) in clay and sandy soil after incorporation of residues of four different cover crop species as well as in bare soil (= no cover crop treatment; $n = 3$). Maize growth lasted for 8 weeks. Different lowercase superscript letters indicate significant differences ($p < 0.05$) between cover crop species within the same soil type, whereas the asterisk indicates a significant difference ($p < 0.05$) between the cover crop species and the bare soil within the same soil type (ANOVA with Fisher LSD post hoc comparisons)

	A. strigosa (Oat)	*B. juncea* (Mustard)	*L. albus* (Lupine)	*P. sativum* (Field pea)	Bare soil
Aboveground biomass *Clay soil*	19.9^{b,*} (1.25)	13.9^{c} (1.38)	15.6^{bc} (2.50)	31.9^{a,*} (2.75)	13.6 (2.67)
Aboveground biomass *Sandy soil*	23.9^{c,*} (2.25)	30.9^{b,*} (3.75)	47.0^{a} (5.78)	58.6^{a} (4.50)	58.32 (2.44)
Belowground biomass *Clay soil*	5.30^{a,*} (0.35)	2.08^{b} (0.62)	3.05^{b} (0.87)	6.30^{a,*} (0.75)	2.55 (0.33)
Belowground biomass *Sandy soil*	5.98^{b,*} (1.33)	9.15^{ab,*} (0.60)	9.31^{ab,*} (1.31)	10.95^{a,*} (1.10)	16.90 (4.07)

Table 2 Mean (± SD, $n = 4$) nitrogen and phosphorus uptake by aboveground biomass (mg pot^{-1}) of maize (*Z. mays*) in clay and sandy soil after incorporation of residues of four different cover crop species as well as for bare soil ($n = 3$). Different lowercase superscript letters indicate significant differences ($p < 0.05$) between cover crop species within the same soil type, whereas the asterisk indicates a significant difference ($p < 0.05$) between the cover crop species and the bare soil treatment within the same soil type (ANOVA with Fisher LSD post hoc comparisons)

	A. strigosa (Oat)	*B. juncea* (Mustard)	*L. albus* (Lupine)	*P. sativum* (Field pea)	Bare soil
Nitrogen *Clay soil*	266.0^{c,*} (20.3)	323.3^{c} (35.5)	456.0^{b,*} (49.9)	624.8^{a,*} (30.3)	350.1 (67.5)
Nitrogen *Sandy soil*	258.1^{c,*} (18.9)	291.6^{c,*} (19.8)	818.0^{b,*} (44.4)	1146.2^{a,*} (192.7)	662.5 (18.7)
Phosphorus *Clay soil*	65.2^{b,*} (2.7)	68.8^{bc,*} (6.3)	79.6^{c} (8.4)	100.7^{a} (9.2)	87.6 (8.1)
Phosphorus *Sandy soil*	86.2^{b,*} (7.4)	97.9^{b} (9.3)	95.7^{b} (5.6)	143.5^{a,*} (11.3)	107.9 (12.1)

compared to the all the other cover crop species, whereas in sandy soil, both the leguminous species had a stronger positive effect on aboveground maize biomass compared to Indian mustard and oat (Table 1). The belowground maize productivity (i.e., the root biomass) followed a pattern similar to the aboveground biomass in response to cover crop species (Table 1). Indeed, in clay soil, the presence of oat and field pea increased maize root biomass compared to bare soil, whereas in sandy soil, the presence of any of the four cover crop species decreased the root biomass compared to bare soil (Table 1). The comparison of cover crop treatments for root productivity showed that, in clay soil, field pea and oat enhanced significantly the root biomass of maize compared to Indian mustard and lupine, whereas in sandy soil, the oat treatment was associated to the lowest maize root biomass only if compared to field pea treatment (Table 1).

3.2 Nitrogen Uptake in Aboveground Biomass

In bare soil, N uptake in aboveground maize biomass was c. 2 times higher in sandy soil than clay soil (Table 2), despite a dilution effect of maize N concentration with higher productivity (Fig. 1). In clay as well as in sandy soil, the burial of field pea litter and lupine litter significantly increased the N uptake in aboveground maize biomass compared to bare soil, whereas the burial of oat litter and Indian mustard litter decreased the maize N uptake compared to bare soil (Table 2). The comparison of cover crop treatments showed that, for both soil types, lupine and, in particular, field pea litter increased maize N uptake more than the other two cover crop species (Table 2).

We found that the relative response of N uptake by maize was negatively related to the initial C:N ratio of cover crop litter so that the litter of lupine and field pea, both characterized by lower C:N ratio, was associated to a higher relative response of N uptake (Fig. 2).

The N nutrition index (NNI) was > 1 only in the treatment with field pea and lupine for both the clay and sandy soil (Fig. 3a). We also observed that soil total N was higher for the leguminous treatments than the non-leguminous treatments before maize sowing for both soil types (Table 3). At the end of maize growth, the concentration of dissolved inorganic N (DIN) in bulk soil was higher in clay than in sandy soil and the leguminous treatments were associated to higher DIN concentrations for both soil types (Fig. 4).

3.3 Phosphorus Uptake in Aboveground Biomass

In bare soils, the P uptake by aboveground maize biomass was c. 1.3 times higher in sandy soil than in clay soil (Table 2), even if a dilution effect of P concentration with higher maize productivity was observed (Fig. 5). In clay soil, the burial of field pea and lupine litter did not modify the P uptake by aboveground maize biomass compared

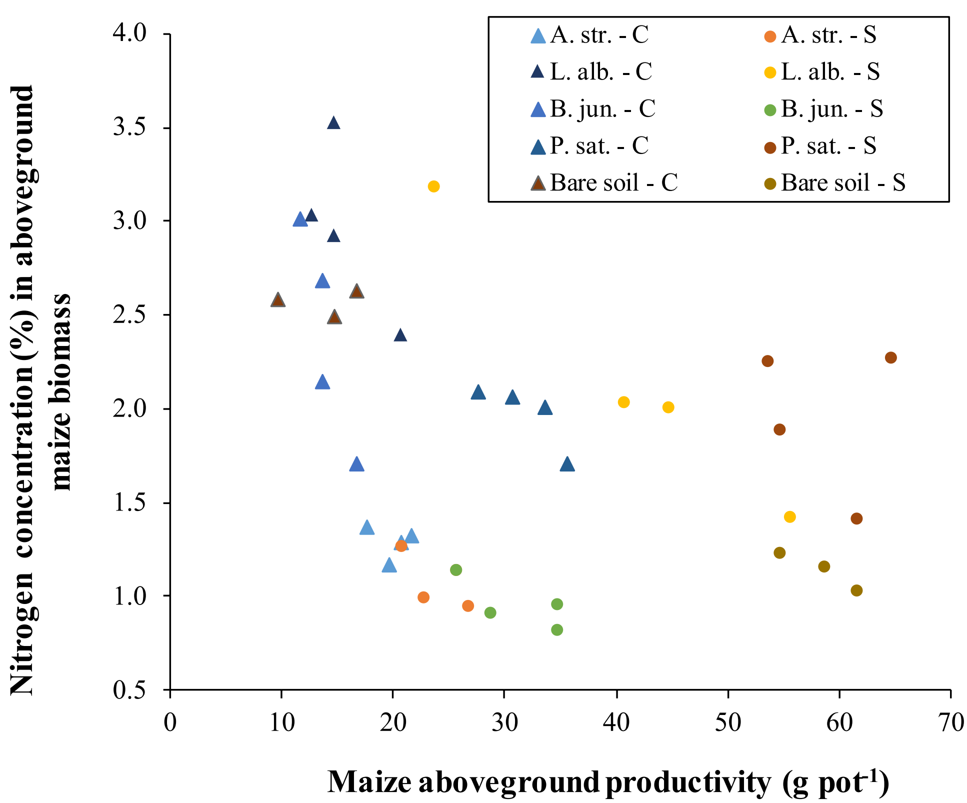

Fig. 1 Nitrogen concentration (%) in aboveground maize biomass in relation to the corresponding aboveground (biomass) productivity (g pot^{-1}) for the four cover crop treatments ($n = 4$) as well as for bare soil ($n = 3$) in clay (C, triangles) and sandy (S, circles) soil. Abbreviation for cover crop species: A. str., *Avena strigosa* (oat); L. alb., *Lupinus albus* (lupine); B. jun., *Brassica juncea* (Indian mustard); P. sat., *Pisum sativum* (field pea)

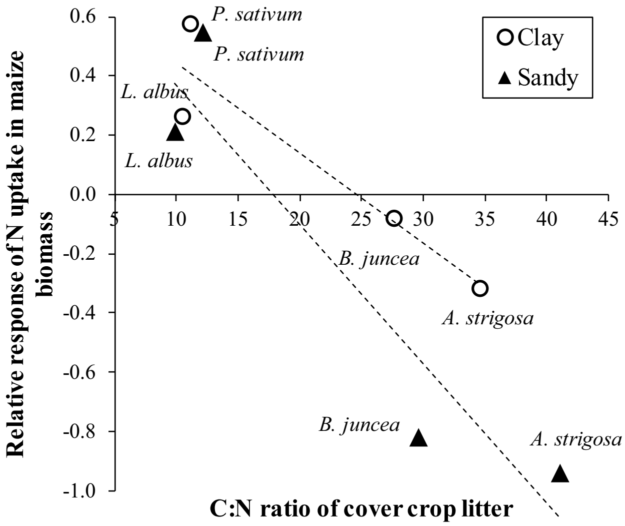

Fig. 2 Mean C:N ratio of cover crop litter and mean relative response of N uptake in maize aboveground biomass in clay and sandy soil ($n = 4$). The relative response corresponds to the ln of the ratio between the N uptake by maize cultivated after burial of cover crop litter and the N uptake by maize cultivated on bare soil. Regression line is $y = -0.03x + 0.74$ ($R^2 = 0.88$, $p = 0.062$) for clay soil and $y = -0.05x + 0.87$ ($R^2 = 0.87$, $p = 0.069$) for sandy soil

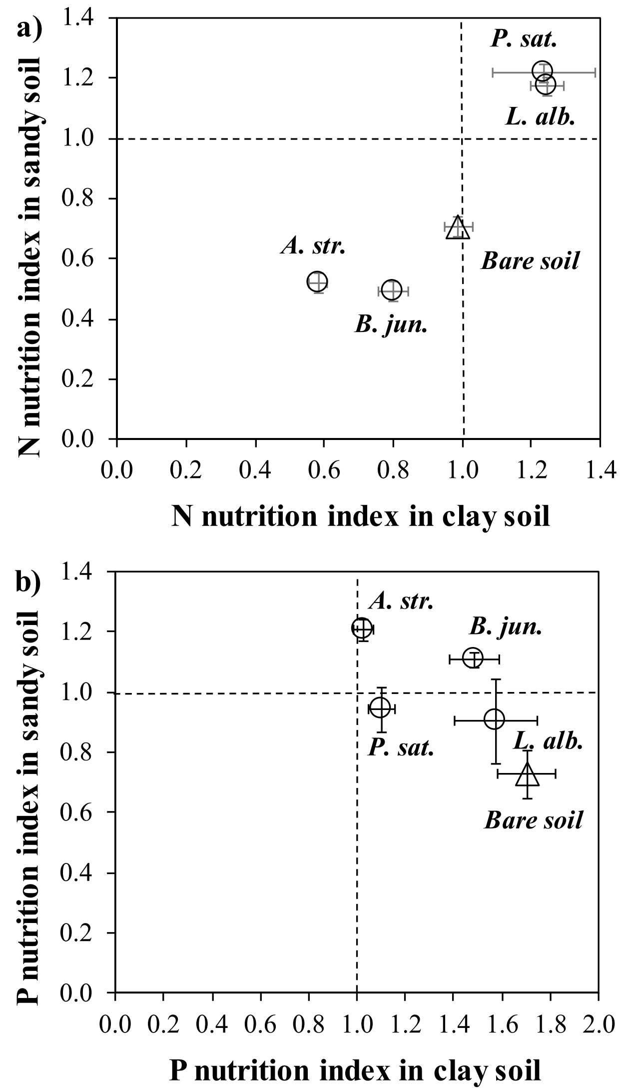

Fig. 3 Mean (± SD, $n = 4$) nitrogen (**a**) and phosphorus (**b**) nutrition index of maize biomass in clay and sandy soil after 8 weeks of growth. The corresponding mean nutrition index ($n = 3$) for maize in bare soils is also reported. Abbreviations for cover crop species are as follows: A. str., *Avena strigosa* (oat); L. alb., *Lupinus albus* (lupine); B. jun., *Brassica juncea* (Indian mustard); P. sat., *Pisum sativum* (field pea)

to bare soil, whereas the presence of oat and Indian mustard litter decreased the P uptake compared to bare soil (Table 2). In sandy soil, the burial of field pea litter and oat litter increased and, respectively, decreased the P uptake by maize aboveground biomass compared to bare soil, whereas no effect was associated to the presence of Indian mustard and lupine (Table 2).

The comparison of cover crop effects showed that, for both soil types, the field pea litter increased P uptake by maize more than the other three cover crop species (Table 2).

Differently from N, there was not any significant relationship between the relative response of P uptake in maize aboveground biomass and the correspondent C:P ratio of cover crop litter for both soil types ($p > 0.31$, $n = 4$).

In clay soil, the P nutrition index (PNI) of maize biomass was > 1 for all the cover crop treatments as well as for bare soil (Fig. 3b). In sandy soil, only the burial of oat and Indian mustard litter was associated to a PNI of maize biomass > 1, whereas for the leguminous treatments and the bare soil, the PNI was slightly < 1 (Fig. 3b).

4 Discussion

In the scientific literature, the effect of soil texture on aboveground maize productivity has shown contrasting results. Generally, yield is higher on coarse-textured soils than on fine-textured soils (Katerij and Mastrorilli 2009; Tremblay et al. 2011) even if in arid climates higher crop yields have been reported on clay soils (Feng et al. 2016; Tolk et al. 2016). Our results clearly highlight that a sandy texture is more favorable for aboveground productivity of maize under no water-limiting conditions, in accordance with previous studies (see Hirte et al. 2021; Ontl et al. 2013; Popleau and Kätterer 2017). We argue that this is the consequence of a better soil oxygenation, as further supported by the higher decomposition rate of cellulose filters in sandy soil (mean loss = 59%; $n = 19$) compared to clay soil (mean loss = 33%; $n = 19$) after 4 weeks of burial (Table 3). The role of soil oxygenation is consistent with the fact that maize roots demand substantial amounts of oxygen, particularly

Table 3 Mean values of (1) cellulose filter decomposition (%) after 8 weeks of burial during the maize growth; (2) aboveground biomass (mg pot^{-1}) and correspondent nitrogen (N) content (mg pot^{-1}) of each cover crop species before burial; and (3) soil concentration of total nitrogen (N_{tot}) and available phosphorus (P_{Olsen}) before the sowing of maize in clay and sandy soil for each cover crop treatment as well as for the bare soil treatment. Different lowercase superscript letters indicate, for the same variable, significant differences ($p < 0.05$) between cover crop treatments within the same soil type based on ANOVA with post hoc Tukey comparison. $n = 4$ for each cover crop treatment and $n = 3$ for the bare soil treatment. *NA*, not available

	Clay soil					Sandy soil				
	Bare soil	*Avena strigosa* (Oat)	*Brassica juncea* (Mustard)	*Lupinus albus* (Lupine)	*Pisum sativum* (Pea)	*Bare soil*	*Avena strigosa* (Oat)	*Brassica juncea* (Mustard)	*Lupinus albus* (Lupine)	*Pisum Sativum* (Pea)
Filter decomposition (%)	25^b	29^b	36^{ab}	43^a	30^b	26^b	83^a	80^a	59^{ab}	48^{ab}
Aboveground cover crop biomass (g pot^{-1})	NA	20^b	19^b	31^a	26^{ab}	NA	27^b	29^b	47^a	42^a
Nitrogen content in cover crop biomass (mg pot^{-1})	NA	273^b	312^b	1438^a	1157^a	NA	298^c	471^b	2427^a	1695^a
Soil N_{tot} concentration (‰)	2.06^a	1.93^b	1.89^b	2.08^a	2.10^a	1.44^a	1.31^b	1.26^b	1.44^a	1.43^a
Soil P_{Olsen} (mg kg^{-1})	33.5	32.1	33.0	33.2	29.8	50.7^a	46.5^c	48.3^{abc}	49.1^{ab}	47.8^{bc}

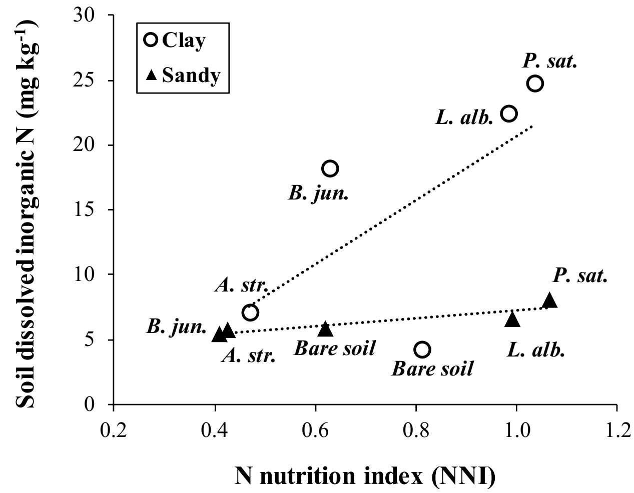

Fig. 4 Relationship between the mean concentration of dissolved inorganic nitrogen (DIN) in clay and sandy soil and the correspondent nitrogen nutrition index of maize biomass after 8 weeks of growth in response to the antecedent cover crop species ($n = 4$) as well as in bare soil ($n = 3$). Regression line for cover crop treatment only ($n = 4$) is $y = 22.1x - 3.2$ ($R^2 = 0.87$, $p = 0.07$) for clay soil, and $y = 2.6x + 4.2$ ($R^2 = 0.77$, $p = 0.122$) for sandy soil

during the early growth stage (Zhou et al. 2019). Although the initial chemical analyses of the two soils showed a lower availability of zinc in the clay soil, we think that this is not a major reason for the observed differences in maize productivity, considering that the exchangeable zinc concentration is still in the expected range for agricultural soils (Mertens and Smolder 2013).

For what concerns the belowground biomass, greater root biomass in sandy soil compared to the clay soil, as observed particularly for the bare soil, seems in accordance with the “root contact” model (Herkelrath et al. 1977). Indeed, a higher physical discontinuity from soil to root in sandy soil is expected to stimulate root development in order to increase root surface for water absorption (Poeplau and Katterer 2017; Wang et al. 2018). Furthermore, such a root development can be further facilitated by the lower mechanical constraint of a sandy soil than a clay soil (Kirby and Benough 2002). Ultimately, higher root surface favors a greater access to nutrients with a positive feedback on aboveground productivity (Duque and Villordon 2019; Qi et al. 2012; Wang et al. 2005).

For what concerns the impact of the preceding cover crop on maize productivity, contrasting results can be found in the literature in particular in relation to the cover crop identity, climate conditions, and production systems (Blanco-Canqui et al. 2015; Jian et al. 2020). For example, Marcillo and Miguez (2017) and Wittwer et al. (2017) observed a positive response of maize yield to antecedent legume cover crops, with no significant effect of non-legume cover crops. Tonitto et al. (2006) found that, under non-leguminous cover

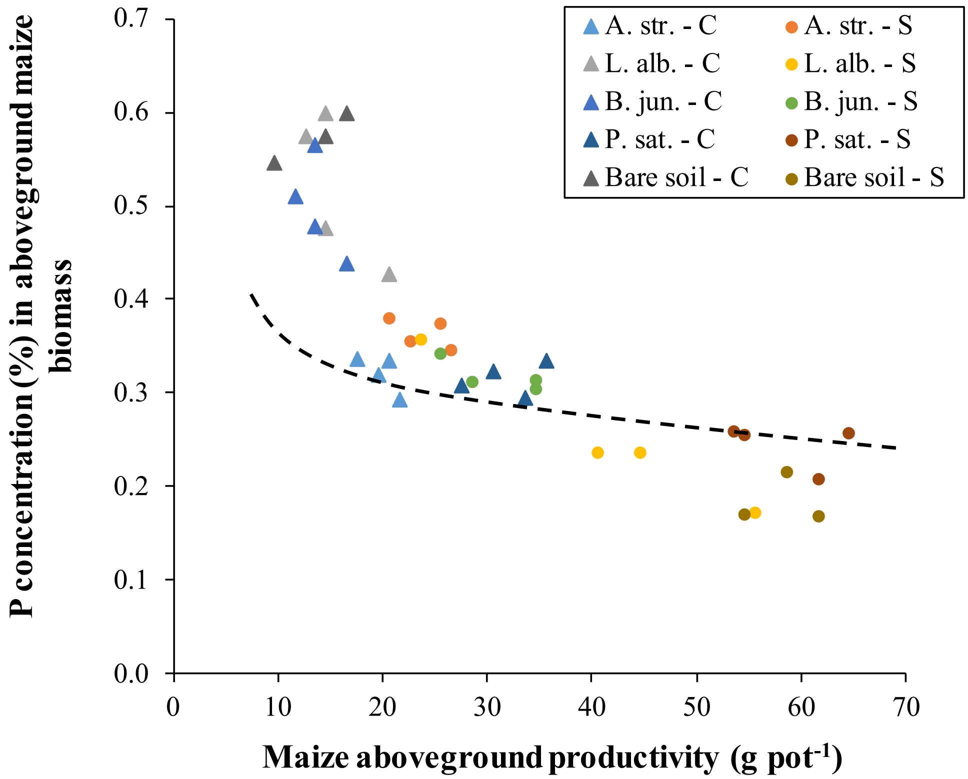

Fig. 5 Phosphorus concentration (%) in aboveground maize biomass in relation to the corresponding aboveground (biomass) productivity for the four cover crop treatments (*n* = 4) as well as for bare soil (*n* = 3) in clay (C, triangles) and sandy (S, circles) soil. Cover crop species abbreviation: A. str., *Avena strigosa* (oat); L. alb., *Lupinus albus* (lupine); B. jun., *Brassica juncea* (Indian mustard); P. sat., *Pisum sativum* (field pea). The dashed line represents the dilution curve as calculated from the equation by Cadot et al. (2018)

crops, the yield of cash crop did not differ from bare fallow systems, but it decreased with legume cover crops. Abdalla et al. (2019) and Alvarez et al. (2017) reported that non-leguminous cover crops can decrease cash crop yield. Our study clearly showed that aboveground and belowground productivity of maize were affected by the preceding cover crop species differently depending on soil type.

Based on the above assessment that clay soil has a more constraining texture for maize productivity, the positive effect of field pea and oat in clay soil may be explained by their fibrous root system that can improve soil macroporosity and pore connectivity much better than the taproot system of Indian mustard and lupine (Lucas et al. 2022). On general, in clay soil, the presence of cover crops promoted or did not modify the aboveground maize productivity compared to bare soil. On the other hand, in sandy soil, the presence of oat and Indian mustard decreased maize productivity compared both to bare soil and to leguminous cover crops as previously reported (Quin et al. 2021). We hypothesize that this pattern is due to N limitation in sandy soil with non-leguminous cover crops as supported by the initial lower soil N_{tot} concentration in the oat and Indian mustard treatments (Table 3). It seems then that the selection of the preceding cover crop species in N-limited sandy soil requires major attention in order to avoid a potential decrease of productivity of aboveground maize biomass.

The negative response of root biomass in sandy soil seems still in accordance with the root contact model (Herkelrath et al. 1977), if we consider that organic debris, released during the decomposition of the buried cover crop, can reduce the physical discontinuity from soil to root and so the necessity for maize to increase the root biomass.

For what concern the N nutrition of maize, in accordance to previous studies (e.g., Gabriel and Quemada 2011; Kaye et al. 2019; Perdigao et al. 2021; Pott et al. 2021; Wittwer and van der Heijden 2020), our data showed that the burial of leguminous litter significantly increased the N uptake by maize. By considering the aboveground cover crop productivity and their higher N concentration (Table 3), as consequence of their N fixing capacity (Adams et al. 2016; Wolf et al. 2017), the leguminous cover crops provided a significantly greater N input in both soil types, on average 1680 mgN per pot versus 338 mgN per pot of the non-leguminous (Table 3). We hypothesize that a similar pattern of N input can also be provided by the roots even if, unfortunately, we did not measure root biomass and corresponding N content in our cover crop species. In addition, the capacity of leguminous species to provide additional N to maize is also reflected by soil chemistry at the end of cover crop growth, i.e., just before the sowing of the maize, when higher N_{tot} concentration can be observed in both soils for the field pea and lupine treatments compared to the non-leguminous treatments (Table 3).

The positive effect of leguminous cover crops on maize N uptake can be related to the stoichiometry of their litter. Generally, higher N content and lower C:N ratio of plant litter are expected to promote litter N mineralization (Bragazza et al. 2021; Carciochi et al. 2021; Chauvin et al. 2015; Thorup-Kristensen et al. 2003). In our study, the lower C:N ratio of leguminous cover crops was associated to a higher relative response of N uptake in maize as well as to higher DIN concentrations in bulk soil at the end of maize growth (Fig. 4). Under such conditions, a N-demanding crop, such as maize, can profit from N easily released by leguminous litter decomposition with, ultimately, a positive effect on biomass productivity and N uptake (Gabriel and Quemada 2011; Gentry et al. 2013; Thorup-Kristensen et al. 2003; Tonitto et al. 2006). Differently, the fact that the oat and the Indian mustard treatment did not improve maize N uptake compared to bare soil, although both cover crops provided a N return through their litter (Table 3), may be explained by a stronger N immobilization during their litter decomposition due to higher C:N ratios (Couëdel et al. 2018; Finney et al. 2016; Nevins et al. 2020; Sievers and Cook 2018). Such a decrease of the N nutrient status with non-leguminous cover crops underlines, from a practical point of view, the importance of the temporal lag between cover crop destruction and cash crop N demand in order to avoid that the immobilized N will remain unavailable for the cash crop (McSwiney et al. 2010).

In our greenhouse experiment, we deliberately provided a low N fertilization rate, i.e., 25% of the official recommendations (Sinaj and Richner 2017). Even under such a limitation of N fertilization, our data show that the burial of leguminous litter still provided, at least after 8 weeks of growth, an optimal N nutrition for the maize that, indeed, did not encounter any N limitation (i.e., NNI > 1) in both soil types. Such a result confirms the role of leguminous cover crops as a source of N for the subsequent maize so contributing to compensate for fertilization shortage (Adeux et al. 2021; Gabriel and Quemada 2011; Ma et al. 2016; Qin et al. 2021; Wittwer et al. 2017).

For what concerns the P nutrition of maize, the PNI values are generally higher or close to 1 for all the cover crop treatments, very likely because our clay and sandy soils were characterized, respectively, by high and very high soil P availability since the beginning of the experiment (Table 3). Ultimately, we can assume that no P limitation occurred for the maize plants during our experiment. Differently from soils characterized by low P availability (Hallama et al. 2019), we can assess that our selected cover crops did not play a major role in improving P nutrition for the following cash crop. However, lower PNI values can be observed in the sandy soil with the leguminous treatments and in the bare sandy soil despite the high Olsen-P concentration (Table 3). We may argue that these lower PNI values were due to the selected P dilution curve that did not sufficiently correct the dilution of P concentration due to the high rates of aboveground biomass productivity (Fig. 5). This is particularly detectable in sandy bare soil where maize had a high aboveground productivity, without receiving any extra input of P from the decomposing cover crop litter, but ultimately showing the lowest PNI value.

By comparing the different cover crop treatments, we can observe that the lupine treatment resulted in a PNI >1 in clay soil, but a PNI < 1 in sandy soil, in combination with a maize P, uptake rather low despite a high aboveground productivity. This result does not match with the reported capability of lupine to mobilize soil P more efficiently in acidic soil than in alkaline soil (De Silva et al. 1994; Moraghan 1993). However, contrasting results have been reported in the scientific literature where lupine residues can be either increase or decrease the P uptake by the following cash crop (e.g., Arrobas et al. 2015; Fontana et al. 2021b; Pavinato et al. 2017). On the other hand, the highest P uptake by maize with the field pea treatment for both the soil types is consistent with the recognized ability of this species to stimulate the mineralization of organic P, subsequently available for the uptake by the cash crop (Piotrowska-Długosz and Wilczewski 2020).

5 Conclusions

Overall, our results clearly show that a sandy texture is more favorable for the aboveground productivity of maize, compared to a clay soil, as consequence of a better soil oxygenation. In line with this, the positive effect of field pea and oat residues in clay soil on aboveground maize biomass can be related to their fibrous root system that can improve soil macro-porosity and pore connectivity much better than the taproot system of Indian mustard and lupine. For what concerns the N nutrition of maize, the burial of leguminous cover crops significantly increased the N uptake by the maize due to the lower C:N ratio of lupine and field pea residues. On the other hand, the observed decrease of the N nutrient status of maize after the burial of non-leguminous cover crops seems to underline, from a practical point of view, the importance of the temporal lag between cover crop destruction and cash crop N demand in order to avoid that N immobilized N in the decomposing cover crop litter remains unavailable for the cash crop. For what concerns the P nutrition of maize, our selected cover crops did not play a major role in improving P nutrition for the following cash crop, probably due to the high initial P availability in the studied soils.

From an agronomic point of view, our study shows that the burial of leguminous litter provided, at least after 8 weeks of growth, an optimal N nutrition for the maize in both the clay and the sandy soil. Such result confirms the interest in promoting the use of leguminous cover crops with the goal of reducing the input of chemical fertilizers so to rely more on legumes as natural input of N for the following cash crops.

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Declarations

Conflict of Interest The authors declare no competing interests.

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