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Soil compaction and insect pollination modify impacts of crop rotation on nitrogen fixation and yield

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Abstract

Pollination and biological nitrogen fixation are key ecosystem services, but their contribution to agricultural production might be influenced by simplified crop rotation and soil compaction, two factors known to limit yield. In a greenhouse experiment, we investigated the combined effect of crop rotation, soil compaction, and insect pollination on yield formation and on the contribution of biological fixation to nitrogen acquisition of faba bean. Seed yield was reduced under high soil compaction, and under ley rotation management and it was enhanced by insect pollination. For plants grown in soil from the ley rotation, insect pollination increased individual seed weight by 50% suggesting a contribution to seed quality by pollination for crop grown in soils where nutrients are limiting yield. Crop monoculture and high soil compaction interactively reduced the contribution of nitrogen fixation by 30%, suggesting that soil compaction exacerbates the negative effect of monoculture on nitrogen fixation.

Overall the results revealed that interactive effects of management factors do affect nutrient acquisition. We provide evidence that reduced soil quality affect the capacity of legumes to deliver key ecosystem services to the agroecosystem.

Zusammenfassung

Bestäubung und biologische Stickstofffixierung sind wichtige Ökosystemleistungen, aber ihr Beitrag zur landwirtschaftlichen Produktion könnte durch vereinfachte Fruchtfolge und Bodenverdichtung beeinflusst werden, zwei Faktoren, die den Ertrag begrenzen. In einem Gewächshaus untersuchten wir experimentell den gemeinsamen Effekt von Fruchtfolge, Bodenverdichtung und Bestäubung durch Insekten auf den Ertrag und auf den Beitrag der biologischen Fixierung zum Stickstofferwerb der Ackerbohne. Der Samenertrag war bei hoher Bodenverdichtung und bei Fruchtfolge mit Grünbrache reduziert, während er durch Insektenbestäubung erhöht wurde. Bei Pflanzen, die in Erde aus der Brachenfruchtfolge wuchsen, erhöhte Insektenbestäubung das individuelle Samengewicht um 50%, was nahelegt, dass Bestäubung bei Böden mit limitierendem Nährstoffangebot einen Beitrag zur Samenqualität leistet. Monokultur und hohe Bodenverdichtung reduzierten gemeinsam den Beitrag der Stickstofffixierung um 30%. Insgesamt zeigten die Ergebnisse, dass interagierende Effekte von Managementfaktoren den Nährstofferwerb beeinflussen. Wir erbringen den Nachweis, dass reduzierte Bodenqualität die Fähigkeit von Leguminosen beeinflusst, entscheidende Ökosystemleistungen für Agrarökosysteme zu erbringen.

Keywords: Nutrient acquisition; Soil quality; Yield; Management practices; Ecosystem services

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Introduction

Maintaining high and sustainable crop yields is a major challenge for agricultural production. Widely implemented practices such as the simplification of crop rotation (Bennett, Bending, Chandler, Hilton, & Mills 2012) and the intensive use of heavy farm machinery leading to soil compaction (Hamza & Anderson 2005) can reduce nutrient availability (Ball, Bingham, Rees, Watson, & Litterick 2005) and explain declines or stagnation of yield in key agricultural regions (Lin & Huybers 2012; Ray, Ramankutty, Mueller, West, & Foley 2012). However, ecosystem services (ES) provided by biodiversity above and below ground offer opportunities to maintain yield growth and stability (Bommarco, Kleijn, & Potts 2013). For instance, direct contributions of biological nitrogen fixation (BNF) and insect pollination to crop yield have become widely recognized (Klein et al. 2007; Peoples et al. 2009; Garibaldi et al. 2013). Nonetheless, it is not clear whether interactive effects between management factors might affect nutrient acquisition and the contribution of ES to crop yield.

Estimations of the contribution of an ES to crop yield most often assume all other production factors as optimal (Bos et al. 2007); a possibly unrealistic assumption as it does not account for that multiple ES, management, and resources might interactively influence yield formation (Boreux, Kushalappa, Vaast, & Ghazoul 2013; Lundin, Smith, Rundlöf, & Bommarco 2013; Klein, Hendrix, Clough, Scofield, & Kremen 2015). For instance, in oilseed rape, the pollinators' contribution to yield was greater in the absence of nitrogen fertilization, compensating for yield losses associated with the lower nutrient availability (Marini et al. 2015). There is a need to determine if such compensation can occur when nutrient acquisition is limited by management factors.

Crop rotations that include perennial legumes can enhance levels of soil organic matter (Cuvardic, Tveitnes, Krogstad, & Lombnæs 2004; Grover, Karsten, & Roth 2009), provide better soil structure (Ball et al. 2005) and higher N-mineralization (van Eekeren et al. 2008) than monoculture and short rotations. Soil compaction, on the other hand, has been shown to reduce root growth, water and nutrient uptake and thereby decreasing yields (Lipiec & Hatano 2003). We need to reconsider the role of ES to maintain yields, and prevent negative side-effects associated with intensive agricultural management.

Services provided below ground influence plants directly, for example, by affecting nutrient availability (Scheu 2001; Wardle et al. 2004). A widely recognized contribution of belowground biodiversity to plant nutrients is the mutualistic association between roots and nitrogen-fixing bacteria (Peoples et al. 2009). Nitrogen acquisition by legumes is partitioned between soil mineral N absorbed by the roots and N derived from BNF. Since BNF allows legumes to have access to different N sources and since management factors affect the availability of this nutrient, there is a need to investigate how N acquisition is partitioned by plants grown under contrasting soil management factors. Besides, the nodulation trait in legumes has been shown to increase pollen length and germination rate when compared to a non-nodulating mutant (Gwata, Wofford, Pfahler, & Boote 2003); a finding suggesting that BNF modulates the outcome of pollination on yield (Barber & Gorden 2014). However, information is missing on how insect pollination influences BNF at the plant level and whether this is modified by cropping practices. So far, no study has investigated the combined effect of pollination and yield limiting cropping practices on the proportion of N derived from BNF by crops. Large knowledge gaps remain of how crop management and ES interactively determine yields.

To unravel the potential interactive effects of pollination, management type, and soil compaction on crop yield and BNF, we experimentally manipulated these factors in a fully-factorial greenhouse experiment. We measured yield components, growth partitioning, and the proportion of N derived from BNF in faba bean (*Vicia faba* var. *minor* L.), a widely cultivated legume used as a protein source and green manure in mixed cropping systems (Jensen, Peoples, & Hauggaard-Nielsen 2010) and partly dependent on pollination for seed set (Cunningham & Le Feuvre 2013). We collected soil from a long-term experiment that had been managed since 1965 either as a barley monoculture, or as a crop rotation including five years of perennial leys (Puentes, Bazely, & Huss-Danell 2007). We subjected these two soils to a low or high compaction treatment. We subsequently bagged the inflorescences on half of the plants and introduced bumblebees to the greenhouse. We hypothesized that (i) in the presence of pollinators, the negative effects of soil compaction on yield will be less pronounced in soil from the ley rotation; (ii) a higher investment from the plant in seed yield would lead to a lower investment on vegetative parts; (iii) N derived from BNF will be more limited in soils with a combination of high soil compaction and monoculture origin; (iv) since insect pollination increases plant demand for N, pollination will increase the amount of N derived from BNF. Understanding how management factors affect the delivery of ES in agricultural systems will help make yield predictions that take into account current management practices in highly productive regions.

Materials and methods

Study system

To test the impact of management type, soil compaction and pollination on yield and nitrogen fixation of faba bean (*Vicia faba* var. *minor* L.) we set up a greenhouse experiment. The soil used in the experiment was a silty loam collected from a long-term agricultural field experiment located in Röbäcksdalen, Sweden (63°45′ N, 20°17′ E), started in 1965 and managed by the Swedish University of Agricultural Sciences (SLU). We selected two contrasting treatments: a monoculture of barley (*Hordeum vulgare* L.) and a