Stagnari *et al. Chem. Biol. Technol. Agric. (2017) 4:2*
DOI 10.1186/s40538-016-0085-1

Chemical and Biological Technologies in Agriculture

REVIEW

Open Access

Multiple benefits of legumes for agriculture sustainability: an overview

Fabio Stagnari[1*], Albino Maggio[2], Angelica Galieni[1] and Michele Pisante[1]

Abstract

Food security, lowering the risk of climate change and meeting the increasing demand for energy will increasingly be critical challenges in the years to come. Producing sustainably is therefore becoming central in agriculture and food systems. Legume crops could play an important role in this context by delivering multiple services in line with sustainability principles. In addition to serving as fundamental, worldwide source of high-quality food and feed, legumes contribute to reduce the emission of greenhouse gases, as they release 5–7 times less GHG per unit area compared with other crops; allow the sequestration of carbon in soils with values estimated from 7.21 g kg^{-1} DM, 23.6 versus 21.8 g C kg^{-1} year; and induce a saving of fossil energy inputs in the system thanks to N fertilizer reduction, corresponding to 277 kg ha^{-1} of CO_2 per year. Legumes could also be competitive crops and, due to their environmental and socioeconomic benefits, could be introduced in modern cropping systems to increase crop diversity and reduce use of external inputs. They also perform well in conservation systems, intercropping systems, which are very important in developing countries as well as in low-input and low-yield farming systems. Legumes fix the atmospheric nitrogen, release in the soil high-quality organic matter and facilitate soil nutrients' circulation and water retention. Based on these multiple functions, legume crops have high potential for conservation agriculture, being functional either as growing crop or as crop residue.

Keywords: Soil fertility, Conservation agriculture, Sustainable agricultural systems, Food security, Climate change, Greenhouse gas, Energy

Introduction

Global population will hit 9.6 billion people by 2050 [108] and will face global challenges among which achieving food security, lowering the risk of climate change by reducing the net release of greenhouse gases into the atmosphere and meeting the increasing demand for energy are the most critical ones. In particular, the impact of climate change and associated biotic and abiotic stresses to which crop systems will be increasingly exposed pose serious implications for global food production [119].

To meet these challenges, a policy framework needs to be developed in which the *sustainability* of production/consumption patterns becomes central. In this context, food legumes and legume-inclusive production systems can play important roles by delivering multiple services in line with sustainability principles. Indeed, legumes play central roles [112]: (1) at food-system level, both for human and animal consumption, as a source of plant proteins and with an increasingly importance in improving humans health [106]; (2) at production-system level, due to the capacity to fix atmospheric nitrogen making them potentially highly suitable for inclusion in low-input cropping systems, and due to their role in mitigating greenhouse gases emissions [53]; and (3) at cropping-system levels, as diversification crops in agroecosystems based on few major species, breaking the cycles of pests and diseases and contributing to balance the deficit in plant protein production in many areas of the world, including Europe [43, 48, 72, 78, 116].

Leguminosae family comprises 800 genera and 20,000 species [54] and represents the third largest family of flowering plants. Some legumes are considered weeds of

---

*Correspondence: fstagnari@unite.it
[1] Faculty of Biosciences and Technologies for Agriculture Food and Environment, University of Teramo, Coste Sant'Agostino, Teramo, TE, Italy
Full list of author information is available at the end of the article

Table 1 Trends for word acreage (million ha) and yield (t ha^{-1}) for legume crops included in FAOSTAT classification starting from 1974 to 2014 [23]; the major three cereal crops are also reported, for comparison

	Harvested area (Million ha)					Yield (t ha^{-1})				
	1974	1984	1994	2004	2014	1974	1984	1994	2004	2014
Legume crops										
Bambara bean	0.05	0.05	0.09	0.12	0.37	0.67	0.66	0.64	0.65	0.77
Dry bean	23.9	26.3	26.7	27.3	30.14	0.53	0.6	0.65	0.67	0.83
Faba bean	3.98	3.32	2.48	2.65	2.37	1.07	1.29	1.45	1.62	1.82
Chickpea	10.6	9.85	9.96	10.5	14.8	0.56	0.67	0.71	0.8	0.96
Cowpea	4.7	3.66	7.35	9.18	12.52	0.35	0.31	0.38	0.45	0.45
Groundnut	19.9	18.2	22	23.7	25.68	0.94	1.1	1.3	1.54	1.65
Lentil	2.03	2.56	3.43	3.85	4.52	0.61	0.68	0.81	0.93	1.08
Lupin	0.76	1.06	1.56	1.05	0.76	0.84	1.05	0.78	1.18	1.3
Pea	8.13	8.91	7.65	6.34	6.87	1.22	1.3	1.88	1.85	1.65
Pigeon pea	3.04	3.61	4.24	4.72	6.67	0.54	0.78	0.74	0.7	0.73
Soybean	37.4	52.9	62.5	91.6	117.72	1.41	1.71	2.18	2.24	2.62
French bean	0.22	0.17	0.22	0.23	0.20[a]	5.76	6.93	7.44	9.04	9.32[a]
Vetch	1.52	1.29	0.93	0.89	0.52	1.24	1.21	1.12	1.43	1.71
Pulses, nes	5.67	5.65	5.33	4.27	6.1	0.54	0.58	0.65	0.82	0.84
Vegetables, leguminous nes	0.14	0.18	0.18	0.25	0.24[a]	5.41	5.09	5.18	6.54	6.86[a]
Major cereal crops										
Wheat	222.12	230.77	215.12	216.57	221.62	1.62	2.22	2.45	2.92	3.29
Maize	119.86	127.76	137.99	147.45	183.32	2.56	3.53	4.12	4.94	5.66
Rice (paddy)	136.89	144.24	147.29	150.58	163.25	2.43	3.23	3.66	4.03	4.54

In Table 2, for each legume crop, item name and code as well as FAO definitions are reported

[a] Data are referred to year 2013 (2014 data not available)

cereal crops, while others are major grain crops; these latter species are known as grain legumes, or pulses,[1] and represent the focus of this review. For some of these species, the trends for word acreage and yield are available, as reported in Table 1.

Despite the growing trends observed during the 50-year period between 1974 and 2014 for some warm-season legumes (e.g. soybean, cowpea, dry bean, groundnut, and pigeon pea), the acreages of several temperate legumes (e.g. pea, faba bean, lupin, french bean and vetch) have declined worldwide with differences between world Regions (Table 3). In any case, food legumes occupy a minimal part of arable land, mostly dominated by cereal crops [99]; soybean represents the most important and cultivated legume, acreage of which reached 117.72 million ha in 2014 (steadily increased over years, see also Table 3), which is about that of the other grain legumes, but still far below the major cereals (e.g. rice, wheat, maize). Such trend is mainly associated to the expansion of more specialized and intensive production systems [82]. Market forces stimulating specialization of cropping systems as non-marketable benefits of diversification, like cultivation/introduction of legumes in the farming system, do not deliver immediate and/or apparent profits [82]. This is, however, not equally perceived throughout the globe, and there is indeed a remarkable diversity in grain legumes' production trends across the world (Table 3).

The European decline in grain legume's production is not mirrored by other regions of the world such as Canada or Australia, where legume's cultivation has been increasing over the last few decades. In these areas, monoculture of cereals, which relies on frequent summer-fallowing and use of mechanical tillage, has been replaced by extended and diversified crop rotations together with the use of conservation tillage [122]. Furthermore, supply chains and markets are inadequately developed for most legume crops (see also [66], for France) with the exception of soybean, for which the global market is well developed [85]. Nevertheless, soybean areas in Europe are constrained by climatic factors although there is considerable potential to develop new varieties suitable to flourish under cool growing conditions [123].

---

[1] Soybean and groundnuts are not defined by FAO as 'pulse crops'.

Table 2 Definition of legume crops focused in Table 1 and corresponding item name in FAOSTAT

Legume crop	Scientific name	Corresponding FAO item name and code	FAO definition
Bambara bean	*Voandzeia subterranea*	Bambara bean [203]	Bambara groundnut, earth pea. These beans are grown underground in a similar way to groundnuts
Dry bean	–	Beans, dry [176]	*Phaseolus* spp.: kidney, haricot bean (*Ph. vulgaris*); lima, butter bean (*Ph. lunatus*); adzuki bean (*Ph. angularis*); mungo bean, golden, green gram (*Ph. aureus*); black gram, urd (*Ph. mungo*); scarlet runner bean (*Ph. coccineus*); rice bean (*Ph. calcaratus*); moth bean (*Ph. aconitifolius*); tepary bean (*Ph. acutifolius*). Several countries also include some types of beans commonly classified as *Vigna* (*angularis, mungo, radiata, aconitifolia*)
Faba bean	*Vicia faba*	Broad beans, horse beans, dry [181]	*Vicia faba*: horse-bean (var. *equina*); broad bean (var. *major*); field bean (var. *minor*)
Chickpea	*Cicer arietinum*	Chick peas [191]	Chickpea, Bengal gram, garbanzos (*Cicer arietinum*).
Cowpea	*Vigna ungiculanta*	Cow peas, dry [195]	Cowpea, blackeye pea/bean (*Vigna sinensis*; *Dolichos sinensis*)
Groundnut	*Arachis hypogaea*	Groundnuts, with shell [242]	*Arachis hypogaea*. For trade data, groundnuts in shell are converted at 70% and reported on a shelled basis
Lentil	*Lens esculenta*	Lentils [201]	*Lens esculenta; Ervum lens*
Lupin	–	Lupins [210]	*Lupinus spp.* Used primarily for feed, though in some parts of Africa and in Latin America some varieties are cultivated for human food
Pea	–	Peas, dry [187]	Garden pea *(Pisum sativum);* field pea *(P. arvense)*
Pigeon pea	*Cajanus cajan*	Pigeon peas [197]	Pigeon pea, cajan pea, Congo bean *(Cajanus cajan)*
Soybean	*Glycine max*	Soybeans [236]	*Glycine soja*
French bean	–	String beans [423]	*Phaseolus vulgaris*; *Vigna* spp. Not for shelling
Vetches	*Vicia sativa*	Vetches [205]	Spring/common vetch (*Vicia sativa*). Used mainly for animal feed
Pulses, nes	–	Pulses, nes [211]	Including inter alia: lablab or hyacinth bean (*Dolichos* spp.); jack or sword bean (*Canavalia* spp.); winged bean (*Psophocarpus tetragonolobus*); guar bean (*Cyamopsis tetragonoloba*); velvet bean (*Stizolobium* spp.); yam bean *(Pachyrrhizus erosus)*; *Vigna* spp. other than those included in 176 and 195; other pulses that are not identified separately because of their minor relevance at the international level. Because of their limited local importance, some countries report pulses under this heading that are classified individually by FAO
Vegetables, leguminous nes	–	Vegetables, leguminous nes [420]	*Vicia faba.* For shelling

The low diffusion of legumes' cultivation is also due to reduced and unstable yields and susceptibility to biotic and abiotic stress conditions; the average yields for unit area have increased (soybean +86%, lentil +77%, groundnut +75%, chickpea +70%) less than cereal crops (+104%, on average) (Table 1). Moreover, legume cultivation depends not only on the effect of farmers' choices, although they play a central role for such decision, but also on policymakers who have the responsibility to provide effective strategies to support the integration of legumes into cropping systems. This aspect is particularly relevant if the overall objective for future agricultural systems is to promote sustainability, improve resource use efficiency and preserve the environment [82].

Grain legumes impacts on atmosphere and soil quality

Among the many important benefits that legumes deliver to society, their role in contributing to climate change mitigation has been rarely addressed. Legumes can (1) lower the emission of greenhouse gases (GHG) such as carbon dioxide (CO_2) and nitrous oxide (N_2O) compared

Table 3 Trend for Region Δ acreage (%) during the 50-year period starting from 1974 to 2014 for legume crops included in FAOSTAT classification [23]; the major three cereal crops are also reported, for comparison

	Δ harvested area 1974–2014 (%)					
	Africa	**Northern America**	**South America**	**Asia**	**Europe**	**Oceania**
Legume crops						
Bambara bean	+612	–	–	–	–	–
Dry bean	+207	+16	−20	+25	−84	+1778
Faba bean	+7	Disappeared	−53	−59	−54	+75,085
Chickpea	+30	Appeared	+1	+37	−35	–
Cowpea	+168	Appeared	Appeared	+402	+153	–
Groundnut	+69	−10	−22	+6	+16	−39
Lentil	−20	+3376	−75	+72	−45	Appeared
Lupin	−82	–	+577	−89	−64	+315
Pea	+49	+1119	+7	−21	−63	+578
Pigeon pea	+226	–	−83	+108	–	–
Soybean	+642	+71	+882	+116	+291	−10
French bean	Appeared[a]	−39[a]	+129[a]	+66[a]	−18[a]	+122[a]
Vetch	+109	–	–	−73	−80	+4757
Pulses, nes	+20	–	−69	−15	+73	+7648
Vegetables, leguminous nes	+180[a]	Appeared[a]	+118[a]	+23[a]	−31[a]	−52[a]
Major cereal crops						
Wheat	+11	−20	+16	+39	−33	+51
Maize	+98	+29	+45	+76	+21	+31
Rice (paddy)	+185	+15	−16	+16	−28	+2

In Table 2, for each legume crop, item name and code as well as FAO definitions are reported

[a] Data are referred to year 2013 (2014 data not available)

with agricultural systems based on mineral N fertilization, (2) have an important role in the sequestration of carbon in soils, and (3) reduce the overall fossil energy inputs in the system.

Greenhouse gas emissions

The introduction of legumes into agricultural rotations help in reducing the use of fertilizers and energy in arable systems and consequently lowering the GHG emissions [52]. N fertilizer savings across Europe [51], in rotations including leguminous crops, range around 277 kg ha^{-1} of CO_2 per year (1 kg $N = 3.15$ kg CO_2, [42]. It has been reported that half of the CO_2 generated during NH3 production would be reused if the NH3 was converted to urea. This is, however, only a time shift of CO_2 release in the atmosphere since, once the urea is applied to the soil, the hydrolyzation activity by urease will release CO_2 originally captured during urea production [39]. Considering an efficiency of 2.6–3.7 kg CO_2 generated per kilogram of N synthesized, the annual global fertilizer leads to a release of 300 Tg of CO_2 into the atmosphere each year [42]. Some studies indicate that at global scale, the amount of CO_2 respired from the root systems of N_2-fixing legumes could be higher than the CO_2 generated during N-fertilizer production [42]. However, it is important to emphasize that the CO_2 respired from nodulated roots of legumes comes from the atmosphere through the photosynthesis activity. Conversely, all the CO_2 released during the process of N-fertilizer synthesis derives from fossil energy, thus determining a net contribution to atmospheric amount of CO_2 [42].

N_2O represents about 5–6% of the total atmospheric GHG, but it is much more active[2] than CO_2 [21]. Agriculture represents the main source of anthropogenic N_2O emissions (about 60%; [84], due to both animal and crop production [38]). A majority of these emissions result from the application of nitrogen fertilizers [84]: every 100 kg of N fertilizer about 1.0 kg of N is emitted as N_2O [42], although different amounts depend on several factors including N application rate, soil organic C content, soil pH, and texture [78, 88]. Denitrification processes are the most important source of N_2O in most cropping and pasture systems [76, 88, 102].

In the recent years, several studies have focalized on the role of legumes in the reduction of GHG emissions. Jeuffroy et al. [44] demonstrated that legume crops

---

[2] N_2O absorbs approximately 292 times as much infra-red radiation per kilogram as CO_2.

emit around 5–7 times less GHG per unit area compared with other crops. Measuring N_2O fluxes, they showed that peas emitted 69 kg N_2O ha^{-1}, far less than winter wheat (368 kg N_2O ha^{-1}) and rape (534 kg N_2O ha^{-1}). Clune et al. [19] reviewed different life cycle-assessment (LCA) studies on GHG emissions carried out from 2000 to 2015 around the world (despite the used literature was predominately European centric) highlighting that pulses have a very low Global Warming Potential (GWP) values (0.50–0.51 kg CO_2 eq kg^{-1} produce or bone-free meat[3]). In a comparison between vetch and barley under Mediterranean environments and alkaline soil, N_2O emissions were higher for barley than vetch; furthermore, the N_2O fluxes derived from the synthetic fertilizers added to the crops were 2.5 times higher in barley compared with vetch [29]. In two field experiments conducted in a black Vertosol in sub-tropical Australia, Schwenke et al. [95] demonstrated that the cumulative N_2O emissions from N-fertilized canola greatly exceeded those from chickpea, faba bean and field pea (385 vs. 166, 166 and 135 g N_2O-N ha^{-1}, respectively). The same authors highlighted that grain legumes significantly reduced their emission factors suggesting that legume-fixed N is a less-emissive form of N input to the soil than fertilizer N.

Nevertheless, it is important to highlight that the influence of legumes in reducing GHG depends also on the management of agro-ecosystems in which they are included. When faba bean was grown as mono cropping, it led to threefold higher cumulative N_2O emissions than that of unfertilized wheat (441 vs. 152 g N_2O ha^{-1}, respectively); conversely, when faba bean was mixed with wheat (intercropping system), cumulative N_2O emissions fluxes were 31% lower than that of N-fertilized wheat [96]. Anyway, the benefits derived from the introduction of legumes in crop rotations become significant when commercially relevant rates of N fertilizer are applied [42].

The mitigation in terms of GHG emissions is also obtained by adopting sustainable agricultural systems, such as conservation tillage and conservation agriculture systems, which are suitable for the cultivation of both grain and green-manure legumes (see "Grain legumes and conservation agriculture" section).

In conclusion, it is noteworthy to underline that field tests and experimental analyses on GHG emissions, and in particular on N_2O, provided quite different results [89] due to the influences of differences of several variables, including climatic, soil and management conditions [45, 78, 88].

In general, N_2O losses from soils covered with legumes are certainly lower than those from both N_2O fertilized grasslands and non-legume crops, as also indicated by Jensen et al. [42] who report a mean of 3.22 kg N_2O-N ha^{-1}, calculated from 67 site years of data. In addition, there is no direct association between N_2O emissions and biological nitrogen fixation [42], since organic N from legume residues is decomposed, mineralized and rapidly immobilized by microorganisms [78]. Emissions of N_2O could occur either during nitrification or due to denitrification, being affected by timing of mineralized N supply [20]: the asynchrony between N supply and utilization from the following crops enhances N loss, especially in winter/early spring in cold wet soils [64].

Soil properties

Cultivation and cropping may cause significant SOC losses through decomposition of humus [18]. Shifting from pasture to cropping systems may result in loss of soil C stocks between 25 and 43% [101].

Legume-based systems improve several aspects of soil fertility, such as SOC and humus content, N and P availability [42]. With respect to SOC, grain legumes can increase it in several ways, by supplying biomass, organic C, and N [27, 53], as well as releasing hydrogen gas as by-product of BNF, which promotes bacterial legume nodules' development in the rhizosphere [49].

In sandy soils, the beneficial effect of grain legumes after three years of study was registered in terms of higher content of SOC compared with soils with oats (7.21 g kg^{-1} DM, on average). Specifically, cultivation of pea exerted the most positive action to organic carbon content (7.58 g kg^{-1}, after harvest, on average), whereas narrow-leaved lupin had the least effect (7.23 g kg^{-1}, on average) [30]. In southern America (Argentina), the intercropping of soybean with maize at different rates favoured a SOC accumulation of 23.6 g C kg^{-1} versus 21.8 g C kg^{-1} of the sole maize; the greatest potential for enhancing SOC stocks occurred in the 2:3 (maize:soybean) intercrop configuration [11]. Furthermore, just only amending the soil with soybean residues allows to obtain an increase of 38.5% in SOC [11].

Thanks to BNF, legumes also affect significantly soil N availability; by using legumes as winter crops in rice–bean and rice–vetch combination, rice residue N content is enhanced by 9.7–20.5%, with values ranging from 1.87 to 1.93 g N kg^{-1} soil [120]. It needs to be underlines that a majority of studies on the role of legumes for soil

---

[3] In the study of Clune et al. [19], each GWP value recorded from the literature data was converted into a common functional unit and system boundary in kg CO_2 eq kg^{-1} bone-free meat (BFM), using the conversion ratios identified in the literature.

N fertility have investigated the shoot N content. In this regard, Carranca et al. [15] found that 7–11% of total legume N was associated with root and nodules and an allocation of 11–14 kg N fixed t^{-1} belowground dry matter, representing half the amount of total aboveground plant.

In intercropping cowpea–maize, Latati et al. [50] found an increase in P availability at rhizosphere level associated with significant acidification (−0.73 U) than in sole cropping. Wang et al. [115], assessing properties related to N and P cycling in the rhizosphere of wheat and grain legumes (faba bean and white lupin) grown in monoculture or in wheat/legume mixtures, found that the less-labile organic P pools (i.e. NaOH-extractable P pools and acid-extractable P pools) significantly accumulated in the rhizosphere of legumes. However, the P uptake and the changes in rhizosphere soil P pools seem to depend also on legume species. Compared with the unplanted soil, the depletion of labile P pools (resin P and $NaHCO_3$-P inorganic) was the greatest in the rhizosphere of faba bean (54 and 39%) with respect to chickpea, white lupin, yellow lupin and narrow-leafed lupin [31]. Of the less-labile P pools, NaOH-P inorganic was depleted in the rhizosphere of faba bean, while NaOH-P organic and residual P were most strongly depleted in the rhizosphere of white lupin [31].

Also in North Rift, Kenya Region, in well-drained, extremely deep, friable clay, acid humic top soil, the effects of cultivation and incorporation of lupine and garden pea were significant in terms of soil-available P with respect to fallow, with lupine showing higher P availability than pea (from 20.3 to 31.0% higher).

Although there is a general agreement on the influence of grain legumes on rhizosphere properties in terms of N supply, SOC and P availability, the magnitude of the impact varied across legume species, soil properties and climatic conditions. Among these, soil type represents the major factor determining plant growth, rhizosphere nutrient dynamics and microbial community structure. The pattern of depletion and accumulation of some macro- and micronutrients differed also between cropping systems (i.e. monoculture, mixed culture, narrow crop rotations) as well as among soil management strategies (i.e. tillage, no-tillage).

Role of grain legumes in cropping systems

Legumes could be competitive crops, in terms of environmental and socioeconomic benefits, with potential to be introduced in modern cropping systems, which are characterized by a decreasing crop diversity [24, 80] and an excessive use of external inputs (i.e. fertilizers and agrochemicals).

Grain legumes into crop-sequences

In the recent years, many studies have focused on the sustainable re-introduction of grain legumes into crop rotations,[4] based on their positive effects on yield and quality characteristics on subsequent crops [46, 82, 103]. However, assessment of the rotational advantages/disadvantages should be based on a pairwise comparison between legume and non-legume pre-crops [82]. Some experimental designs involving multi-year and multispecies rotations do not provide information on yield benefits to the subsequent species in the rotation sequence. Therefore, it is difficult to formulate adequate conclusions [2].

The agronomic pre-crop benefits of grain legumes can be divided into a 'nitrogen effect' component and 'break crop effect' component. The 'nitrogen effect' component is a result of the N provision from BNF [77], which is highest in situations of low N fertilization to subsequent crop cycles [82]. The second one (break crop effect) includes non-legume-specific benefits, such as improvements of soil organic matter and structure [34], phosphorus mobilization [98], soil water retention and availability [2], and reduced pressure from diseases and weeds [87]. In this case, benefits are highest in cereal-dominated rotations [82].

Several authors have reviewed the yield benefits of legumes for subsequent cereal crops.

In Australia, Angus et al. [2] reported higher yield of wheat after legumes (field peas, lupins, faba beans, chickpeas and lentils) than those of wheat after wheat. In particular for a wheat–wheat yield of 4.0 t ha^{-1}, the mean grain legume-wheat yield was 5.2 t ha^{-1} (+30% on average). Other studies from Australia quantified yield benefits compared to pure cereal crop sequences at 40–50% for low N levels and 10–17% for high N levels [3].

In Europe yields benefits of grain legumes have been shown to strongly depend on climatic factors which affect N dynamics in soils [52]. In temperate environments, cereals yield is on average 17 and 21% higher in grain-legume based systems than wheat monocropping, under standard and moderate fertilization levels, respectively [40]. Conversely, yield benefits are lower in Mediterranean climates where water availability is the limiting factor to cereal yields [46, 61, 62].

The yield advantage to subsequent cereal crops provided by legumes depends also on the species and amounts of fixed N [114, 121]. Field pea and faba bean

---

[4] According to Angus et al. [2], crop-sequences experiments can be classified into rotation experiments and break crop experiments. Rotation strictly defined, refers to a recurring sequence of crops, forages and fallows, or more loosely defined, to a cropping sequence that contains fallows, or crops and forages in addition to the locally dominant species. A break crop generally refers to a single alternative crop followed by the dominant species.

accumulate about 130 and 153 kg N ha^{-1} in their above-ground biomass, respectively [77] and significant quantities (30–60% of the accumulated total N) may also be stored in belowground biomass [77]. Differences in BNF patterns are also found between the same species. For example, Mokgehle et al. [69] compared 25 groundnut varieties for plant BNF at three differing agro-ecologies in South Africa, highlighting N-fixed range between 76 and 188 kg ha^{-1}, depending also on soil and environmental conditions as well as on N-uptake. Other factors influencing BNF include salinity and sodicity (alkalinity) of soils, as observed in chickpea [83], common bean [22] and faba bean [109].

It is, however, rather difficult to quantify the legume dependent increase in N uptake in subsequent crops, versus other sources of N [46, 77]. In temperate environments of Australia, measurements of the additional N-nitrate available to wheat crops following legumes instead of cereals, averaged around 37 kg N ha^{-1} [17]. In Denmark, nitrogen uptake in crops that follow legume crops has been reported to increase by 23–59% after field pea and narrow-leafed lupin on different soil types [40], but only 14–15% for durum wheat following vetch in a semi-arid Mediterranean environment [28]. Increased N uptake of crops after grain legumes reached up to 61% or 36 kg ha^{-1} for a vetch-barley rotation in Cyprus [74]. Further, some legume residues have beneficial effects on some quality aspects of the subsequent crops in southern Italy [104].

Among other beneficial effects brought about by legumes, the production of hydrogen gas (H_2) as a by-product of BNF greatly affects the composition of the soil microbial population, further favouring the development of plant growth-promoting bacteria [2].

Some grain legumes, including chickpea, pigeon pea and white lupin can mobilize fixed forms of soil P through the secretion of organic acids such as citrate and malate and other P mobilizing compounds from their roots [36]. Among grain legumes, white lupin most strongly solubilize P, a function that can be facilitated by its proteoid roots that may englobe small portions of soil [2]. Glasshouse experiments using a highly P-fixing soil showed better wheat growth following white lupin than soybean [37], suggesting that the cereal was able to access P made available by the previous white lupin break crop. 'Break crop' effects also include increased soil water content, since the break-crop stubble can affect retention of soil water and infiltration and retention of rain water [47]. A species-specific response has also been documented. Soil profiles after pea field can be wetter than after a wheat crop [2]. In Saskatchewan, Canada, Miller et al. [68] reported that post-harvest soil water status up to 122 cm-depth was 31 and 49 mm greater for all legumes (field pea, lentil and chick pea) with respect of wheat under loam and clay soils, respectively. This was primarily due to increased plant water use efficiency. Lentil in rotation with cereals has been shown to increase total grain production by increasing residual soil water in dry areas of Saskatchewan [25].

In general, grain legumes are not susceptible to the same pests and diseases as the main cereal crops (non-host), resulting suitable as break crops in wheat-based rotations [121]. Grain legumes as break crops can also contribute to weed control [97] by contrasting their specialization and helping stabilizing the agricultural crop weed community composition [7].

Despite the described beneficial effects, there are still concerns on the introduction of grain legumes into cropping sequences. Cropping systems that include legume crops in farm rotations must be supported by best crop-management practices (e.g. N fertilization rates and timing, soil management, weeding, irrigation), which often do not match standard techniques normally applied by farmers. For example, some possible risks in terms of nitrate leaching associated to grain legumes cultivation can be counteracted by including cover crops in the system [33, 81]. Additional reasons may explain why grain legumes are not very common in high-input cropping systems. These include (1) their low and unstable yields [16, 86]; (2) inadequate policy support [14]; (3) lack of proper quantification (and recognition) of long-term benefits of legumes within cropping systems [82]. However, other efforts could be addressed, for example, to breeding programs for improved crop cultivars, to better sustain livelihood and increase the economic return to farmers. Indeed, during last years significant progresses in breeding for quality traits for food [110] and feed uses [79], as well as for resistances to biotic [91] and abiotic stresses [4] are being achieved, but several others, many of which are controlled quantitatively by multiple genes, have been more difficult to achieve.

Grain legumes in intercropping

Intercropping systems consist in simultaneous growth of two or more crop species on the same area and at the same time [13]. Intercropping is widely used in developing countries or in low-input and low-yield farming systems [73]. Despite several recognized beneficial aspects of intercropping such as better pest control [60], competitive yields with reduced inputs [70, 107], pollution mitigation [63], more stable aggregate food or forage yields per unit area [100], there are a number of constrains that make intercropping not common in modern agriculture, such as example the request of a single and standardized product and the suitability for mechanization or use of other inputs as a prerogative in intensive farming system [13]. It is therefore necessary to optimize intercropping systems to enhance resource-use efficiency and crop yield simultaneously [55], while also promoting multiple ecosystem services (see also [13]). Most recent research has focalized on the potential of intercropping in sustainable productions and in particular on grain legumes that can fix N_2 through biological mechanisms (BNF). Indeed, legumes are pivotal in many intercropping systems, and of the top 10 most frequently used intercrop species listed by Hauggaard-Nielsen and Jensen [32], seven are legumes One of the basic spatial arrangements used in intercropping is strip intercropping, in which two or more crops grow together in strips wide enough to permit separate crop production using inputs but close enough for the crops to interact. The current challenge is how to determine an optimal intercropping width to maximise the resources use efficiency and, consequently, the crop productivity. In a maize-bean strip intercropping, Mahallati et al. [65] suggested that strip width of 2 and 3 rows was superior compared with monoculture and other strip intercropping combinations in terms of radiation absorption, radiation use efficiency and biological yields of both species, also allowing to an improve of total land productivity and land equivalent ratio (1.39 and 1.37). Gao et al. [26] showed a total yield increase of 65 and 71% in a system of 1 and 2 rows of maize (planted at a higher density in intercropping) alternated with 3 rows of soybean compared with both crops grown as monoculture. However, Liu et al. [59] showed a reduction in the photosynthetically active radiation and R:FR ratio at the top of soybean canopy intercropped with maize - under two intercropping patterns: 1 row of maize with 1 row of soybean; 2 rows of maize with 2 rows of soybean - leading to increased internode lengths, plant height and specific leaf area (SLA), but reduced branching of soybean plants. In order to gain sufficient light in the most shaded border rows of the neighbouring, shorter crops, efforts could be addressed to (i) the selection of highly productive maize cultivars with reduced canopy height and LAI; (ii) the increase of the strip width under a higher fraction of direct PAR; (iii) the selection of crops and cultivars suitable under the shade levels that likely occur in strip-intercropping systems with maize [71].

The increase in N availability in intercrops hosting legumes occurs because the competition for soil N from legumes is weaker than from other plants. Moreover, non-legumes obtain additional N from that released by legumes into the soil [56, 117] or via mycorrhizal fungi [113]. Legumes can contribute up to 15% of the N in an intercropped cereal [57], thus increasing biomass production and carry-over effects [75], reducing synthetic mineral N-fertilizer use and mitigating N_2O fluxes [9, 96]. However, the adoption of grain legume intercropping systems should benefit from the identification of suitable legumes that are less susceptible to N fertilizer-induced inhibition of BNF—that is, legumes that sustain higher %BNF in the presence of increasing soil mineral N. To this purpose, Rose et al. [90] indicated that faba bean is more suitable as intercrop than chickpea when supplementary N fertilizer additions are required, with about 40%BNF and 29%BNF maintained in faba bean and chickpea, respectively, supplying both crops with 150 kg N ha^{-1}.

BNF represents the most common plant growth stimulating factor that can also improve crop competition with respect to weeds in both organic and sustainable farming systems [10]. Grain legumes are weak suppressors of weeds, but mixing species in the same cropping system could represent a valid way to improve the ability of the crop itself to suppress weeds [41, 94]. In a wheat-chickpea intercropping system (20 cm spacing without weeding treatment) it was observed a 69.7% reduction in weed biomass and 70% in weed population as compared to un-weeded monocrop wheat at 20 cm spacing [6]. Similar results on weed smothering have been obtained by Midya et al. [67] in rice-blackgram (20 cm) intercropping system although the deferred seeding of blackgram in rice field (30 cm) with one weeding may be recommended for both better yield and weed suppression.

Direct mutual benefits in cereal-legumes intercropping involve below-ground processes in which cereals while benefiting of legumes-fixed N, increase Fe and Zn bioavailability to the companion legumes [118].

Physiology, agronomy and ecology can simultaneously contribute to the improvement of intercropping systems, allowing to enhance crop productivity and resource-use efficiency, so making intercropping a viable approach for sustainable intensification, particularly in regions with impoverished soils and economies where measured benefits have been greatest [93]. But to realize these goals, major efforts in research programs still remain. For example: (1) breeding for intercrops; (2) better understanding of the interactions between plants and other organisms in crop systems, focusing on the roles of above- and below-ground interactions of plants with other organisms; (3) improving agricultural engineering and management, i.e. developing new machinery that can till, weed and harvest at small spatial scales and in complex configurations to encourage the uptake of intercropping without greater demands for labour [58]; (4) adoption of a wider 'systems thinking' through the enactment of schemes, including payment for ecosystem services [105].

Grain legumes and conservation agriculture

Legumes have some characteristics particularly suitable for sustainable cropping systems and conservation agriculture, and making them functional either as growing crop or as crop residue. Conservation agriculture is based on minimal soil disturbance and permanent soil cover combined with rotations [35]. As previously described, major advantages of legumes include the amount of nitrogen fixed into the soil and the high quality of the organic matter released to the soil in term of C/N ratio. Some legume species have also deep root systems, which facilitate nutrients solubilization by root exudates and their uptake/recycling as well as water infiltration in deeper soil layers.

Many countries already rely on conservation agriculture. Brazil has implemented conservation agriculture systems using soybean as legume crop. Grain legumes like lentil, chickpea, pea and faba bean play a major role in conservation agriculture in North America, Australia, and Turkey. In Australia, some advantages of minimum tillage for grain legumes have been quantified for water-limited environments. Some studies indicate that the majority of grain-legumes producers use direct seeding after a legume pre-crop [1]. This change from conventional tillage (CT) to reduced or no tillage (NT) systems (with at least 30% of the soil surface covered) would lead to significant positive impacts on SOC [18]. In contrast, other results indicate that such positive effects are limited to the first 20 cm depth, while little or no difference between CT and NT in total SOC can be seen lower down the soil profile [5, 111]. Such findings suggest that C stock changes in the soil are mainly dependent to the net N-balance in the system. With high N harvest index legumes, SOC stocks are not preserved due to the high amount of N taken off from the field into the grain [42]. Conversely, the effect of legumes on soil carbon sequestration is more detectable for forage, green-manures and cover-crops which return to the soil large amounts of organic C and N [52]. Boddey et al. [12] indicate that vetch under no tillage may increase SOC stocks under NT (0–100 cm) at a rate between 0.48 and 1.53 Mg C ha^{-1} per year [42].

The implementation of practices of conservation tillage could significantly reduce the GWP, especially when a grain legumes is added to the rotation. In Mediterranean agro-ecosystems, Guardia et al. [29] compared three tillage treatments (i.e. no tillage: NT, minimum tillage: MT, conventional tillage: CT) and two crops (i.e. vetch, barley) and recorded the emission of N_2O, CH_4 and CO_2 during one year. Authors found a significant 'tillage × crop' interaction on cumulative N_2O emissions with vetch releasing higher N_2O amount than barley only in CT and MT, whereas similar fluxes were observed under NT. This was attributable to the soil water-filled pore space, dissolved organic carbon content and denitrification losses, in spite of the presumable predominance of nitrification. In any case, the most sustainable crop and tillage treatments in terms of GWP were represented by the non-fertilized vetch and NT, due to higher carbon sequestration, lower fuel consumption and the absence of mineral N fertilizers [29]. In subtropical Ultisol, under legume cover crops, NT soil exhibited increased N_2O emissions with respect to CT soil (531 vs. 217 kg CO_2 eq ha^{-1} $year^{-1}$); however, emissions of this gas from NT soil were fully offset by CO_2 retention in soil organic matter (-2063 to -3940 kg CO_2 ha^{-1} $year^{-1}$) [8]. Moreover, NT soil under legume cover crops behaved as a net sink for GHG (GWP ranged from -971 to -2818 kg CO_2 eq ha^{-1} $year^{-1}$) [8].

The expansion of ecological-based approaches like conservation agriculture opens opportunities to food legumes to be profitably included in sustainable cropping systems. There are still major challenges for conservation agriculture that need to be overcome, including the development of effective methods for weed control (see also [92]) that can avoid the use of herbicides or tillage. Overall conservation agriculture is an environmentally sustainable production system that may boost the incorporation of grain legumes within large and small-scale farming.

Conclusion

The roles and importance of grain legumes in a context of sustainability in agriculture could be enhanced by the emerging research opportunities for the major topics discussed above.

A major task in the future will be the selection of legume species and cultivars which could be effectively introduced across different cropping systems. An important point concerns balancing yield, which gives economic return, with the environmental and agronomic benefits.

Some priority areas seem emerge. Nitrogen fixation activity of grain legumes should be evaluated in relation with soil, climatic, plant characteristics and management conditions to find the suitable approach to achieve the best improvements. With this respect, the ability of the host plant to store fixed nitrogen appears to be a major component of increasing nitrogen fixation input. A particular focus should be paid also to the study of abiotic stress limitations and in particular water deficit, salinity and thermal shocks require extensive investigation.

Legumes that can recover unavailable forms of soil phosphorus could be major assets in future cropping systems. Consequently, those legumes which are able to accumulate phosphorus from forms normally unavailable need to be further studied, since phosphorus represents an expensive and limiting resource in several cropping systems.

Because of the growing request for plant products, i.e. protein and oils, and to the increased economic and environmental pressures on agro-eco systems, it emerges that grain legumes would play a major role in future cropping systems.

Abbreviations

GHG: greenhouse gases; CO_2: carbon dioxide; N_2O: nitrous oxide; LCA: life cycle assessment; GWP: global warming potential; BNF: biological nitrogen fixation; NT: no tillage; CT: conventional tillage.

Authors' contributions

FS participated in the topic literature view and selection, and in drafting of the manuscript. AM drafted the manuscript and revised it critically. AG participated in the topic literature view and selection, and in the drafting of the manuscript. MP drafted the manuscript and revised it critically. All authors read and approved the final manuscript.

Author details

[1] Faculty of Biosciences and Technologies for Agriculture Food and Environment, University of Teramo, Coste Sant'Agostino, Teramo, TE, Italy. [2] Department of Agricultural Science, University of Naples Federico II, Via Università 100, Portici, Italy.

Authors information

FS: Associate Professor of Agronomy and Crop Sciences at University of Teramo (ITALY). AM: Associate Professor of Agronomy and Crop Sciences at University Federico II°, Naples (ITALY). AG: Researcher in Agronomy and Crop Sciences at University of Teramo (ITALY). MP: Full Professor of Agronomy and Crop Sciences at University of Teramo (ITALY).

Availability of data and materials

Data will not be shared, because they care adapted from other works of several different authors.

Competing interests

The authors declare that they have no competing interests.

Consent for publication

Each author give his personal consent for publication.

Funding

No funds were received for this work.

Received: 27 September 2016 Accepted: 15 December 2016

References

1. Alpmann D, Braun J, Schäfer BC. Analyse einer Befragung unter erfolgreichen Körnerleguminosen anbauern im konventionellen Landbau. Erste Ergebnisse aus dem Forschungsprojekt LeguAN. In: Wintertagung DLG, Im Fokus: Heimische Körnerleguminosen vom Anbau bis zur Nutzung. Berlin; 2013.
2. Angus JF, Kirkegaard JA, Hunt JR, Ryan MH, Ohlander L, Peoples MB. Break crops and rotations for wheat. Crop Pasture Sci. 2015;66:523–52.
3. Angus JF, van Herwaarden AF, Howe GN. Productivity and break crop effects of winter-growing oilseeds. Animal Prod Sci. 1991;31:669–77.
4. Araújo SS, Beebe S, Crespi M, Delbreil B, González EM, Gruber V, et al. Abiotic stress responses in legumes: strategies used to cope with environmental challenges. Crit Rev Plant Sci. 2014;34:237–80.
5. Baker JM, Ochsner TE, Venterea RT, Griffis TJ. Tillage and carbon sequestration-what do we really know? Agric Ecosyst Environ. 2007;118:1–5.
6. Banik P, Midya A, Sarkar BK, Ghose SS. Wheat and chickpea intercropping systems in an additive series experiment: advantages and weed smothering. Eur J Agron. 2006;24:325–32.
7. Barbery P. Weed management in organic agriculture: are we addressing the right issues. Weed Res. 2002;42:177–93.
8. Bayer C, Gomes J, Zanatta JA, Vieira FCB, Dieckow J. Mitigating greenhouse gas emissions from a subtropical Ultisol by using long-term no-tillage in combination with legume cover crops. Soil Tillage Res. 2016;161:86–94.
9. Beaudette C, Bradley RL, Whalen JK, McVetty PBE, Vessey K, Smith DL. Tree-based intercropping does not compromise canola (*Brassica napus* L.) seed oil yield and reduces soil nitrous oxide emissions. Agric Ecosyst Environ. 2010;139:33–9.
10. Berry PM, Sylvester-Bradley R, Philipps L, Hatch SP, Cuttle FW, Gosling P. Is the productivity of organic farms restricted by the supply of available nitrogen? Soil Use Manag. 2002;18:248–55.
11. Bichel A, Oelbermann M, Voroney P, Echarte L. Sequestration of native soil organic carbon and residue carbon in complex agroecosystems. Carbon Manag. 2016;7:1–10.
12. Boddey RM, Jantalia CP, Zanatta JA, Conceição PC, Bayer C, Mielniczuk J, et al. Carbon accumulation at depth in Ferralsols under zero-till subtropical agriculture in southern Brazil. Global Change Biol. 2010;16:784–95.
13. Brooker RW, Bennett AE, Cong W-F, Daniell TJ, George TS, Hallett PD, et al. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. New Phytol. 2015;206:107–17.
14. Bues A, Preißel S, Reckling M, Zander P, Kuhlmann T, Topp K, et al. The Environmental Role of Protein Crops in the New Common Agricultural Policy. European Parliament, Directorate General for Internal Policies, Policy Department B: Structural and Cohesion Policies, Agricultural and Rural DevelopmentIP/B/AGRI/IC/2012-067; 2013. Access www.europarl.europa.eu/studies.
15. Carranca C, Torres MO, Madeira M. Underestimated role of legume roots for soil N fertility. Agron Sustain Dev. 2015;35:1095–102.
16. Cernay C, Ben-Ari T, Pelzer E, Meynard J-M, Makowski D. Estimating variability in grain legume yields across Europe and the Americas. Sci Rep. 2015;5:11171.
17. Chalk PM. Dynamics of biologically fixed N in legume-cereal rotations: a review. Aust J Agric Res. 1998;49:303–16.
18. Christopher SF, Lal R. Nitrogen management affects carbon sequestration in North American cropland soils. Crit Rev Plant Sci. 2007;26:45–64.
19. Clune S, Crossin E, Verghese K. Systematic review of greenhouse gas emissions for different fresh food categories. J Clean Prod. 2017;140:766–83.
20. Crews TE, Peoples MB. Can the synchrony of nitrogen supply and crop demand be improved in legume and fertilizer-based agroecosystems? A Review. Nutr Cycl Agroecosyst. 2005;72:101–20.
21. Crutzen PJ, Mosier AR, Smith KA, Winiwarter W. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos Chem Phys Discuss. 2007;7:11191–205.
22. Faghire M, Mohamed F, Taoufiq K, Faghire R, Bargaz A, Mandri B, et al. Genotypic variation of nodules'enzymatic activities in symbiotic nitrogen fixation among common bean (*Phaseolus vulgaris* L.) genotypes grown under salinity constraint. Symbiosis. 2013;60:115–22.
23. FAOSTAT. www.faostat.fao.org (visited 18 November 2016).
24. FAO. The State of the World's Land and Water Resources for Food and Agriculture (SOLAW)—Managing Systems at Risk. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London; 2011.
25. Gan Y, Hamel C, Kutcher HR, Poppy L. Lentil enhances agroecosystem productivity with increased residual soil water and nitrogen. Renew Agr Food Syst 2016:1–12. doi:10.1017/S1742170516000223.
26. Gao Y, Duan A, Qiu X, Liu Z, Sun J, Zhang J, Wang H. Distribution of roots and root length density in a maize/soybean strip intercropping system. Agric Water Manag. 2010;98:199–212.
27. Garrigues E, Corson MS, Walter C, Angers DA, van der Werf H. Soil-quality indicators in LCA: method presentation with a case study. In: Corson MS, van der Werf HMG, editors. Proceedings of the 8th international conference on life cycle assessment in the agri-food sector, 1–4 October 2012, INRA, Saint Malo; 2012. p 163–68.

28. Giambalvo D, Stringi L, Durante G, Amato G, Frenda AS. Nitrogen efficiency component analysis in wheat under rainfed. Mediterranean conditions: effects of crop rotation and nitrogen fertilization. In: Cantero-Martínez C, Gabiña D, editors. Mediterranean rainfed agriculture: strategies for sustainability. Mediterranean Agronomic Institute of Zaragoza, Zaragoza; 2004. p. 169–73.
29. Guardia G, Tellez-Rio A, García-Marco S, Martin-Lammerding D, Tenorio JL, Ibáñez MÁ, Vallejo A. Effect of tillage and crop (cereal versus legume) on greenhouse gas emissions and Global Warming Potential in a non-irrigated Mediterranean field. Agric Ecosyst Environ. 2016;221:187–97.
30. Hajduk E, Właśniewski S, Szpunar-Krok E. Influence of legume crops on content of organic carbon in sandy soil. Soil Sci Ann. 2015;66:52–6.
31. Hassan HM, Hasbullah H, Marschner P. Growth and rhizosphere P pools of legume–wheat rotations at low P supply. Biol Fertil Soils. 2013;49:41–9.
32. Hauggaard-Nielsen H, Jensen ES. Facilitative root interactions in intercrops. Plant Soil. 2005;274:237–50.
33. Hauggaard-Nielsen H, Mundus S, Jensen ES. Nitrogen dynamics following grain legumes and catch crops and the effects on succeeding cereal crops. Nutr Cycl Agroecosyst. 2009;84:281–91.
34. Hernanz JL, Sanchez-Giron V, Navarrete L. Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. Agric Ecosyst Environ. 2009;133:114–22.
35. Hobbs PR, Sayre K, Gupta R. The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc Lond, Ser B. 2008;363:543–55.
36. Hocking PJ. Organic acids exuded from roots in phosphorus uptake and aluminum tolerance of plants in acid soils. Adv Agron. 2001;74:63–97.
37. Hocking PJ, Randall PJ. Better growth and phosphorus nutrition of sorghum and wheat following organic acid secreting crops. In: Horst WJ, et al., editors. Proceedings of the 14th international plant nutrition colloquium Germany. Dordrecht: Kluwer Academic Publishers; 2001. p. 548–9.
38. IPCC. Climate change 2007: Synthesis report. summary for policymakers. Intergovernmental panel on climate change (IPCC); 2007.
39. Jenkinson DS. The impact of humans on the nitrogen cycle, with focus on temperate agriculture. Plant Soil. 2001;228:3–15.
40. Jensen CR, Joernsgaard B, Andersen MN, Christiansen JL, Mogensen VO, Friis P, Petersen CT. The effect of lupins as compared with peas and oats on the yield of the subsequent winter barley crop. Eur J Agron. 2004;20:405–18.
41. Jensen ES, Ambus P, Bellostas N, Boisen S, Brisson N, Corre-Hellou G, et al. Intercropping of cereals and grain legumes for increased production, weed control, im-proved product quality and prevention of N–losses in European organic farming systems. In: International conferences: joint organic congress - Theme 4: crop systems and soils, 9 May 2006.
42. Jensen ES, Peoples MB, Boddey RM, Gresshoff PM, Hauggaard-Nielsen H, Alves BJ, Morrison MJ. Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. Agron Sustain Dev. 2012;32:329–64.
43. Jensen ES, Peoples MB, Hauggaard-Nielsen H. Faba bean in cropping systems. Field Crops Res. 2010;115:203–16.
44. Jeuffroy MH, Baranger E, Carrouée B, Chezelles ED, Gosme M, Hénault C. Nitrous oxide emissions from crop rotations including wheat, oilseed rape and dry peas. Biogeosciences. 2013;10:1787–97.
45. Jones SK, Rees RM, Skiba UM, Ball BC. Influence of organic and mineral N fertiliser on N_2O fluxes from a temperate grassland. Agric Ecosyst Environ. 2007;121:74–83.
46. Kirkegaard JA, Christen O, Krupinsky J, Layzell DB. Break crop benefits in temperate wheat production. Field Crop Res. 2008;107:185–95.
47. Kirkegaard JA, Ryan MH. Magnitude and mechanisms of persistent crop sequence effects on wheat. Field Crops Res. 2014;164:154–65.
48. Köpke U, Nemecek T. Ecological services of faba bean. Field Crop Res. 2010;115:217–33.
49. La Favre JS, Focht DD. Conservation in soil of H_2 liberated from N_2 fixation by H up-nodules. Appl Environ Microb. 1983;46:304–11.
50. Latati M, Bargaz A, Belarbi B, Lazali M, Benlahrech S, Tellah S. The intercropping common bean with maize improves the rhizobial efficiency, resource use and grain yield under low phosphorus availability. Eur J Agron. 2016;72:80–90.
51. Legume Futures Report 4.2. Reckling M, Schläfke N, Hecker J-M, Bachinger J, Zander P, Bergkvist G, et al. Generation and evaluation of legume-supported crop rotations in five case study regions across Europe; 2014. Available from www.legumefutures.de.
52. Legume Futures Report 1.6. Reckling M, Preissel S, Zander P, Topp CFE, Watson CA, Murphy-Bokern D, Stoddard FL. Effects of legume cropping on farming and food systems; 2014. Available from www.legumefutures.de.
53. Lemke RL, Zhong Z, Campbell CA, Zentner RP. Can pulse crops play a role in mitigating greenhouse gases from North American agriculture? Agron J. 2007;99:1719–25.
54. Lewis G, Schrire B, Mackinder B, Lock M. Legumes of the World. Kew: Royal Botanic Gardens; 2005.
55. Li L, Tilman D, Lambers H, Zhang F-S. Biodiversity and over yielding: insights from belowground facilitation of intercropping in agriculture. New Phytol. 2014;203:63–9.
56. Li L, Zhang L-Z, Zhang F-Z. Crop mixtures and the mechanisms of overyielding. In: Levin SA, editor. Encyclopedia of biodiversity, vol. 2. 2nd ed. Waltham: Academic Press; 2013. p. 382–95.
57. Li YF, Ran W, Zhang RP, Sun SB, Xu GH. Facilitated legume nodulation, phosphate uptake and nitrogen transfer by arbuscular inoculation in an upland rice and mung bean intercropping system. Plant Soil. 2009;315:285–96.
58. Lithourgidis AS, Dordas CA, Damalas CA, Vlachostergios D. Annual intercrops: an alternative pathway for sustainable agriculture. Aust J Crop Sci. 2011;5:396.
59. Liu X, Rahman T, Song C, Su B, Yang F, Yong T, et al. Changes in light environment, morphology, growth and yield of soybean in maize-soybean intercropping systems. Field Crop Res. 2017;200:38–46.
60. Lopes T, Hatt S, Xu Q, Chen J, Liu Y, Francis F. Wheat (*Triticum aestivum* L.)-based intercropping systems for biological pest control: a review. Pest Manag Sci. 2016;72:2193–202.
61. López-Bellido L, Munoz-Romero V, Benítez-Vega J, Fernández-García P, Redondo R, López-Bellido RJ. Wheat response to nitrogen splitting applied to a Vertisols in different tillage systems and crop-ping rotations under typical Mediterranean climatic conditions. Eur J Agron. 2012;43:24–32.
62. López-Bellido L, Munoz-Romero V, López-Bellido RJ. Nitrate accumulation in the soil profile: long-term effects of tillage, rotation and N rate in a Mediterranean Vertisol. Soil Tillage Res. 2013;130:18–23.
63. Luo S, Yu L, Liu Y, Zhang Y, Yang W, Li Z, Wang J. Effects of reduced nitrogen input on productivity and N_2O emissions in a sugarcane/soybean intercropping system. Eur J Agron. 2016;81:78–85.
64. Magid J, Henriksen O, Thorup-Kristensen K, Mueller T. Disproportionately high N-mineralisation rates from green manures at low temperatures-implications for modelling and management in cool temperate agro-ecosystems. Plant Soil. 2001;228:73–82.
65. Mahallati MN, Koocheki A, Mondani F, Feizi H, Amirmoradi S. Determination of optimal strip width in strip intercropping of maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L.) in Northeast Iran. J Clean Prod. 2015;106:343–50.
66. Meynard JM, Messéan A, Charlier A, Charrier F, Farès M, Le Bail M, et al. Crop diversification: obstacles and levers. Study of farms and supply chains. Synopsis of the study report. INRA, Paris. 2013.
67. Midya A, Bhattacharjee K, Ghose SS, Banik P. Deferred seeding of blackgram (*Phaseolus mungo* L.) in rice (*Oryza sativa* L.) field on yield advantages and smothering of weeds. J Agron Crop Sci. 2005;191:195–201.
68. Miller PR, Gan Y, McConkey BG, McDonald CL. Pulse crops for the Northern Great Plains: I. Grain productivity and residual effects on soil water and nitrogen. Agron J. 2003;95:972–9.
69. Mokgehle SN, Dakora FD, Mathews C. Variation in N_2 fixation and N contribution by 25 groundnut (*Arachis hypogaea* L.) varieties grown in different agro-ecologies, measured using 15 N natural abundance. Agric Ecosyst Environ. 2014;195:161–72.
70. Monti M, Pellicanò A, Santonoceto C, Preiti G, Pristeri A. Yield components and nitrogen use in cereal-pea intercrops in Mediterranean environment. Field Crop Res. 2016;196:379–88.
71. Munz S, Graeff-Hönninger S, Lizaso JI, Chen Q, Claupein W. Modeling light availability for a subordinate crop within a strip–intercropping system. Field Crop Res. 2014;155:77–89.

72. Nemecek T, von Richthofen J-S, Dubois G, Casta P, Charles R, Pahl H. Environmental impacts of introducing grain legumes into European crop rotations. Eur J Agron. 2008;28:380–93.
73. Ngwira AR, Aune JB, Mkwinda S. On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. Field Crop Res. 2012;132:149–57.
74. Papastylianou I. Effect of rotation system and N fertiliser on barley and vetch grown in various crop combinations and cycle lengths. J Agric Sci. 2004;142:41–8.
75. Pappa VA, Rees RM, Walker RL, Baddeley JA, Watson CA. Legumes intercropped with spring barley contribute to increased biomass production and carry-over effects. J Agric Sci. 2012;150:584–94.
76. Peoples MB, Boyer EW, Goulding KWT, Heffer P, Ochwoh VA, Vanlauwe B, et al. Pathways of nitrogen loss and their impacts on human health and the environment. In: Mosier AR, Syers KJ, Freney JR, editors. Agriculture and the nitrogen cycle, the Scientific Committee on Problems of the Environment (SCOPE). Covelo: Island Press; 2004. p. 53–69.
77. Peoples MB, Brockwell J, Herridge DF, Rochester IJ, Alves BJR, Urquiaga S, et al. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis. 2009;48:1–17.
78. Peoples MB, Hauggaard-Nielsen H, Jensen ES. The potential environmental benefits and risks derived from legumes in rotations. In: Emerich DW, Krishnan HB, editors. Nitrogen fixation in crop production. Madison: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America; 2009. p. 349–85.
79. Phelan P, Moloney AP, McGeough EJ, Humphreys J, Bertilsson J, O'Riordan E, O'Kiely P. Forage legumes for grazing and conserving in ruminant production systems. Crit Rev Plant Sci. 2015;34:281–326.
80. Plaza-Bonilla D, Nolot J-M, Raffaillac D, Justes E. Innovative cropping systems to reduce N inputs and maintain wheat yields by inserting grain legumes and cover crops in southwestern France. Eur J Agron. 2016. doi:10.1016/j.eja.2016.05.010.
81. Plaza-Bonilla D, Nolot JM, Raffaillac D, Justes E. Cover crops mitigate nitrate leaching in cropping systems including grain legumes: field evidence and model simulations. Agric Ecosyst Environ. 2015;212:1–12.
82. Preissel S, Reckling M, Schläfke N, Zander P. Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: a review. Field Crop Res. 2015;175:64–79.
83. Rao DLN, Giller KE, Yeo AR, Flowers TJ. The effects of salinity and sodicity upon nodulation and nitrogen fixation in chickpea (*Cicer arietinum*). Ann Bot Lond. 2002;89:563–70.
84. Reay DS, Davidson EA, Smith KA, Smith P, Melillo JM, et al. Global agriculture and nitrous oxide emissions. Nat Clim Change. 2012;2:410–6.
85. Reckling M, Hecker J-M, Bergkvist G, Watson CA, Zander P, Schläfke N, et al. A cropping system assessment framework—evaluating effects of introducing legumes into crop rotations. Eur J Agron. 2016;76:186–97.
86. Reckling M, Döring T, Stein-Bachinger K, Bloch R, Bachinger J. Yield stability of grain legumes in an organically managed monitoring experiment. Aspects Appl Biol. 2015;128:57–62.
87. Robson MC, Fowler SM, Lampkin NH, Leifert C, Leitch M, Robinson D, et al. The agronomic and economic potential of breakcrops for ley/arable rotations in temperate organic agriculture. Adv Agron. 2002;77:369–427.
88. Rochester IJ. Estimating nitrous oxide emissions from flood irrigated alkaline grey clays. Aust J Soil Res. 2003;41:197–206.
89. Rochette P, Janzen HH. Towards a revised coefficient for estimating N_2O emissions from legumes. Nutr Cycl Agroecosyst. 2005;73:171–9.
90. Rose TJ, Julia CC, Shepherd M, Rose MT, Van Zwieten L. Faba bean is less susceptible to fertiliser N impacts on biological N_2 fixation than chickpea in monoculture and intercropping systems. Biol Fert Soils. 2016;52:271–6.
91. Rubiales D, Fondevilla S, Chen W, Gentzbittel L, Higgins TJV, Castillejo MA, et al. Achievements and challenges in legume breeding for pest and disease resistance. Crit Rev Plant Sci. 2014;34:195–236.
92. Rühlemann L, Schmidtke K. Evaluation of monocropped and intercropped grain legumes for cover cropping in no-tillage and reduced tillage organic agriculture. Eur J Agron. 2015;65:83–94.
93. Rusinamhodzi L, Corbeels M, Nyamangara J, Giller KE. Maize–grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. Field CropRes. 2012;136:12–22.
94. Šarūnaitė L, Deveikytė I, Kadžiulienė Ž. Intercropping spring wheat with grain legume for increased production in an organic crop rotation. Žemdirbystė = Agric. 2010;97:51–8.
95. Schwenke GD, Herridge DF, Scheer C, Rowlings DW, Haigh BM, McMullen KG. Soil N_2O emissions under N_2-fixing legumes and N-fertilised canola: a reappraisal of emissions factor calculations. Agric Ecosyst Environ. 2015;202:232–42.
96. Senbayram M, Wenthe C, Lingner A, Isselstein J, Steinmann H, Kaya C, Köbke S. Legume-based mixed intercropping systems may lower agricultural born N_2O emissions. Energy Sustain Soc. 2016;6:2.
97. Seymour M, Kirkegaard JA, Peoples MB, White PF, French RJ. Break-crop benefits to wheat in Western Australia-insights from over three decades of research. Crop Pasture Sci. 2012;63:1–16.
98. Shen J, Yuan L, Zhang J, Li H, Bai Z, Chen X, et al. Phosphorus dynamics: from soil to plant. Plant Physiol. 2011;156:997–1005.
99. Siddique KH, Johansen C, Turner NC, Jeuffroy MH, Hashem A, Sakar D, Gan Y, Alghamdi SS. Innovations in agronomy for food legumes: a review. Agron Sustain Dev. 2012;32:45–64.
100. Smith J, Pearce BD, Wolfe M, Martin S. Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? Renew Agric Food Syst. 2013;28:80–92.
101. Soussana JF, Loiseau P, Vuichard N, Ceschia E, Balesdent J, Chevallier T, Arrouays D. Carbon cycling and sequestration opportunities in temperate grasslands. Soil Use Manag. 2004;20:219–30.
102. Soussana JF, Tallec T, Blanfort V. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal. 2010;4:334–50.
103. St. Luce M, Grant CA, Zebarth BJ, Ziadi N, O'Donovan JT, Blackshaw RE, et al. Legumes can reduce economic optimum nitrogen rates and increase yields in a wheat-canola cropping sequence in western Canada. Field Crop Res. 2015;179:12–25.
104. Stagnari F, Pisante M. Managing faba bean residues to enhance the fruit quality of the melon (*Cucumis melo* L.) Crop. Sci. Hort. 2010;126:317–23.
105. Swinton SM, Lupi F, Robertson GP, Hamilton SK. Ecosystem services and agriculture: cultivating agricultural ecosystems for diverse benefits. Ecol Econ. 2007;64:245–52.
106. Tharanathan RN, Mahadevamma S. Grain legumes—a boon to human nutrition. Trends Food Sci Tech. 2003;14:507–18.
107. Tosti G, Guiducci M. Durum wheat–faba bean temporary intercropping: effects on nitrogen supply and wheat quality. Eur J Agron. 2010;33:157–65.
108. United Nations: World population prospects: The 2012 revision, key findings and advance tables. Working paper no. ESA/P/WP.227; 2013 (United Nations, Department of Economic and Social Affairs, Population Division, New York).
109. Van Zwieten L, Rose T, Herridge D, Kimber S, Rust J, Cowie A, Morris S. Enhanced biological N_2 fixation and yield of faba bean (*Vicia faba* L.) in an acid soil following biochar addition: dissection of causal mechanisms. Plant Soil. 2015;395:7–20.
110. Vaz Patto MC, Amarowicz R, Aryee AN, Boye JI, Chung HJ, Martín-Cabrejas MA, Domoney C. Achievements and challenges in improving the nutritional quality of food legumes. Crit Rev Plant Sci. 2015;34:105–43.
111. VandenBygaart AJ, Gregorich EG, Angers DA. Influence of agricultural management on soil organic carbon: a compendium and assessment of Canadian studies. Can J Soil Sci. 2003;83:363–80.
112. Voisin AS, Guéguen J, Huyghe C, Jeuffroy MH, Magrini MB, Meynard JM, et al. Legumes for feed, food, biomaterials and bioenergy in Europe: a review. Agron Sustain Dev. 2014;34:361–80.
113. Wahbi S, Maghraoui T, Hafidi M, Sanguin H, Oufdou K, Prin Y, et al. Enhanced transfer of biologically fixed N from faba bean to intercropped wheat through mycorrhizal symbiosis. Appl Soil Ecol. 2016;107:91–8.
114. Walley FL, Clayton GW, Miller PR, Carr PM, Lafond GP. Nitrogen economy of pulse crop production in the Northern Great Plains. Agron J. 2007;99:1710–8.
115. Wang Y, Marschner P, Zhang F. Phosphorus pools and other soil properties in the rhizosphere of wheat and legumes growing in three soils in monoculture or as a mixture of wheat and legume. Plant Soil. 2012;354:283–98.

116. Westhoek H, Rood T, van den Berg M, Janse J, Nijdam D, Reudink M, Stehfest E. The protein puzzle. The consumption and production of meat, dairy and fish in the European Union. Netherlands Environmental Assessment Agency (PBL); 2011.
117. White PJ, George TS, Gregory PJ, Bengough AG, Hallett PD, McKenzie BM. Matching roots to their environment. Ann Bot Lond. 2013;112:207–22.
118. Xue Y, Xia H, Christie P, Zhang Z, Li L, Tang C. Crop acquisition of phosphorus, iron and zinc from soil in cereal/legume intercropping systems: a critical review. Ann Bot Lond 2016;117:363–77. doi:10.1093/aob/mcv182..
119. Yadav SS, Hunter D, Redden B, Nang M, Yadava DK, Habibi AB. Impact of climate change on agriculture production, food, and nutritional security. In: Redden R, Yadav SS, Maxted N, Dulloo MS, Guarino L, Smith P, editors. Crop wild relatives and climate change. New Jersey, USA: Wiley; 2015. p. 1–23.
120. Yu Y, Xue L, Yang L. Winter legumes in rice crop rotations reduces nitrogen loss, and improves rice yield and soil nitrogen supply. Agron Sustain Dev. 2014;34:633–40.
121. Zander P, Amjath-Babu TS, Preissel S, Reckling M, Bues A, Schläfke N, et al. Grain legume decline and potential recovery in European agriculture: a review. Agron Sustain Dev. 2016;36:26.
122. Zentner RP, Wall DD, Nagy CN, Smith EG, Young DL, Miller PR, et al. Economics of crop diversification and soil tillage opportunities in the Canadian prairies. Agron J. 2002;94:216–30.
123. Zimmer S, Messmer M, Haase T, Piepho HP, Mindermann A, Schulz H, et al. Effects of soybean variety and *Bradyrhizobium* strains on yield, protein content and biological nitrogen fixation under cool growing conditions in Germany. Eur J Agron. 2016;72:38–46.