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Intercropping leek (*Allium porrum* L.) with dyer's woad (*Isatis tinctoria* L.) increases rooted zone and agro-ecosystem retention of nitrogen

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ABSTRACT

Nitrate leaching can be high in organic vegetable production. Late-harvested crops like leek limit the use of autumn catch crops. The aim of this study was to investigate the growing of a combination of a deep-rooted catch crop and a shallow-rooted vegetable to reduce the risk of nitrate leaching. We compared a leek sole crop (S) with two intercropped systems of leek and early-sown dyer's woad (five weeks after leek planting) (IE) or late-sown dyer's woad (eight weeks after leek planting) (IL) in two seasons: 2012 and 2013. To reveal root and resource competition, leek with dyer's woad rows left empty (S_{emp}), and early and late-sown dyer's woad with leek rows left empty (DE_{emp}, DL_{emp}) were included. Yield, dry aboveground biomass, aboveground N accumulation and soil inorganic N (N_{inorg}) were measured as well as root growth by use of minirhizotrons to 2.3 m soil depth. Results showed that the marketable yield of leek in IE and IL systems was comparable with the yield in the S system when calculated per length of leek row. The Relative Competition Index (RCI) revealed that interspecific competition facilitated the growth of leek but hampered that of dyer's woad. The rooted zone increased from 0.5 m in the S system to more than 2 m depth in those of the intercropped systems. Dyer's woad ceased growing above ground but kept growing below ground after crop harvest and extended roots under the leek root system in 2012. Intercropping increased the root intensity of late-sown dyer's woad after leek harvest in the 0.75–1.75 m soil layer compared to dyer's woad growing alone (DL_{emp}), while the root depth was not affected. The intercropped system with early-sown dyer's woad reduced soil N_{inorg} by 52 kg ha^{-1} relative to the sole-cropped system, and dyer's woad accumulated 48 kg N ha^{-1} in aboveground biomass at harvest in 2013. Late-sown dyer's woad had fewer roots, left higher soil N_{inorg} and had lower aboveground N accumulation than early-sown dyer's woad until the following spring. Therefore, early-sown dyer's woad is applicable in an organic intercropped system with high yields of leek to decrease the risk of nitrate leaching.

1. Introduction

Organic vegetable production relies on mineralization of organic N sources, but may still have high nitrate leaching to the environment. This is due to the mismatch of the timing in mineralization of N and plant N uptake between seasons, and the growing of vegetables with high N demand but low N use efficiency. Catch crops grown after crop harvest are known for reducing nitrate leaching and improving N use efficiency in field crop rotations as well as in vegetable production (Tuulos et al., 2015; Wyland et al., 1996). However, late-harvested crops, such as leek (*Allium porrum* L.), may leave insufficient time for catch crop growth and N uptake before winter, which increases the risk of nitrate leaching (Kristensen and Thorup-Kristensen, 2007).

Intercropped systems with a cash crop and a catch crop growing in alternating rows allow the catch crop to take up N during the crop growth season and after crop harvest. This has been shown to reduce the risk of nitrate leaching in organic cropping system (Thorup-Kristensen et al., 2012), but reports of the effect of intercropped catch crops on N cycling are scarce. Autumn catch crops with high N-sink capacity have been reported to take up more N from the soil and prevent nitrate leaching, compared to fallow. For example, winter rape (*Brassica napus* L.) and fodder radish (*Raphanus sativus* L. var. *oleiformis* Pers.) were found to take up 127 and 167 kg N ha^{-1} from August to November (Thorup-Kristensen, 1994). Additionally, the root depth and subsoil root intensity of catch crops were found to have a strong correlation with soil N_{inorg} left for leaching in the subsoil (Thorup-Kristensen and Rasmussen, 2015). Species from the *Brassica* family are well known for their

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deep root systems, which play an important role in depleting N_{inorg} in deep soil layers. For example, fodder radish with root depth of more than 2.4 m could take up N from more than 2 m depth (Kristensen and Thorup-Kristensen, 2004). Apart from the genetic traits, the root growth is influenced by the growing environment such as the availability and distribution of N (Kristensen and Thorup-Kristensen, 2007), phosphorus (Kang et al., 2014) and water (Ebrahimi et al., 2014) as well as the presence of neighboring plants (Hauggaard-Nielsen et al., 2001). However, studies on the effect of deep-rooted catch crops on root growth in intercropped systems are scarce.

Attention should also be paid to the interspecific competition in intercropped systems for nutrients, light and water, which may hamper crop growth. Strategies for catch crop management, like appropriate choice of species, mowing (Theriault et al., 2009), pruning the roots (Båth et al., 2008) and delayed sowing (Vanek et al., 2005) as well as maintaining overall plant density (Thorup-Kristensen et al., 2012) could reduce the interspecific competition and result in acceptable yields.

Dyer's woad (*Isatis tinctoria* L.) was cultivated throughout Europe as a source of blue dye, but is considered a noxious weed in the western United States (Dewey et al., 1991). Its low plasticity in response to changes in soil N indicated that it has low N requirements or low N productivity (Monaco et al., 2005), suggesting that it may be less competitive for N compared to many cash crops. Due to its root depth of 2.4 m, it reduced the subsoil nitrate to 15 kg N ha^{-1}, compared to the 62 kg N ha^{-1} without a catch crop (Thorup-Kristensen and Rasmussen, 2015). On the contrary, leek is known to have a shallow root system with a root depth of 0.5 m leaving a higher amount of soil N_{inorg} for leaching in the autumn compared to deep-rooted vegetables (Kristensen and Thorup-Kristensen, 2007). We hypothesized that combining deep-rooted dyer's woad with shallow-rooted leek would reduce the risk of nitrate leaching. Since delayed sowing of catch crops relative to cash crops may increase the competitiveness of cash crops by allowing them to dominate for nutrients and space (Vanek et al., 2005), we hypothesized that delayed sowing of dyer's woad would also be an effective tool to increase the competiveness of leek.

Therefore, we aimed to investigate the feasibility of introducing dyer's woad as intercrop to reduce the risk of nitrate leaching, and the effect of delayed sowing of dyer's woad to control the interspecific competition. The hypotheses in the present study are: 1) Early sown dyer's woad has strong competiveness against leek and affects leek yield, while late sown dyer's woad reduces the interspecific competition having less roots and biomass, compared to early sown dyer's woad. 2) Introducing dyer's woad reduces the risk of nitrate leaching after harvest, while the effect is reduced by delayed sowing of dyer's woad. 3) Dyer's woad increases the soil volume explored by roots compared to the sole-cropped system, and grows beneath the leek root system. 4) Dyer's woad keeps growing and taking up soil N_{inorg} after leek harvest. 5) Dyer's woad develops a deeper root system in the intercropped system than when grown alone.

We tested these hypotheses in a two-year field experiment in which we assessed leek crop yields and biomass of all plants, root distribution, plant N accumulation and soil N_{inorg} in treatments with and without a dyer's woad catch crop, and in which sowing of the catch crop occurred at five and eight weeks after leek planting.

2. Material and methods

2.1. Field sites and experimental design

A field experiment was conducted during two cropping cycles in 2012 and 2013 at the Research Centre Aarslev, Denmark (10°27′E, 55°18′N) on a sandy loam (Typic Agrudalf) which contained 9 g C kg^{-1}, 134 g kg^{-1} clay, 151 g kg^{-1} silt and 696 g kg^{-1} sand at the 0–0.5 m soil layer; 2 g C kg^{-1}, 188 g kg^{-1} clay, 132 g kg^{-1} silt, and 676 g kg^{-1} sand at the 0.5–1 m soil layer; 2 g C kg^{-1}, 181 g kg^{-1} clay, 138 g kg^{-1} silt, and 678 g kg^{-1} sand at the 1–2.5 m soil layer. The P content was 24, 19 and 16 mg kg^{-1} and the K content was 119, 102 and 105 mg kg^{-1} at the soil layers of 0–0.5, 0.5–1 and 1–2.5 m. The pH_{CaCl2} value was 6.8, 5.9 and 7.3. The mean annual air temperature and mean precipitation were 8.5 °C and 664 mm recorded at the meteorological station at the research center, Aarslev (1987–2012). Daily mean temperatures and precipitation during the experimental period are shown in Fig. 1. The field management was according to the Danish organic management regulations since 1996 without use of pesticides or inorganic fertilizers.

The experiment was run in 2012 and 2013 at two adjacent fields with a distance of 286 m. In the 2012 experiment a mixture of perennial ryegrass (*Lolium perenne* L.), red clover (*Trifolium pratense* L.) and black medick (*Medicago lupulina* L.) had been sown in late April, 2010 and incorporated in late July, 2011. Then fodder radish was sown as an autumn catch crop in early August, 2011 and incorporated into the soil in early April, 2012. In the 2013 experiment, the same mixture of grass and legumes had been sown in late April, 2011 and incorporated in December, 2012.

Each year a completely randomized block design with three replicates was applied. The plot size was 3.2 m × 6.5 m. Six rows of plants were planted in one plot with a row distance of 0.53 m and plant distance of 0.08 m. Leek (open pollinated cv. Hannibal) was germinated and grown under organic greenhouse conditions since March 9, 2012 and March 13, 2013. The leeks were transplanted to the field on May 25, 2012 and May 31, 2013 and grown either as a sole crop (S), an intercrop with every third row replaced by a row of dyer's woad (I) or as a sole crop with every third row left empty (S_{emp}). Although not relevant for growers the S_{emp} system was included to be able to separate effects of changes in leek density between the systems. The dyer's woad was sown at 100 germinating seeds per meter row at two different dates denoted as early sowing (IE) (July 4, 2012; July 5, 2013), and late sowing (IL) (July 23, 2012; July 26, 2013). The design with a row of dyer's woad replacing a row of leek is called a substitutive design. In order to observe the effect of intercropping on the root growth of dyer's woad, an additional system was included where dyer's woad was grown solely in every third row at early sowing dates (DE_{emp}) and late sowing dates (DL_{emp}) with empty crop rows. The amount of N fertilizer in the form of dried chicken manure applied was 70 and 123 kg ha^{-1} in 2012 and 2013 respectively, reaching to a total of 200 and 210 kg N ha^{-1} (soil N_{inorg} and N fertilizer) right after leek transplanting. The density of leek was 23 plants m^{-2} in the S system and 15.6 plants m^{-2} in the IE, IL and S_{emp} systems due to the lower number of rows. Over the growing season the leeks were irrigated at moderate soil water deficits. The total amount of water given was equivalent to 65 and 150 mm of precipitation in 2012 and 2013, respectively.

2.2. Root measurements

The root growth was registered over time by use of the minirhizotron method, which were transparent plastic tubes of 3 m length. In each plot, two minirhizotrons were inserted into the soil at an angle of 36° from vertical to reach 2.3 m depth per plot. Details of the method are given in (Kristensen and Thorup-Kristensen, 2004). The minirhizotrons were installed in the leek, dyer's woad and empty rows within a few days after planting/sowing in the systems to reveal the effect of intercropping on root growth. Two counting grids (40 mm × 40 mm crosses) had been drawn on the upper side of each minirhizotron. The roots in the grids were recorded by a mini-video camera. Root density was registered as intensity of the