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REVIEW ARTICLE

Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis

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Abstract
Planetary boundaries for terrestrial inputs of reactive nitrogen (Nr) are transgressed and reducing the input of new Nr and its environmental impacts are major global challenges. Grain legumes fix dinitrogen (N_2) in symbiosis with soil bacteria and use soil N sources, but often less efficient than cereals. Intercropping grain legumes with cereals may be a means of increasing use efficiency of soil N. Here, we estimate the global sole cropped grain legume acquisition of N from soil to approximately 14.2 Tg N year^{-1}, which corresponds to one-third of the global synthetic fertilizer N use (109 Tg N year^{-1}) for all crops, assuming that grain legumes recover on average 40% of the fertilizer N. Published data from grain legume-cereal intercrop experiments, employing stable ^{15}N isotope methods, have shown that due to competitive interactions and complementary N acquisition in intercrops, the cereals recover a more than proportional share of the soil N sources. As a consequence, the intercropped legume derives more of its N from the atmosphere, compared with when it is grown as legume sole crop. We estimated that the increased N use efficiency in intercropping can reduce the requirements for fossil-based fertilizer N by about 26% on a global scale. In addition, our estimates indicate that if all current grain legume sole crops would instead be intercropped with cereals, a potential net land saving would be achieved, when also replacing part of the current cereal sole crop area with intercropping. Intercropping has additional potential advantages such as increased yield stability and yield per unit area, reduced pest problems and reduced requirements for agrochemicals, while stimulating biodiversity. It is concluded that crop diversification by intercropping has the potential to reduce global requirements for synthetic fertilizer N and consequently support the development of more sustainable cropping systems.

Keywords Biochemical flows of nitrogen · Crop diversification · Greenhouse gas emissions · Soil nitrogen use efficiency · Symbiotic N_2 fixation

Contents

1 Introduction

Anthropogenic inputs of new reactive nitrogen (Nr) are damaging terrestrial and aquatic ecosystems, causing climate change and imposing risks to human health (MEA 2005; Rockström et al. 2009; Steffen et al. 2015; Sutton et al. 2011). From 1860 to 2005 the annual flux of Nr to the land surface has doubled, with an anthropogenic supply of roughly 187 Tg of Nr per year on top of the natural flux of N from the atmosphere to land (Galloway et al. 2008). The anthropogenic inputs of Nr are mainly industrial fossil-based fertilizer N and legume crops fixing atmospheric dinitrogen (N_2) in symbiosis with soil bacteria, collectively referred to as rhizobia. Much of the growth in the emissions of the important greenhouse gas (GHG) nitrous oxide (N_2O), since the pre-industrial era, is attributed to the expansion in agricultural land area and increase in fertilizer N use (Reay et al. 2012).

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Post-World War II the use of synthetic N fertilizer (hereafter referred to as N fertilizer) has led to significant increases in food production, due to the fossil-based Haber-Bosch process of N fertilizer production (Crews and Peoples 2004; Smil 2002). The current global use of N fertilizer was estimated to approx. 109 Tg of N per year in 2017 (FAOSTAT 2019) and the N_2 fixed by grain legumes (including soybean and groundnut) to be approx. 21.5 Tg N and of pasture and forage legumes to between 12 and 25 Tg N per year (Herridge et al. 2008). Before the common introduction of N fertilizers, typically 25–50% of farmed land was cropped with legume-based pastures or cover crops in the global North to regenerate soil fertility or was fertilized with animal manures (Crews and Peoples 2004).

The planetary boundary work highlights the zone of uncertainty or high risk of the biochemical flow of N (Rockström et al. 2009; Steffen et al. 2015). To be within the planetary boundary, new Nr inputs should be limited to less than half of present inputs at a global level, with even more drastic reductions in some regions (Steffen et al. 2015). The reduction of new Nr inputs will require new paradigms in terms of N use and cycling in global food production.

More efficient N use and reduced N losses are key factors in reducing inputs of new Nr (MEA 2005). These factors have been and still are at the top of the global agricultural research agenda. The increased food production, availability of cheap fossil energy for N fertilizer production, increased meat consumption and lack of action on mitigating greenhouse gases (Foley et al. 2011) have counterbalanced knowledge gains, innovations and policies on the reduction of N losses and increased nitrogen use efficiency. Real transition towards closing the agricultural N cycles involves redesign of cropping systems for a more balanced use of new Nr, based primarily on enhanced recycling at several levels, e.g., from household organic waste to agriculture or between farms with or without animals, and on new crops and fertilization methods for more efficient use of different N sources, such as perennials grain crops (Crews et al. 2016) and differential fertilization based on field-scale variability.

Currently, the N fertilizer production (incl. Transport and storage) requires between 65 and 100 MJ per kg N fertilizer (Kongshaug 1998; Wood and Cowie 2004) depending on factory and fossil fuel type. It results in an emission of 2.1–5.5 kg CO_2 equivalents per kg^{-1} N fertilizer. The emission of greenhouse gasses from the production of fertilizer N can thus be estimated to between 229 and 545 Tg CO_2 equivalents. Additional N-fertilizer driven emissions as N_2O occur in agricultural fields, adding up to a total GHG emission of 703 Tg CO_2 equivalents, or 13.4% of agriculture's total GHG emissions caused by the production and use of N fertilizer (FAOSTAT 2018).

Nitrogen fixation by legumes is not associated with fossil carbon costs and N_2O emissions are seldom greater than emissions from bare soil or N fertilized crops (Jensen et al. 2012; Jeuffroy et al. 2013). Thus, in addition to the aim of reducing the amount of new Nr entering agricultural cropping systems, the new Nr must be fixed with the lowest energy cost possible via either renewable energy sources or photosynthetic-driven symbiotic N_2 fixation.

Driven by photosynthesis, legume crops deliver the valuable ecosystem service of atmospheric N_2 fixation (Peoples et al. 2009). The N_2 fixed by cultivated legume crops contributes to valuable protein for food, feed, materials, and N for improved soil fertility (Jensen et al. 2012; Voisin et al. 2014).

Legumes are often found as pioneer plants in the early succession of ecosystems with low availability of N (Vitousek and Walker 1989). As they fix N_2 and enrich the soil, mineralization will often make non-fixing plants become dominant and gradually out-compete the legumes. Even though legumes are suited to environments with lower N availability and are found in natural ecosystems with a diversity of other plant species, grain legumes (soybean, common bean, pea, and others) are normally grown as sole crops on temperate arable agricultural soils with N mineralization rates of 50 to 300 kg mineral N per ha and year in the rooting depth (1–2% of total organic N; Christensen 2004). Legumes assimilate nitrate and ammonium mineralized from soil organic matter, but often with a reduction of the total N_2 fixation (Peoples et al. 2009).

Most grain legumes need only a limited amount of soil mineral N during early establishment until functioning nodules are established (Mahon and Child 1979). Several studies have shown that "starter N" may be relevant only under conditions of low levels of soil mineral N during establishment, but responses to N-fertilizer in soybean are inconsistent (Mendes et al. 2003; Mourtzinis et al. 2018). Sole crop grain legumes are often less efficient in recovering soil N as compared with cereals (Table 2; Fig. 2a and b) and losses of N by the emission of N_2O are lower from legumes than from N-fertilized crops (e.g., Jensen et al. 2012, Fig. 2a and b). During the first winter after grain legumes, the N leaching may be slightly greater or similar to the leaching after cereals (Thomsen et al. 2001; Hauggaard-Nielsen et al. 2003; Engström et al. 2011), but increased N leaching due to grain legume may be prevented by the use of cover crops or intercropping with cereals (Hauggaard-Nielsen et al. 2003).

We question the resource use efficiency in a system where grain legumes accumulate significant quantities of soil-derived N and suggest that crop diversification using cereal-grain legume intercropping (Fig. 1) can be used in the design of cropping systems with higher N use efficiency. Improved agroecosystem N economy is promoted, when the cereal utilizes the soil N resource.

The aims of this study are to (1) estimate the approximate global acquisition of N from soil by grain legumes and (2) determine how much of this N can be used by cereals in grain legume-cereal intercropping and potentially reduce global requirement for new Nr inputs by synthetic N fertilizers, while still producing grain legumes on the land.

Fig. 1 Intercrop of spring wheat (*Triticum aestivum* L.) and faba bean (*Vicia faba* L.). Photo E.S. Jensen

2 Global acquisition of N from the soil by grain legumes

Global symbiotic terrestrial N_2 fixation by legumes and other N_2 fixing species was estimated for 2005 by Herridge et al. (2008). Their estimate was based on the cultivated area of legumes and their yields obtained from FAOSTAT. Based on published data on the relationships between grain, above- and below-ground residue yields, their nitrogen concentrations, and proportions of N in the crop derived from symbiotic N_2 fixation (%Ndfa), they estimated global N_2 fixation (Herridge et al. 2008). The data on percent N derived from N_2 fixation accounted for the use of fertilizer N in soybean and other species that normally receive some “starter-N” (Herridge et al. 2008). The estimate indicated that grain legumes grown on 186 Mha fixed approx. 21.5 Tg N annually and 12–25 Tg N was fixed by pastures and forage legumes (clovers, alfalfa, etc.). We have updated the grain legume estimates with 2017 crop data (FAOSTAT 2019) including pigeon pea (Table 1). We estimated the global amount of soil-derived N in grain legume crops, by using the same factors as Herridge et al. (2008) for estimating the N_2 fixation and to determine the %N derived from soil N sources (%Ndfs).

The area of grain legumes has increased by 30% to 241 Mha in 2017 (Table 1) and the total estimated N_2 fixation has increased by 32% to 28.4 Tg, with the majority being fixed in soybean and groundnut, as compared to the area and N_2 fixation estimate in 2005 (Herridge et al. 2008). Our estimate of grain legume N derived from soil N sources was 14.2 Tg in 2017, with approx. 73% of this soil-derived N being assimilated by global soybean production (Table 1). The global average recovery of fertilizer N in cereal crops was estimated at 30–50% (Cassman et al. 2002; Ladha et al. 2005). Assuming an average N recovery rate of plant-available soil N of 40% in grain legumes, i.e., similar to cereals, we find that global soil N accumulation in grain legumes corresponds to (14.2*100%/40%=) 35.5 Tg fertilizer N applied to crops. However, since grain legumes are often less efficient in recovering soil N than cereals, this is probably an underestimate of the amount of soil N having the same availability as fertilizer N. Global fertilizer N use in 2017 was 109 Tg of N (FAOSTAT 2019). Consequently, grain legumes use an amount of N from soil N sources, which is comparable to one-third of global fertilizer use. This N could partly be used for cereals and other non-fixing crops intercropped with grain legumes, thereby reducing the total need for fertilizer N inputs.

3 Soil nitrogen dynamics and use in grain legume-cereal intercropping

Intercropping (mixed cropping, polyculture), defined as the simultaneous growing of two or more crops near in the same field (Fig. 1), is an agroecological practice (Jensen 1996a; Bedoussac et al. 2015; Wezel et al. 2014). Intercropping of grain legumes and the cereal has the potential to improve the use efficiency of N sources, due to competitive, complementary or facilitative interactions (Fig. 2c; Table 2). Several studies have shown that the competitive interactions in intercrops of cereals and grain legumes result in a non-proportional sharing of soil N sources (e.g., Jensen 1996a; Table 2). Consequently, the cereal will normally acquire a much larger proportion of the soil N as compared to its abundance in the intercrop, and the grain legume compensates for its lower share of the soil N by fixation of atmospheric N_2 (Hauggaard-Nielsen et al. 2008; Hauggaard-Nielsen et al. 2009; Rodriguez et al. 2020). With increasing soil N availability or N fertilization and with

Table 1 Global cultivated grain legume area, estimated crop N (incl. roots), accumulated symbiotic N_2 fixation, and soil N acquisition in 2017

Crop species	World Area 2017[a] (Mha)	Crop N[b] (Tg N)	%N[b] derived from N_2	Estimated (Tg N)	
				N_2 fixation	N acquisition from soil
Soybean	123.6	32.0	68	21.70	10.3
Groundnut	27.9	3.73	68	2.54	1.19
Common bean	36.5	1.95	40	0.78	1.17
Pigeonpea[c]	7.0	1.00	88	0.89	0.11
Chickpea	14.6	1.04	63	0.66	0.38
Pea	8.1	1.17	63	0.74	0.43
Cowpea	12.6	0.60	63	0.37	0.23
Lentil	6.6	0.58	63	0.36	0.22
Faba bean	2.5	0.34	70	0.24	0.10
Lupin and vetches	1.7	0.11	63	0.07	0.04
Total legumes	241.1	42.52	67	28.35	14.17

[a] Cultivated area of grain legumes according to FAOSTAT (2019)

[b] The estimates of total crop N, $\%N_2$ from fixation and the global amount fixed are based on the approach developed by Herridge et al. (2008), see also the text

[c] Pigeonpea data was obtained from FAOSTAT (2019) and Kumar Rao and Dart (1987)

increasing distance between intercropped species (from mixed to strip intercropping) the advantage of complementarity in use of N sources will diminish because the legume will take up more soil N and reduce the symbiotic N_2 fixation (Jensen 1996a; Bedoussac and Justes 2010; Naudin et al. 2010).

Analysing the 13 published intercropping studies employing ^{15}N methodology to determine the rates of symbiotic N_2 fixation and soil (and fertilizer) N acquisition in sole and intercrops in different pedo-climatic conditions, it can be shown that sole crop cereals and grain legumes acquired on average 84 and 67 kg soil N ha^{-1}, respectively (Table 2). The intercrops acquired on average 82 kg soil N ha^{-1} in total, with the majority (65 × 100 / 82 = 79%) of the soil N accumulated by the cereal (Table 2). Sole and intercropped legumes fixed an additional 126 and 68 kg N ha^{-1}, respectively.

Intercropping offers additional advantages such as lower (10–16%) nitrate leaching compared with sole crops (Hauggaard-Nielsen et al. 2003, Fig. 2c). A few studies have been carried out showing reduced N_2O emission when intercropping as compared to sole crops (Pappa et al. 2011; Dyer et al. 2012; Huang et al. 2014; Senbayram et al. 2016; Fig. 2c). These effects may be due to the improved use of soil N sources and carbon:nitrogen ratio of crop residues, which are less favorable for net mineralization of soil N in the autumn and consequently reduces the risks of N-losses as compared to sole crop grain legumes.

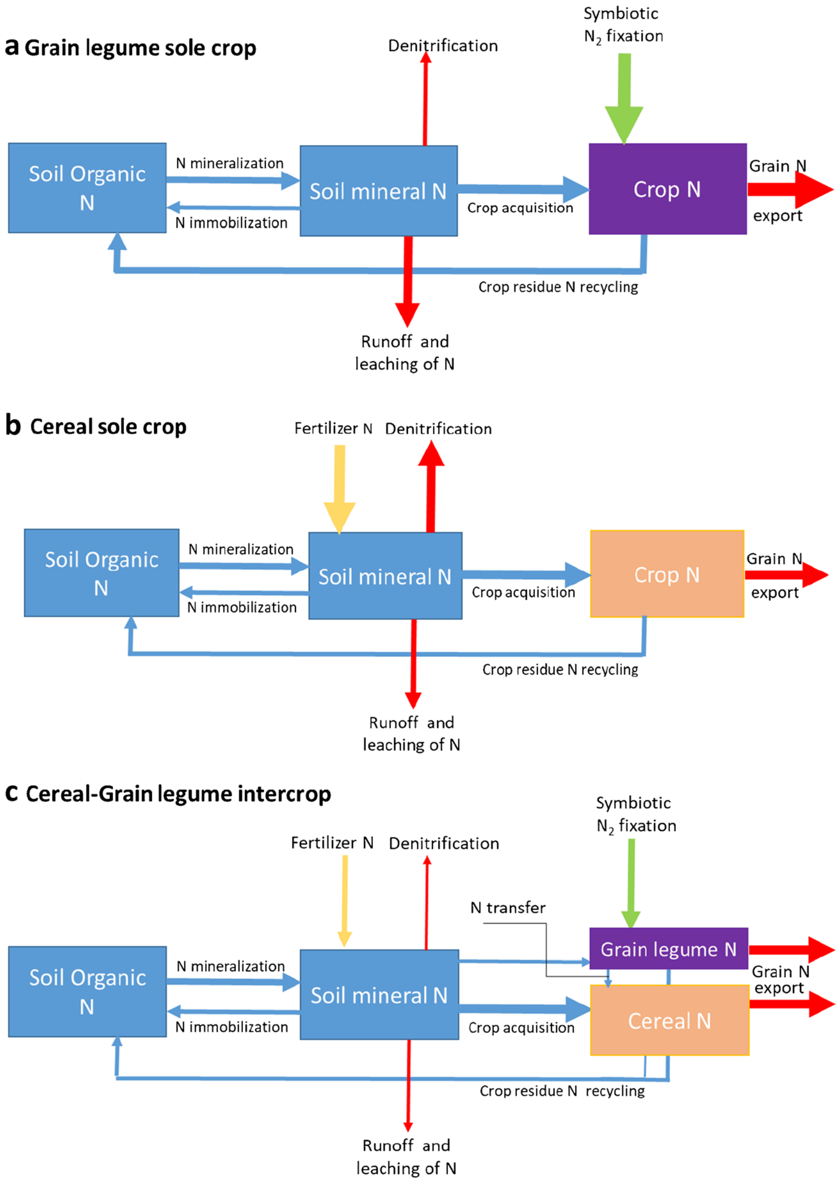
The rhizodeposition of symbiotically fixed N_2 and the subsequent potential recovery by the intercropped cereal may also diminish the requirement for fertilizer N in the cereal (Fig. 2c). However, the "transfer" of fixed N_2 is less important compared with the differential competitive ability for soil N sources between the intercropped species (Jensen 1996b; Hauggaard-Nielsen and Jensen 2005; Chalk et al. 2014).

4 Global soil N use by intercrops and potential fertilizer N and land sparing

Based on our compilation of data on N acquisition in intercrops (Table 2), 28.0 Tg (79% × 35.5 / 100) soil-derived N having an availability similar to fertilizer N, would be available for cereals, if the land presently used for grain legume sole crops were used for cereal-grain legume intercrops instead. This would mean a potential saving for cereal sole crop production of (28Tg/109Tg=) 26% of global fertilizer N use. Such more efficient use of soil N sources would have major implications for greenhouse gas emissions and other environmentally damaging effects of new Nr inputs as fertilizer N. Reducing the global input of fertilizer N by 26% would significantly reduce the requirement for fossil energy to produce and use the fertilizer N, and less N would be lost as greenhouse gas N_2O or as nitrate leaching to aquatic environments and improve sustainability of agricultural systems.

As a mean of all experiments grain legumes intercropped with cereals have ([68 + 17] × 100 / [126 + 67]=) 44% of the N accumulated in sole crop grain legumes (Table 2). This means that more than twice as much land (241 / [44 / 100] = 548 Mha) would be required to maintain the current global production of grain legume protein through intercropping (Table 3). At the same time, this increased land requirement would be balanced by a higher resource use efficiency for the combined production of cereals and grain legumes as

Fig. 2 Conceptual presentation of the most important N cycle processes in (a) cereal sole crops, (b) grain legume sole crops, and (c) intercrops of cereals and grain legumes. The width of arrows indicate the relative importance of processes but may vary significantly between cropping systems



intercrops, as shown by the following numbers. Assuming that the (548–241=) 307 Mha additional land required for grain legume production through intercropping (Table 3) would replace cereal sole crops, we have compared cereal production from 548 Mha intercrops with 307 Mha sole crops. Based on the estimate that intercropped cereals provide (65 × 100 / 84=) 77% of their sole crop yields (i.e., assuming the same ratio of intercrop: sole crop cereal grain yield as in intercrop: sole crop cereal total N acquisition; Table 2), the cereal production obtained from 548 Mha intercrops would be larger than what is produced from 307 Mha cereal sole crops. This higher land-use efficiency would correspond to a land saving of 115 Mha (Table 3), land that could be diversified by the cultivation of other crops. In addition to the 26% of fertilizer N saved by intercropping on the 241 Mha grain legume sole crop area, significant amounts of fertilizer N would potentially also be saved on the 307 Mha converted from cereal sole cropping to intercropping.

Nevertheless, the studies presented in Table 2 did not include intercrops with the most commonly cultivated grain legumes, soybean, common bean, and groundnut. Thousands of hectares of soybean and groundnut are intercropped with maize and other species, especially in China, but also in other parts of the world (Monzon et al. 2014; Du et al. 2018; Raza et al. 2019). To be able to determine the competition and differential sharing of soil N sources between, e.g., soybean and maize, it is essential that stable ^{15}N isotope methodology is used to determine the N in the grain legume from different N pools (N_2 fixation and soil N sources). Despite a thorough literature search, we did not find studies reporting such measurements in soybean or groundnut intercrops with cereals. Several intercrop studies with soybean have used ^{15}N to investigate nitrogen dynamics, but the study

Table 2 Accumulation of soil/fertilizer N and symbiotic N_2 fixation in sole and intercrops of grain legumes and cereal from 13 published studies on nitrogen use in inter- and sole crops of grain legumes and cereals using ^{15}N isotope methodologies

Intercrop, fertilizer N level (kg N ha^{-1}, and ^{15}N methodology for determining soil and N_2 fixation in the grain legume.	Cereal sole crop	Grain legume sole crop		Intercrop			Reference
	Soil and fertilizer (kg N ha^{-1})	Soil and fertilizer (kg N ha^{-1})	N_2 fixation (kg N ha^{-1})	Soil and fertilizer (kg N ha^{-1})		N_2-fixation (kg N ha-1)	
				Cereal/ Legume	Total		
Wheat-faba bean, 50, ^{15}N	138	100	181	132/13	145	108	Jensen (1986)
Maize-cowpea, 25, ^{15}N	105	71	82	88/35	121	73	Ofori and Stern (1987)
Sorghum-pigeonpea, ^{15}N	18	12	88	13/3	16	65	Kumar Rao et al. (1987)
Maize-cowpea, 50, ^{15}N depleted	78	49	35	57/17	74	12	Van Kessel and Roskoski (1988)
Barley-pea, 10, ^{15}N	89	74	116	42/16	58	81	Izaurralde et al. (1992)
Barley-pea, 50, ^{15}N	109	105	177	102/8	110	51	Jensen (1996a)
Barley-pea, 50, ^{15}N	108	109	183	108/15	123	43	Jensen (1997)
Barley-pea, 40, ^{15}N	56	70	114	47/6	53	38	Andersen et al. (2004)
Oilseed rape-pea, 40, ^{15}N	75			61/20	81	51	
Barley-lentil, 0, NA	91	60	136	73/13	86	68	Schmidtke et al. (2004)
Wheat-pea, 40, 15N	68	30	109	52/6	58	59	Ghaley et al. (2005)
Barley/pea, 0, 30, 130, NA	92	91	169	63/51	114	121	Corre-Hellou et al. (2006)
Oat-pea, 0, NA	100	81	83	80/22	102	56	Neumann et al. (2007)
Barley-pea cultivars, 0, NA	55	56	139	39/17	52	96	Hauggaard-Nielsen et al. (2008)
Barley-faba bean, 0, NA		58	140	44/17	61	83	
Barley-blue lupin, 0, NA		37	133	42/14	56	76	
Mean of all experiments	84	67	126	65/17	82	68	

Table 3 Calculated effects of intercropping grain legumes (GL) and cereals on present land used for grain legume sole cropping (SC) (241 Mha) plus additional 307 Mha cereal SC land. Calculations are based on the assumption that the crop N accumulation/yield reflects the dry matter grain yields. The N yields are derived from the mean of the 13 experiments presented in Table 2

Land use or yield proportion	Calculation	Mha
Global grain legume (GL) land		241
Ratio of GL yield in IC compared to GL yield in sole crop (SC) yield	(68 + 17)/(126 + 67) = 0.44	
Total land area for IC required for GL similar to SC production	241/0.44	548
Additional IC land required for the same product as in SC GL	548–241	307
Yield of cereals in IC compared with SC cereal yield (X)	65/84 = 0.77	
Cereal SC yield on 307 Mha	307*X	
Cereal IC yield on 548 Mha	548*X*0.77	
Potential cereal SC land saving due to IC	(548*X*0.77–307*X)/X	115

objectives, the design, the reporting or quality of data did not result in experiments for soybean or groundnut that could be included in Table 2. From the following two studies it was possible to estimate the sharing of soil-derived N resources. Abaidoo and van Kessel (1989) found that in a pot experiment with soybean/maize and common bean/maize intercrops (50%:50%), maize acquired 85% and 63% of the N from soil sources, respectively. Liua et al. (2017) studied intercrops of peanut and maize (50%:50%) and found that maize acquired 76% of the soil N sources in the intercrop. These values are not significantly different from the 79% we found as an average of the 13 published studies in Table 2, but the two studies were carried out in pots or containers. We have no evidence claiming that the competitive dynamics between soybean or peanut and an intercropped cereal is significantly different from the interactions in other grain legume-cereal intercrops, such as those presented in Table 2.

In the perspective of global change and increasing environmental variability, intercropping also enhances yields and yield stability over sole crops (Lithourgidis et al. 2011; Raseduzzaman and Jensen 2017; Vandermeer 1989) while improving the use efficiency of nutrients (e.g., N, P, and Fe) (Zhang and Li 2003) reducing pests and diseases (Malézieux et al. 2009), enhancing ecosystem services (Kremen et al. 2012) and economic profitability (Malézieux et al. 2009; Pelzer et al. 2012).

Several challenges are associated with a global upscaling of grain legume-cereal intercropping (Jensen et al. 2015): (1) farmers and advisory service must regain knowledge on how to intercrop, (2) food systems from field to plate are used to work with homogeneous sole crops and need to be able to handle diverse crops, (3) plant breeding and crop protection for intercropping of species have not been developed to the same extent as for sole crops, (4) knowledge on the reintegration of intercrops in crop rotations are required to diminish problems with soil-borne diseases and finally, (5) machinery for sowing, harvesting, and sorting of seeds needs further development. Thus, research and development are needed to strengthen implementation strategies to gain from the potential ecosystem functions and services associated with increased crop diversification. Furthermore, greater utilization of ecosystem services and eco-functional intensification requires enhanced interactions between farmers, researchers and other food system actors regarding the complex system dynamics and the implementation of crop diversification strategies.

5 Conclusions and perspectives

We estimated that global sole crop grain legume soil-derived N accumulation equals approximately one-third of global fertilizer N use, with soybean as the dominant species. We suggest that by intercropping grain legumes with cereals, the cereals may be able to use approx. Eighty percent of the soil-derived N in the grain legume field and consequently is possible to diminish the global fertilizer N production and use by approx. 26%. Reducing inputs of fertilizer N in global agriculture will markedly reduce the emission of CO_2 and N_2O. Ecological intensification by intercropping may also reduce the combined area required for the production of cereals and grain legumes, leaving space for contributing additional ecosystem services leading to more sustainable agricultural production systems.

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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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