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Functional trait-based design of cover crops for maize yield, resource use, and nitrogen dynamics

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Abstract

Cover crops are usually grown to conserve nutrients and make them available to the succeeding crop. The type and extent of this conservation depends, among other things, on the functional traits of the cover crops and is influenced in particular by rooting depth, biological N_2-fixation and winter hardiness. If cover crops are not terminated before the following main crop, but are maintained as living mulch (LM) systems, there are competitive effects that are reflected in biomass yield and nutrient uptake. However, little is known about effects of the functional composition and much less about niche occupancy in the root zone when different LM combinations are grown with maize. We evaluated eight cover crop treatments, as LM or non-living mulch (NLM), on maize yield and nitrogen (N) uptake. NLM treatments did not significantly affect maize yield (control: 23.7 Mg DM ha^{-1}; NLM: 22.4 Mg DM ha^{-1}), whereas LM significantly reduced yield (10.1 Mg DM ha^{-1}), regardless of functional composition. At harvest, mineral N (N_{min}) was lowest in LM, intermediate in NLM, and highest in the control, reflecting differences in root competition and N uptake. After this first year of evaluation, functional traits of cover crops seem of much lesser importance than the cover crop management.

Keywords: cover crops, functional traits, living mulch, maize yield, nutrient uptake

Introduction

Cover crops are a sustainable agronomic practice that improve nutrient cycling, soil structure, and weed suppression, thereby enhancing resource use efficiency, subsequent crop productivity, and long term sustainability of cropping systems (Quintarelli *et al.*, 2022). The realization of these benefits depends largely on cover crop functional traits, such as rooting depth, biological N_2-fixation, and winter hardiness, as well as management optimization, among other factors (Kühling *et al.*, 2023). In maize-based systems, terminated cover crops primarily act as nutrient catch crops, releasing resources to the following maize crop, whereas LM persist throughout the season, providing continuous ground cover, supporting biodiversity, and reducing nitrate leaching (Huss *et al.*, 2022). However, LM may also compete with maize for light, water, and nutrients, raising questions about whether functional trait diversity can mitigate these trade-offs. Despite their potential, little is known about how functional trait combinations in cover crops influence maize performance, particularly in terms of root-zone niche occupancy, and belowground resource capture under LM systems. Therefore, in this study, we assessed silage maize above and belowground biomass and soil N_{min} to address the research question: How do cover crop functional traits and management strategies influence maize yield, root distribution, and N dynamics?

Materials and methods

The experiment was conducted at the Reinshof experimental site, Göttingen, Germany, as part of a multi-year, multi-site field study. The soil is a silty loam Phaeozem (pH 7.1). Eight cover crop treatments and a control (fallow) were arranged in a randomized complete block design with four replicates. Treatments included single and multi-species mixtures differing in key functional traits and managed as either LM or NLM. Cover crops were sown in August 2023 following barley harvest, at 15 kg ha^{-1}. LM treatments included white clover (*Trifolium repens*), sorghum (*Sorghum sudanense*) with white clover, and a four-species mixture of red fescue (*Festuca rubra*), sorghum, white clover, and Persian clover (*Trifolium resupinatum*). NLM treatments included sorghum, white clover, sorghum with white clover, and two four-species mixtures: one with red fescue, sorghum, white clover, Persian clover, and the other with red fescue, sorghum, oilseed radish (*Raphanus sativus*), and winter rapeseed (*Brassica napus*). Silage maize (*Zea mays*) was sown in mid-May 2024 at 100 000 seeds ha^{-1} with 75 cm row spacing in 10 × 10 m plots. Fertilization included 120 kg N, 46 kg P, and 120 kg K ha^{-1}. Aboveground biomass was sampled at maize BBCH 33, 65 and 85 by harvesting ten plants per plot from two central rows; subsamples were oven dried at 60°C to constant weight. Root biomass was collected at maize BBCH 33 and 65 using a soil corer of 9 cm diameter at 0–30 and 30–60 cm depths and three positions relative to the maize row: maize row (MR), near maize row (NMR), and between maize rows (BMR). Soil N_{min} (NO_3^- and NH_4^+) was collected in triplicate per plot at 0–30, 30–60 and 60–90 cm at five time points (before and after winter and maize BBCH33, 65 and 85). Statistical analyses were performed in R (v4.2.2) using linear mixed effects models ('nlme' package) with block as a random factor. Post hoc comparisons of estimated marginal means were performed using the 'emmeans' package with Tukey adjustment.

Results and discussion

Maize aboveground biomass at BBCH 85 was not significantly affected by the functional composition of cover crop mixtures but was strongly influenced by management (Table 1). LM significantly reduced maize biomass (10.1±0.76 Mg DM ha^{-1}) compared to control (23.7 ± 1.31 Mg DM ha^{-1}) and NLM (22.4 ± 0.59 Mg DM ha^{-1}), which did not differ from each other, reflecting competition with living cover crops possibly for light, nutrients, and water. Root biomass at 0–30 cm differed among treatments and positions (Table 2). In the MR, LM significantly reduced root biomass (2.08 ± 0.20 Mg DM ha^{-1}) relative to control (3.47 ± 0.44 Mg DM ha^{-1}) and NLM (4.52 ± 0.24 Mg DM ha^{-1}), indicating strong belowground competition, whereas LM significantly increased root biomass in NMR (0.60 ± 0.11 Mg DM ha^{-1}) and BMR (0.50 ± 0.10 Mg DM ha^{-1}), suggesting lateral root development to avoid direct competition. No significant differences were observed at 30–60 cm depth, showing that competition was concentrated in the upper soil layer where maize and LM roots

Table 1. Mean aboveground maize biomass at BBCH85 under control, living mulch, and non-living mulch treatments.

Treatment	Aboveground biomass (Mg ha^{-1})
Control	23.7 ± 1.31 b
Living mulch (LM)	10.1 ± 0.76 a
Non-living mulch (NLM)	22.4 ± 0.59 b

Values are mean±SE; different letters indicate significant differences (Tukey-adjusted, $P < 0.05$).

Table 2. Mean root biomass of maize at 0–30 cm depth across three positions under control, living mulch, and non-living mulch treatments.

Treatment	MR (Mg ha^{-1})	NMR (Mg ha^{-1})	BMR (Mg ha^{-1})
Control	3.47 ± 0.44 b	0.17 ± 0.10 a	0.17 ± 0.10 ab
Living mulch (LM)	2.08 ± 0.20 a	0.60 ± 0.11 b	0.50 ± 0.10 b
Non-living mulch (NLM)	4.52 ± 0.24 b	0.16 ± 0.05 a	0.12 ± 0.04 a

Values are mean±SE; different letters indicate significant differences (Tukey-adjusted, $P < 0.05$). No significant differences were observed at 30–60 cm depth. MR, maize row; NMR, near maize row; BMR, between maize rows.

Table 3. Mean soil mineral N (0–90 cm) after winter (March 2024) and at final harvest (September 2024) under control, living mulch, and non-living mulch treatments.

Treatment	After winter (kg N ha^{-1})	Final harvest (kg N ha^{-1})
Control	89.7 ± 16.66 b	68.4 ± 12.70 b
Living mulch (LM)	45.6 ± 04.89 a	31.0 ± 03.33 a
Non-living mulch (NLM)	45.2 ± 03.75 a	38.1 ± 03.16 ab

Values are mean±SE; different letters indicate significant differences among treatments within each sampling date (Tukey-adjusted, $P < 0.05$).

co-occur. Soil N_{min} (0–90 cm) also varied among treatments and seasons (Table 3). After winter, control plots contained 89.7 ± 16.7 kg N ha^{-1}, nearly double that of LM (45.6 ± 4.9 kg N ha^{-1}) and NLM (45.2±3.8 kg N ha^{-1}), which did not differ significantly from each other, indicating that both LM and NLM effectively captured N over winter, and likely reduced leaching. At harvest, N_{min} was lowest in LM (31.0±3.3 kg N ha^{-1}), intermediate in NLM (38.1 ± 3.2 kg N ha^{-1}), and highest in control (68.4 ± 12.7 kg N ha^{-1}). In LM, strong belowground competition limited N availability, whereas in NLM, maize accessed N efficiently and residue mineralization contributed additional N, resulting in intermediate N_{min} level. In the Control, no cover crop competed for N, so maize uptake alone possibly left the highest soil N_{min}.

Conclusion

Cover crop management, more than functional trait composition, determined maize yield and soil N dynamics. LM maximised N retention but reduced yield, whereas NLM sustained yields comparable to control while lowering residual N_{min}, offering a more balanced trade-off between productivity and N conservation.

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