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REVIEW ARTICLE

Integrating legumes to enhance cereal production: The relative inputs of fertiliser nitrogen and legume biological nitrogen fixation in major wheat and maize producing countries

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Abstract
Background Cereal crops dominate arable agriculture and underpin global food supply. Cereal grain yield is closely related to crop nitrogen (N) uptake. However, excessive inputs of N fertiliser in cereal production systems can have negative environmental consequences and represent high financial risk for farmers.
Scope This review explores opportunities to reduce the current reliance of the global staples, wheat (*Triticum aestivum*) and maize (*Zea mays*), on N fertiliser by diversifying cereal-based cropping systems with legumes, in both time (rotation) and space (via intercropping). Increases in cereal grain yield and N uptake resulting from the inclusion of legumes in wheat and maize cropping systems are examined across different geographic regions. The role of grain legumes and legume-based forages, cover-crops and green manures is described for the 15 countries responsible for producing > 70% of the world's wheat and maize and consuming > 80% of the global applications of N fertiliser to these two cereals. Estimates of the contributions from biological N_2 fixation and legume residual N to cropping soils are provided for individual countries and compared to the N offtake in wheat and maize grain and the quantities of N fertiliser applied. The potential increased area of legumes

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required for the returns of legume N to match the current amounts of N removed in grain or supplied as fertiliser is assessed for each country, and the strategies that might be necessary to encourage farmers to increase the frequency of legumes used in cereal-dominated cropping systems are outlined.

Keywords Biological nitrogen fixation · Cropping systems · Intercropping · Grain production · Rotation

Introduction

Cereals such as wheat (*Triticum aestivum* L.), durum wheat (*Triticum durum* Desf.), maize (corn; *Zea mays* L.), rice (*Oryza sativa* L.), sorghum (*Sorghum bicolor* (L.) Moench), millet (*Pennisetum glaucum* (L.) R.Br.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), rye (*Secale cereale* L.) and triticale (*Triticosecale* Wittm. ex A. Camus.) were grown on 728 million hectares (Mha) annually during the period 2018–2022, representing > 50% of the total 1.38 billion ha of arable land available globally for cropping (FAOSTAT 2025). Analysis of crop production data indicates that 417 Mha (57% of all arable land used for cereals) were allocated to growing wheat and maize (Fig. 1 and Supplementary Information Table S1). Wheat and maize are the most widely grown and traded crops, producing 1,925 Tg (million tonnes; million Mg; 10^{12} g) of grain each year (Fig. 1) that underpin the diet of billions of households globally, either directly as grain products or indirectly through grain-fed livestock (Erenstein et al. 2022; Ladha et al. 2022).

Since large areas of arable land are regularly used to grow cereals in all geographic regions of the world, it is perhaps unsurprising to find that grain yields of wheat and maize have either stagnated, or made slow progress towards closing on-farm 'yield gaps' (i.e. difference between grain yields achieved on-farm and potential yield) (Chauhan et al. 2012; Fischer et al. 2014; Patrignani et al. 2014; Ray et al. 2012). These production constraints are associated

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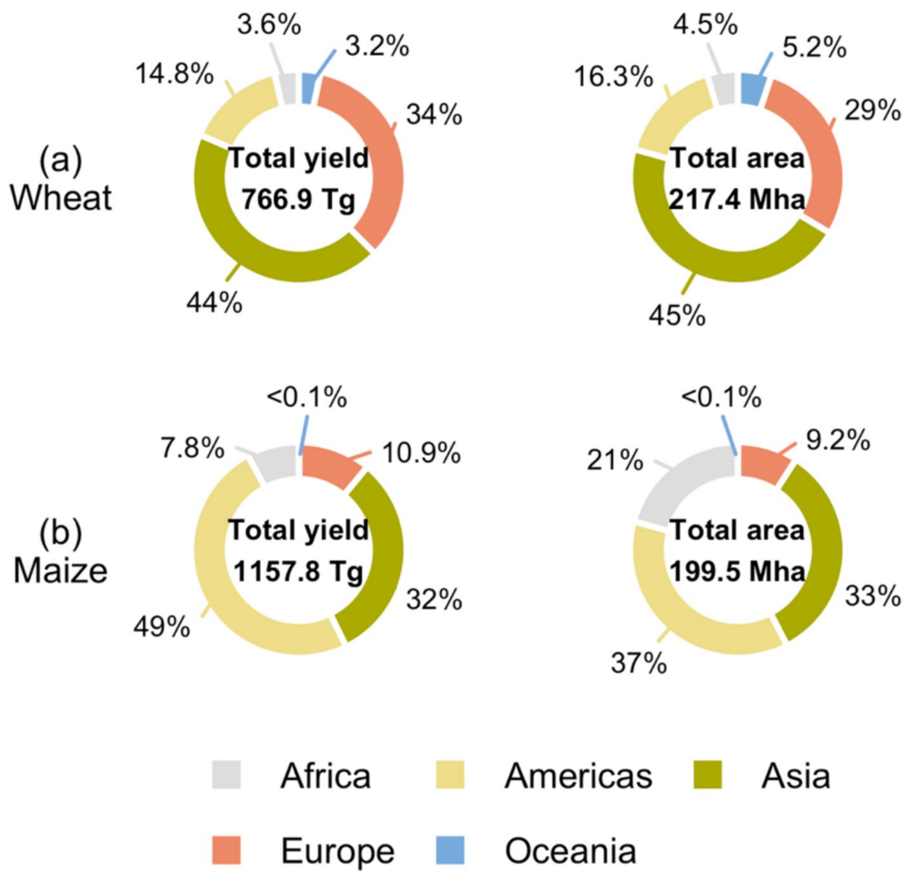

Fig. 1 The mean geographic regional contributions to annual global grain production (Tg per year) and the total areas harvested (Mha) by (a) wheat and (b) maize over the five-year period 2018–2022 (FAOSTAT 2025; detailed data available in Supplementary Information Table S1)

with a range of issues including a high incidence of cereal shoot and root diseases and pests (Angus et al. 2015; Kirkegaard et al. 2008), sub-optimal weed control leading to increasing competition from herbicide-resistant weeds (Chauhan et al. 2012; Sulc and Tracy 2007; Swan et al. 2023; Woźniak 2020), the depletion of soil organic fertility and an imbalanced nutrient supply (Chauhan et al. 2012; Fischer et al. 2014; Gora et al. 2024). Cereal monoculture (continuous cereal cropping) can be disrupted to address many of these issues, and the functional biodiversity of the agricultural landscape restored. Systems that are more complex, involving a diverse range of different plant species grown across a farm at any one time, can spread the risk of crop failure due to adverse climatic conditions, disease and pest outbreaks, and market fluctuations. A diverse system is also likely to be more resilient and have better environmental outcomes than a landscape dominated by highly specialised, frequent cereal cropping (Beillouin et al. 2021; de Faccio Carvalho et al. 2021; Gora et al. 2024; Reckling et al. 2022; Zhao et al. 2022). Crop species diversity in both time (rotations) and space (growing cereals with other plant species) are both components of more flexible systems of food production (Angus et al. 2015; Franke et al. 2018; Jensen et al. 2015, 2020; Kermah et al. 2019).

Nitrogen fertiliser use by major cereal producing countries

Cereal grain yield and nitrogen (N) uptake are closely linked across many different environments (Ciampitti and Lemaire 2022; Espinoza et al. 2015; Hunt et al. 2021; Peoples et al. 1995c; Setiyono et al. 2011; St Luce et al. 2015), with each tonne (t, Mg; 10^6 g) of harvested wheat grain containing around 20 kg N, and 16 kg N per t for maize (Ludemann et al. 2024). A combined total of 34 Tg N is harvested globally in wheat (15.3 Tg N) and maize grain (18.5 Tg N; Table S1), and 40 Tg N (38%) of the total 106 Tg of fertiliser-N used in agriculture annually is applied directly to wheat and maize (IFA 2022; Ludemann et al. 2022).

During the period 2018–2022, around 80% of the total annual wheat harvest (601 Tg grain; Table S1) was produced in Asia and Europe (Fig. 1a). More than 95% of the wheat in Europe, the Americas and Oceania was grown in rainfed (dryland) systems. By contrast, much of the estimated 60 Mha of irrigated wheat (just over one-quarter of the total land used for wheat) occurred in South Asia (primarily on the Indo-Gangetic Plains of north-west India, Pakistan, northern Bangladesh, Nepal), East Asia (southern China and North China Plains), West Asia (Iran and Afghanistan), and Central Asia (Uzbekistan, Turkmenistan, Kyrgyzstan, Tajikistan), as well as in areas of North Africa (Egypt and Sudan), Brazil (Cerrado region) and Mexico (Dadrasi et al. 2023; Dixon et al. 2009; Fischer et al. 2014; Juárez-Hernández et al. 2019; Singh et al. 2009). Collectively ten countries were responsible for 70% (536 Tg grain; Fig. 2a and Table S2) of the total global wheat production during 2018–2022 (Fig. 1a). The contrasting levels of mean grain yields achieved in these countries (from around 2 t/ha in Australia to over 7 t/ha in France and Germany; Fig. 2a and Table S2) reflect differences in climatic conditions (water, temperature, solar radiation), fertiliser-N supply (Fig. 2), soil fertility and management practices (e.g. input use, technology adoption). The average rates of N fertiliser applied to wheat across the ten countries represented 83–132% of the N offtake in harvested grain for all countries except in China, India and Pakistan where the amounts of fertiliser-N used substantially exceeded grain N demand (equivalent to 161–269% of grain N offtake) due to cheap, subsidised N fertiliser (Table S2; Ladha et al. 2020). In the Russian Federation on the other hand, the supply of fertiliser-N was less than the N removed in grain (61% of grain N offtake; Table S2) presumably reflecting the prevalence of fertile, organic carbon (C)-rich Chernozem soils across the 130 Mha of Russian cropland (Stolbovoi 2025).

The Americas and Asia (particularly East Asia) dominated maize production (Fig. 1b and Table S1) (Erenstein et al. 2022). The ten countries that produce the most maize account for 79% of the total maize harvest (920 Tg grain; Fig. 2b and Table S3). Around 80% of global maize production was rainfed, with irrigation mainly restricted to areas of South Asia's Indo-Gangetic Plains and Egypt (Erenstein et al. 2022; Portmann et al. 2010; Singh et al. 2009). Maize is particularly important for resource-constrained smallholders in Asia, South America, and sub-Saharan Africa who are often dependent on it for their food security and livelihoods (Acevedo-Siaca and Goldsmith 2020; Erenstein et al. 2022; Fischer et al. 2014). Rainfed maize systems have some of the largest farmer yield gaps among cereal crops and are considered to represent the greatest potential for grain yield improvements (Erenstein et al. 2022; Fischer et al. 2014; Schut and van Ittersum 2025). Grain yields range from 3 t/ha in India to almost 11 t/ha in the USA (Fig. 2b and Table S3). Trends in N fertiliser use across the major maize producing countries were similar to wheat in so much as the average rates of fertiliser-N applied were often comparable to amounts of N removed in grain (81–132% grain N offtake), but in China, India and Mexico the amount of N fertiliser supplied to maize greatly exceeded the N harvested in grain (189–206% of grain N offtake; Table S3). Argentina was the only country where the amounts of N fertiliser applied were markedly lower than N in grain (43% grain N offtake; Fig. 2b and Table S3).

Five countries featured in both the top-ten wheat and maize producing list (China, India, USA, Russian Federation, and Ukraine). Wheat and maize cropping by these five countries consumed 26.3 Tg fertiliser-N (11.3 Tg N by wheat and 15.0 Tg N by maize), representing two-thirds of the N fertiliser applied to these two cereals globally (Fig. 2, Tables S2 and S3). When considered across all 15 countries responsible for the bulk of wheat and maize production, some 34.3 Tg fertiliser-N was used (15.8 Tg N by wheat and 18.8 Tg N by maize), equivalent to > 86% of the total fertiliser-N applied to wheat and maize (Fig. 2, Tables S2 and S3).

Although in some regions of the world N fertiliser has been grossly under-supplied in relation cereal N offtake (e.g. sub-Saharan Africa; Ladha et al. 2020; Schut and van Ittersum 2025), N fertiliser has historically played a key contributory role in the three to four-fold improvement in global wheat grain yields, and the five to six-fold increase in maize since the early 1960s which has been crucial to support the growth in human population over that time (Erismann et al. 2008; Ladha et al. 2022; Tilman et al. 2002). However, there can be environmental consequences

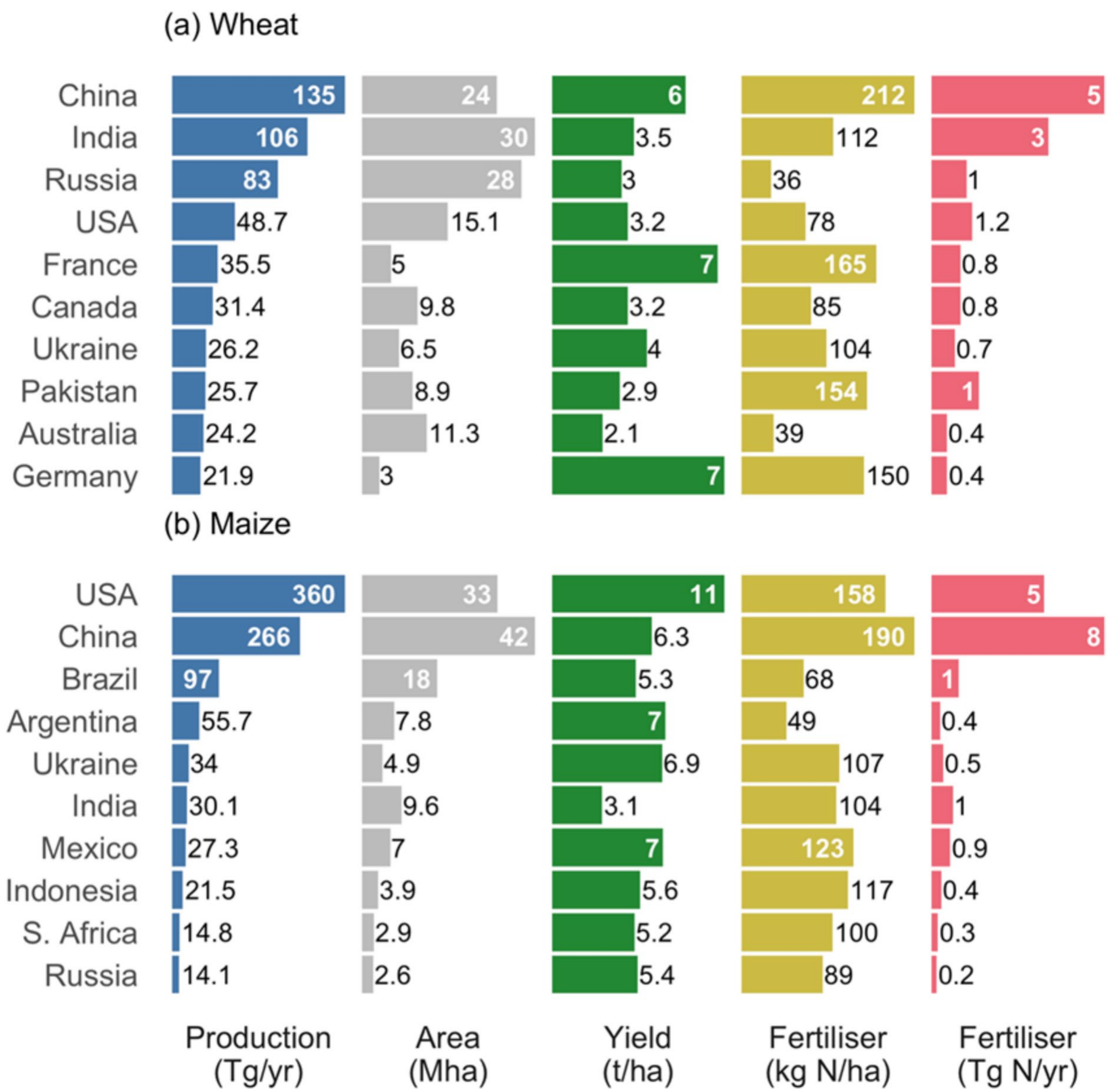

Fig. 2 The ten largest (**a**) wheat and (**b**) maize producing countries indicating the average annual grain production (Tg per year) and the areas harvested (Mha) for each country over the five-year period 2018–2022, the grain yields obtained (t/ha) and the average rates and amounts of fertiliser-N applied by each country in 2018 (FAOSTAT 2025; Tables S2 and S3)

associated with the applications of N fertiliser for cereal production (Erismann et al. 2008; Ladha et al. 2020; Peoples et al. 2004). In addition to the consumption of large amounts of non-renewable energy resources and carbon dioxide (CO_2) emissions involved with the industrial synthesis, transport and application of N fertiliser, generating high C-footprints (Jensen and Hauggaard-Nielsen 2003; Jensen et al. 2012; Juárez-Hernández et al. 2019; Peoples et al. 2009b, 2019; Zentner et al. 2001), cereal crops frequently recover less than half of the applied fertiliser-N in grain and vegetative biomass in the year of application (Chakraborty et al. 2025; Gardner and Drinkwater 2009; Ladha et al. 2005; Lassaletta et al. 2014; Vonk et al. 2022; Yu et al. 2022). While on average slightly less than half of the unutilised

N fertiliser (one-quarter of that initially applied) remains in the soil as the result of immobilisation by the microbial community (Barton et al. 2022; Jenkinson et al. 1985; Recous et al. 1988) and is potentially available to ensuing crops (Chakraborty et al. 2025; Vonk et al. 2022), the remainder is lost from the cropping system via:

(i) Erosion, runoff, lateral flow or leaching which can contaminate groundwater and waterways or acidify the soil (Ladha et al. 2022; Peoples et al. 2004),

(ii) Gaseous emissions of di-nitrogen (N_2), nitrogen oxides (NO and NO_2), and nitrous oxide (N_2O) during the transformation of fertiliser-derived nitrate (NO_3) and ammonium (NH_4) in soil. With the important exception of N_2, these emissions represent long-lived greenhouse gases (GHGs), and/or ozone-depleting substances (Barton et al. 2022; Erismann et al. 2008; Jensen et al. 2012; Peoples et al. 1995a), and.

(iii) Volatilisation of ammonia (NH_3) which forms aerosols and contributes to acid rain and N deposition that negatively impacts terrestrial and aquatic ecosystems, as well as providing a secondary source of N for the further formation of GHGs (Barton et al. 2022; Erismann et al. 2008; Ladha et al. 2020; Peoples et al. 1995a).

Based on the meta-analysis of the fate of fertiliser-N undertaken by Gardner and Drinkwater (2009) and the average rates of N fertiliser applied to the ten countries who produce the most wheat and maize (Fig. 2, Tables S2 and S3), the N losses at a country-level were estimated to range from 5–65 kg N/ha for wheat and 10–58 kg N/ha for maize (Fig. 3). In both cases, China was predicted to have the greatest losses (Fig. 3).

Most of the negative externalities associated with N fertiliser use result from poor management practices, a mismatch between N supply and crop demand, and/or an oversupply of N due to low relative costs (e.g. subsidies: Crews and Peoples 2005; Ladha et al. 2020). A multitude of strategies and N use efficiency indicators have been proposed as ways to either improve N fertiliser decision-making, enhance the utilisation of fertiliser N by cereals, reduce the extent of N losses, and/or lessen the environmental impact of food production (Antille and Moody 2021; Chakraborty et al. 2025; Crews and Peoples 2005; Cui et al. 2018; Duncan et al. 2018; Giller et al. 2004;

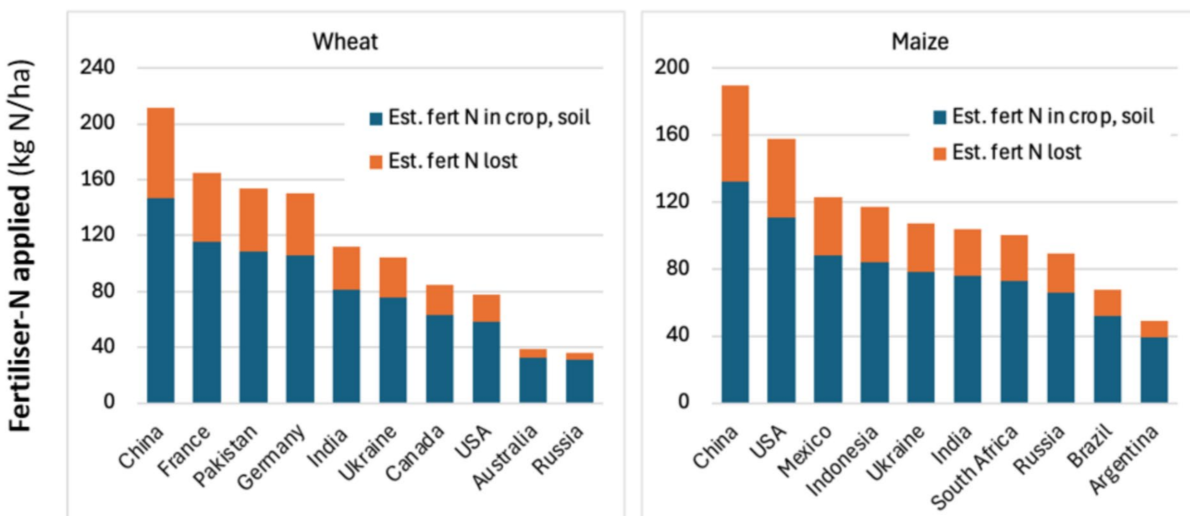

Fig. 3 Comparison of the fate of N fertiliser applied to cereals in the ten countries producing the most wheat and maize. Countries were ranked highest to lowest based on the average rates of fertiliser-N applied. The relative amounts of N lost from the system were calculated using the following function derived from the meta-analysis of the recovery of ^{15}N-labelled N fertiliser applied to cropping systems undertaken by Gardner and Drinkwater (2009) (*all values expressed as kg N/ha*): Fertiliser-N lost = 0.34 x (Fertiliser N applied) - 6.9

Gu et al. 2023; Lam et al. 2022; Peoples et al. 1995a). Regardless of whether any of these approaches are extensively adopted by farmers in the future, one of the aims in the development of new cereal systems should be to reduce rather than increase the overall reliance on N fertiliser, especially in countries where N is currently over-supplied (Crews and Peoples 2004; Ladha et al. 2022; Quemada and Lassaletta 2024).

An increased role for legumes

Legumes can contribute significantly to redesigned systems of cereal production. Not only would species diversity be increased in otherwise cereal-dominated cropping sequences (Reckling et al. 2022; Notz et al 2023), but legumes also:

- (i) Produce quality high-protein grain and forage without the need for fertiliser N (Mahmood et al. 2018; Wery and Ahlawat 2008). This is due to biological N_2 fixation (BNF) through symbiotic relationships with soil bacteria, rhizobia, which typically satisfy between 40–80% of a legume's N requirements depending upon the legume species and farming system (Barbieri et al. 2023; Carlsson and Huss-Danell 2003; Ciampitti and Salvagiotti 2018; Palmero et al. 2022; Peoples et al. 2012; 2021),
- (ii) Emit less GHG's than N fertilised cereals during growth (Barton et al. 2022; Gora et al. 2024; Jensen et al. 2012; Reckling et al. 2022; Williams et al. 2017) and, depending upon management and rainfall, systems that utilise legume residues as a source of N for subsequent crops generally have a lower risk of N losses than where fertiliser-N is used (Beillouin et al. 2021; Crews and Peoples 2005; Gardner and Drinkwater 2009; Garnier et al. 2024; Jeuffroy et al. 2013; Schwenke et al. 2015; Zentner et al. 2001),
- (iii) Induce beneficial changes in soil biology, structure, nutrient and water availability, as well as slowing the decline in soil organic C compared to cereal monocultures, and in some cases encouraging C sequestration (Angus et al. 2015; Fillery 2001; Guan et al. 2016; Jensen et al. 2012; Lemaire et al. 2015; Ma et al. 2021; McCallum et al. 2004; Peoples et al. 2019; Persson et al. 2008; Yao et al. 2025), and.
- (iv) Reduce the N fertiliser requirements for (Flohr et al. 2024; Jensen et al. 2020; Ladha et al. 2022; Mahmood et al. 2018; Pott et al. 2021; Singh et al. 2004; Simon-Miquel et al. 2024; St Luce et al. 2015; Thorup-Kristensen et al. 2003; Weiner et al. 2024), and improve the N fertiliser use efficiency of, subsequent crops (Espinoza et al. 2015; Lasisi and Liu 2023).

This review primarily focuses on examining and comparing the contributions of fertiliser and legume N to wheat and maize production. It differs from previous reviews (Al-Musawi et al. 2025; Angus et al. 2015; Franke et al. 2018; Kirkegaard et al. 2008; Ladha et al. 2022; Preissel et al. 2015; Ryan et al. 2008) and meta-analyses (Cernay et al. 2018; Garba et al. 2022; Lasisi and Liu 2023; Ma et al. 2021; Mundare et al. 2025; Zhao et al. 2022) regarding the effects of legumes on cereal productivity, or national, regional and global N budgets in crop production (Anglade et al. 2015; Billen et al. 2014; Karimi et al. 2020; Smil 1999; Zhang et al. 2021), as it provides new insights into the role of legumes and their inputs of N in the farming systems of the 15 countries producing the majority of the world's wheat and maize.

This paper aims to:

1. Describe the varied uses of legumes in agriculture and their global inputs of BNF,
2. Summarise the impact of different legume systems on cereal grain yield, biomass production, and N uptake across different geographic regions,
3. Compare the net inputs of legume N as BNF and in legume residues to cropping soils in the major wheat and maize producing countries to the amounts of N removed in grain and applied as fertiliser,
4. Calculate the extent to which areas of legumes would need to be increased in each country to match the current N offtake in wheat and maize grain or the N supplied by N fertiliser, and
5. Outline a range of prospective strategies that might be required to facilitate more legumes being grown by farmers in cereal-based cropping systems.

The different abiotic and biotic interactions responsible for the observed rotational effects of legumes on cereal production will be examined in detail in a future review.

Uses of legumes in agriculture

Grain legumes

Grain legumes include different crop species that are either collectively known as 'pulses' which are predominantly grown for dry grain for human consumption and as feed for livestock (Fig. 4a, Table S4; Manickavasagan and Thirunathan 2020) or are described as 'oilseed legumes' (Fig. 4b, Table S5). Combined, the pulse and oilseed legumes produced an average 495 Tg grain from 251 Mha annually during 2018–2022 (Fig. 4, Tables S4 and S5).

Many hundreds of legume species are of local importance and have been used for centuries as human foods in different countries (Chongtham et al. 2021; Giller 2001; Peoples et al. 2014; Sprent and James 2009). However, the 93 Mha of pulses reportedly grown globally each year (Fig. 4a) is dominated by just four cool-season crops; namely chickpea (Bengal gram, garbanzo bean: *Cicer arietinum* L.), field pea (pea: *Pisum sativum* L.), lentil (*Lens culinaris* Medik.) and faba bean (broad bean: *Vicia faba* L.; Fig. 5), and the five warm-season crops, green gram (mungbean: *Vigna radiata* (L.) R. Wilczek), black gram (urad bean, mashbean, mash daal: *V. mungo* (L.) Hepper), cowpea (black-eyed bean: *V. unguiculata* (L.) Walp.), common bean (dry bean: *Phaseolus vulgaris* L.) and pigeonpea (red gram, toor: *Cajanus cajan* (L.) Millsp.) (Fig. 6 and Table S4). Individually each of these crops are grown on 2.7–19.8 Mha (Figs. 5 and 6), and together they represent 86 Mha (92%) of the total global area of pulses (Fig. 4a, Table S4). The FAOSTAT (2025) database indicated that the remaining 8% of land used for pulses (7.6 Mha) consisted of 0.98 Mha of lupin (narrow-leaf lupin, blue lupin: *Lupinus angustifolius* L.; white lupin: *L. albus* L.; yellow lupin: *L. luteus* L.), 0.34 Mha of vetch (common vetch: *Vicia*

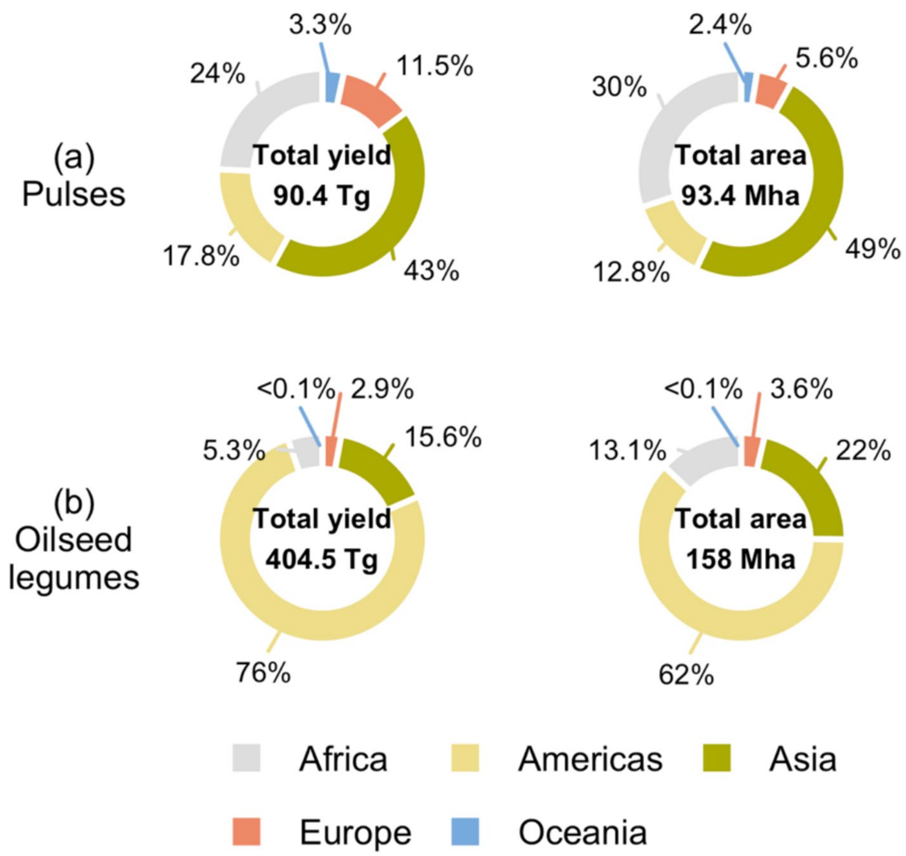

Fig. 4 The mean geographic regional contributions to annual global grain production (Tg per year) and total areas harvested (Mha) by all (**a**) pulse and (**b**) oilseed legumes over the five-year period 2018–2022 (FAOSTAT 2025; species details provided in Tables S4 and S5)

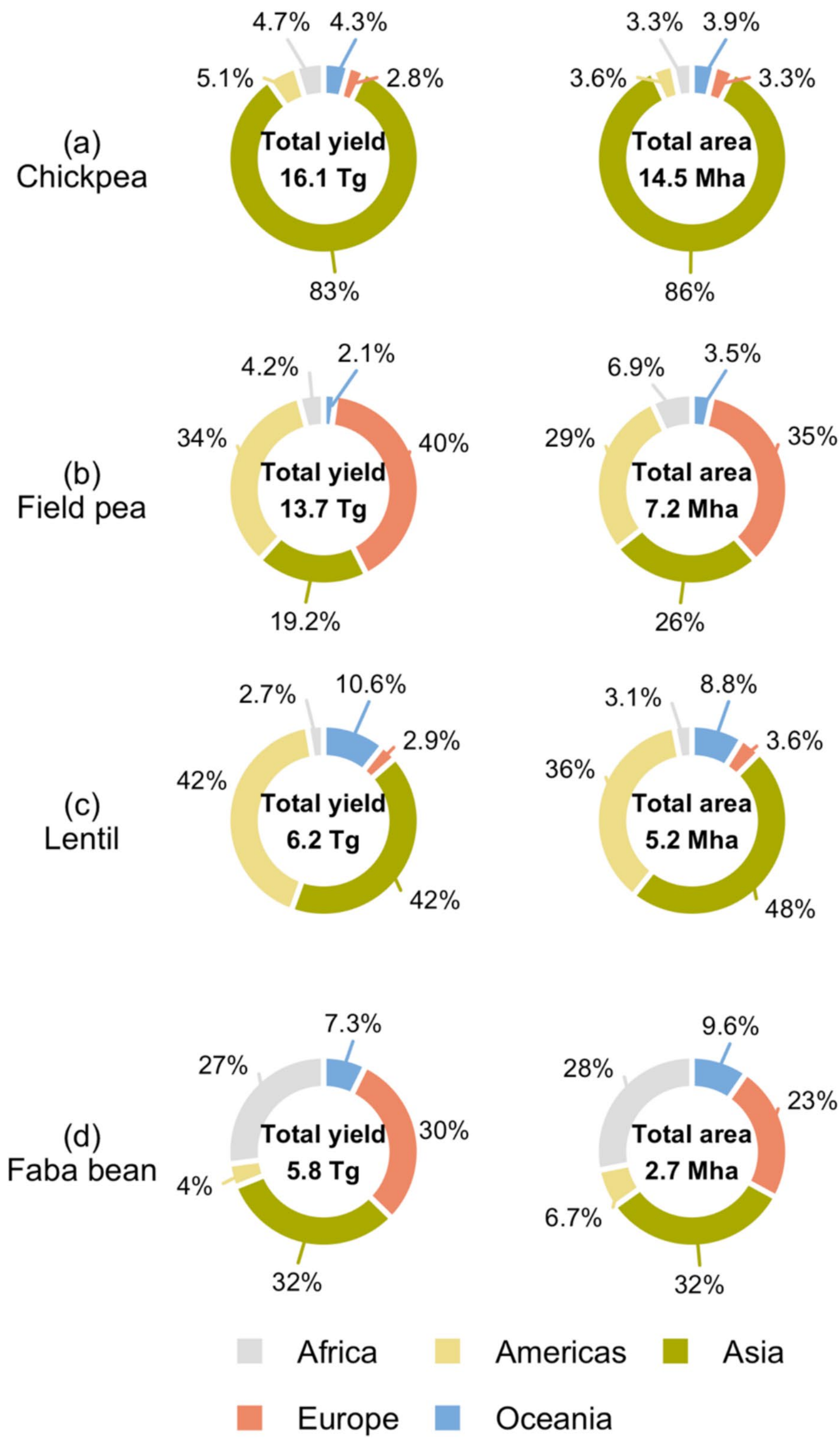

Fig. 5 The mean geographic regional contributions to annual global grain production (Tg per year) and the total areas harvested (Mha) by the four largest cool-season pulse legume crops (**a**) chickpea, (**b**) field pea, (**c**) lentil and (**d**) faba bean over the five-year period 2018–2022 showing comparisons of the production and area data for the three most important producing countries (FAOSTAT 2025; Table S4)

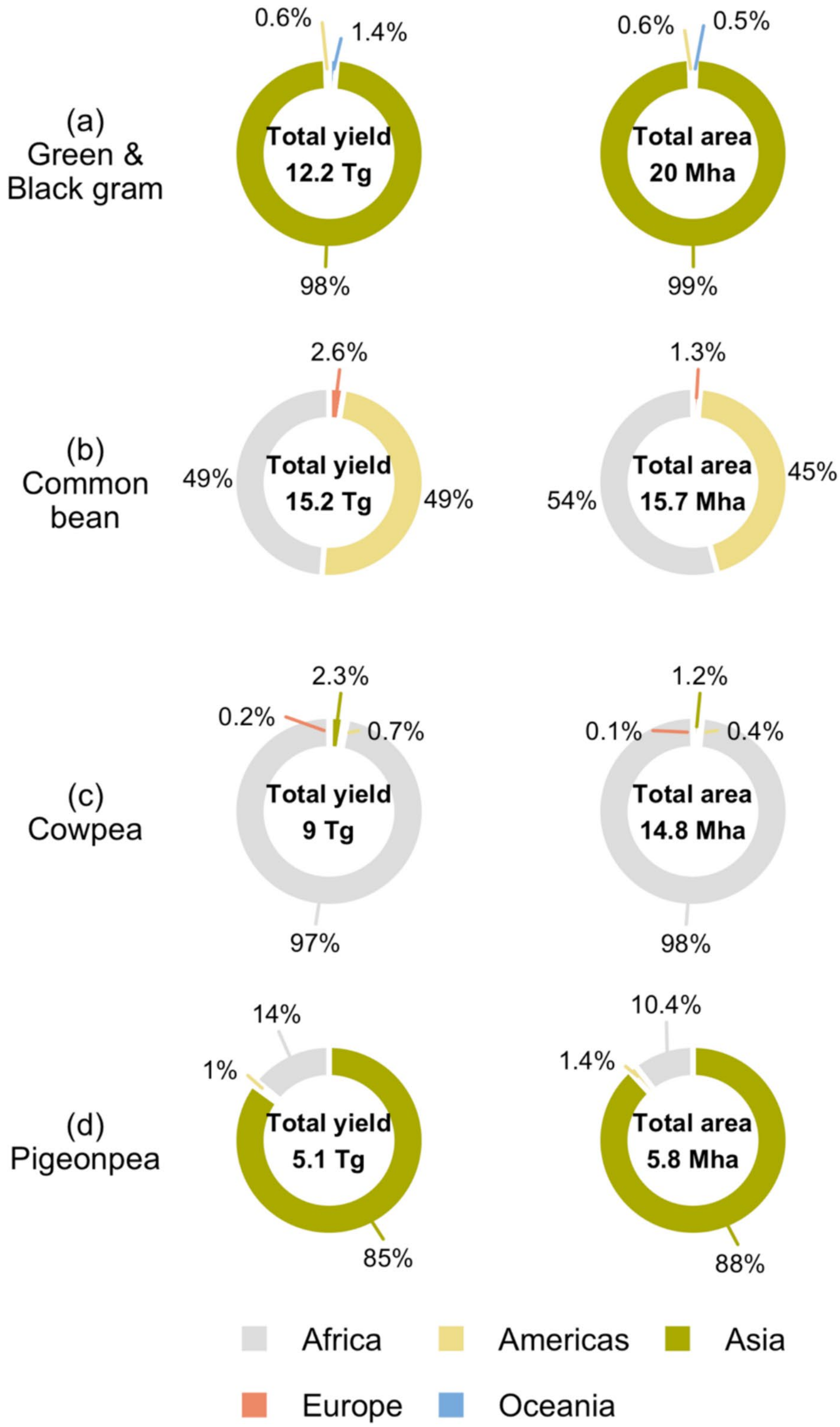

Fig. 6 The mean geographic regional contributions to annual global grain production (Tg per year) and the total areas harvested (Mha) by the five largest warm-season pulse legume crops (**a**) green and black gram, (**b**) common bean, (**c**) cowpea and (**d**) pigeonpea over the five-year period 2018–2022 (FAOSTAT 2025; Table S4)

sativa L., and other *Vicia* species), 0.31 Mha of Bambara groundnut (*Vigna subterranea* (L.) Verdc.), and a cohort of unnamed legume species (5.96 Mha; Table S4). These unidentified legumes are likely to include minor, but regionally important, crops such as Kersting's groundnut (*Macrotyloma geocarpum* (Harms) Maréchal & Baudet), horse gram (*M. uniflorum* (Lam.) Verdc.), lablab (Hyacinth bean: *Lablab purpureus* (L.) Sweet), grasspea (chickling vetch: *Lathyrus sativus* L.), tepary bean (*Phaseolus acutifolius* A. Gray), lima bean (*P. lunatus* L.), winged bean (*Psosphocarpus tetragonolobus* (L.) DC.), moth bean (*Vigna aconitifolia* (Jacq.) Maréchal), adzuki bean (*V. angularis* (Wild.) Ohwi & H. Ohashi) and ricebean (*V. umbellate* (Thumb.) Ohwi & H. Ohashi) (Giller 2001; Ladha et al. 2022; Manickavasagan and Thirunathan 2020; Peoples and Herridge 1990; Peoples et al. 2009a; Vanlauwe et al. 2019).

Some of the pulse species listed above are also used as fresh vegetables. This includes immature pods of crops such as common bean and runner bean (*Phaseolus coccineus* L.), as well as the unripe seeds of crops such as field pea and faba bean. We consider these fresh (green) legumes out of scope of the current discussion since the area of production of all legumes grown as fresh vegetables (< 5 Mha; FAOSTAT 2025) are dwarfed by dry grain pulse and oilseed crops (Fig. 4a, Table S4) and they are frequently grown in more fertile soils that are remote from the main areas of cereal production.

Occurrence of the major pulses differed across geographic regions during 2018–2022 (Figs. 4–6). Asia produced 43% of the global pulse grain (Fig. 4a), with South Asia responsible for over three-quarters of the Asian total (Ladha et al. 2022). However, crops such as common bean, field pea and cowpea were predominantly grown in geographic regions outside of Asia (Figs. 5 and 6). The three most important producing countries for pulse crops except common bean generated between 60–90% of the global grain harvested for each species (Table S4). These differences in the geographic distribution of pulses and the concentration of production in just a few countries reflects the adaptation of specific crops to certain soil types and climatic zones in addition to local dietary preferences and trade opportunities (Maaz et al. 2018).

Important as pulses may be as staple food crops and livestock feed, the global areas of individual pulse crops (Figs. 5 and 6, Table S4) were small when compared to the land used for the production of oilseed legumes soybean (soyabean: *Glycine max* (L.) Merr.; 127 Mha) and groundnut (peanut: *Arachis hypogaea* L.; 30.5 Mha) (Fig. 7, Table S5). The Americas dominated global soybean production, while Asia and Africa were the main regions for groundnut (Fig. 7).

Grain legumes are usually grown as sole crops, although there are also systems in which legumes are grown in conjunction with either wheat or maize on the same land within the same growing-season (i.e. the legume and cereal are intercropped) (Hobbs and Osmanzai 2011; Lithourgidis et al. 2011; Rerkasem et al. 1988). Such polyculture systems are common in smallholder agriculture in rainfed cropping areas of Africa, Asia, and South America (Hobbs and Osmanzai 2011; Li et al. 2016; Lithourgidis et al. 2011) and occur in some organic production systems (Bedoussac et al. 2015; Jensen et al. 2015; Yan et al. 2025). Interest is also growing in legume-cereal intercropping elsewhere (Fletcher et al. 2016; Mbanyele et al. 2024; Tzemi et al. 2025). Various evaluations suggest that < 20% of soybean grown in China may be intercropped, but over 70% of common bean in South America and 90% of cowpea in Africa may be intercropped (Lithourgidis et al. 2011; Li et al. 2016).

The contribution of BNF to legume nutrition is often considered to play a fundamental role in the subsequent rotational benefits that grain legumes provide cereals. While each of the different methodologies used to quantify BNF are based on various assumptions and subject to error (Soper et al. 2021; Unkovich et al. 2008), experimental and on-farm estimates of the percentage of legume N derived from atmospheric N_2 (%Ndfa) for 14 major grain legumes consolidated from > 5000 observations from around the world suggest that, with exception of soybean, %Ndfa of grain legume crops tend to be relatively consistent within species across geographic regions (Peoples et al. 2021). This knowledge has been combined with reported FAO production data for pulse and oilseed legumes to derive estimates of BNF on an individual country and regional basis and then collated to provide global determinations of BNF (Herridge et al. 2022; Ladha et al. 2022; Reis Ely et al. 2025). Such calculations indicate that soybean provided 25 Tg fixed N (70%) of the total global inputs of 33–36 Tg fixed N by all grain legumes, > 80% of which was derived from soybean grown in South

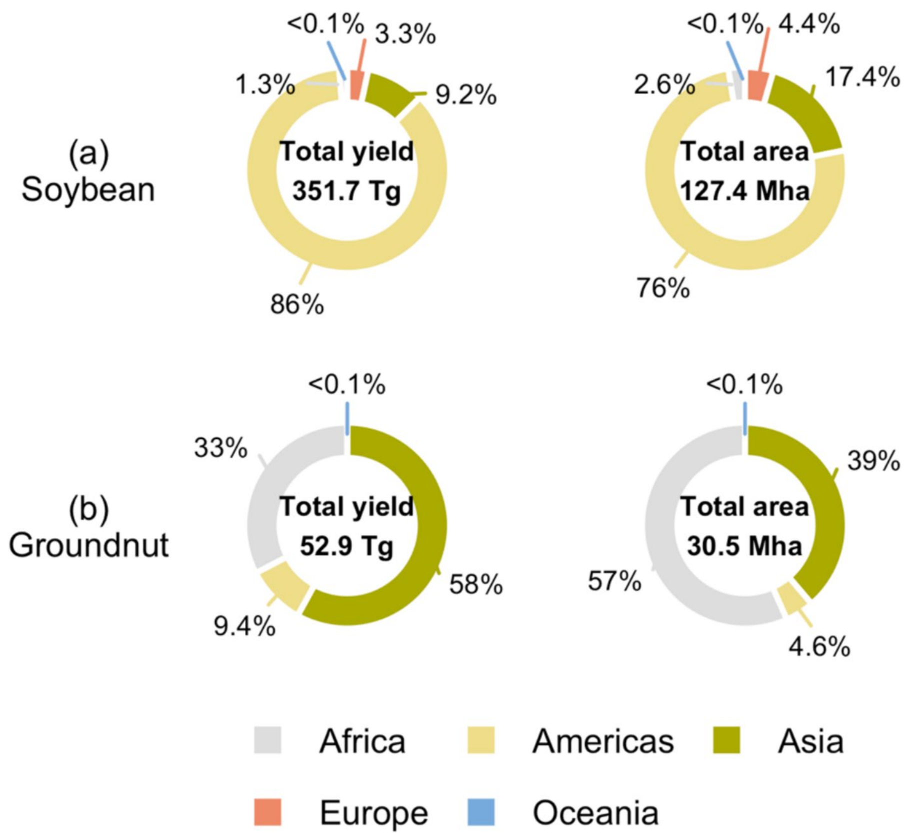

Fig. 7 The mean geographic regional contributions to annual global grain production (Tg per year) and the total areas harvested (Mha) by the oilseed legume crops (**a**) soybean and (**b**) groundnut over the five-year period 2018–2022 (FAOSTAT 2025; Table S5)

America (13.1 Tg fixed N) and North American cropping systems (7.8 Tg fixed N; Herridge et al. 2022). The contribution of BNF by pulse crops represented 7.2 Tg fixed N (29%), and groundnut 3.3 Tg fixed N (1% of the global total; Herridge et al. 2022).

Forage legumes

Just over one-quarter (~3.5 billion ha) of the world's land area and 70% of all agricultural land may be occupied by various temporary or permanent pastures and grasslands (FAOSTAT 2025; Peoples et al. 1995c; Putnam and Orloff 2014). The annual herbage dry matter (DM) yield in these systems can range from < 1 t/ha in low input, rainfed pastures in semi-arid regions to 10–20 t/ha in intensive, high input, hay and silage production (Julier et al. 2017; Peoples et al. 2012; Phelan et al. 2015). How legumes feature in these forage systems in terms of area or production are poorly documented and extremely difficult to estimate (Herridge et al. 2022; Phelan et al. 2015). This is because the botanical composition of farmers' pastures within individual countries can vary from pure legume swards to pure grass or contain multiple species where legumes might represent between < 10% to > 75% of the total foliage biomass depending upon the original species sown, growing-season rainfall, fertilisation practices, grazing management, and pasture age (Armstrong et al. 1999; Bowman et al. 2004; Peoples and Baldock 2001; Peoples et al. 1998; Putnam and Orloff 2014; Swan et al. 2014).

Over 150 different annual and perennial legume species have been reported to be utilised for forage, but a much smaller number are recognised as being of commercial significance (Tables 1 and 2) (Franzluebbers et al. 2011; Peoples et al. 2012; Phelan et al. 2015; Putnam and Orloff 2014; Rótolo et al. 2011). Of this smaller list of forage legumes, lucerne (alfalfa; *Medicago sativa* L.) is the most important globally. Lucerne is cultivated on ~13 Mha in the USA and is the country's highest value hay crop, it is the most widely grown forage legume in Europe, and is such a common component of many forage systems

Table 1 Examples of important annual legume species grown for forage at commercial-scale.[a]

Common name	Scientific name
Cool-season legumes	
Biserrula	*Biserrula pelecinus* L
Strand medic	*Medicago littoralis* Lois
Murex medic	*M. murex* Willd
Burr medic	*M. polymorpha* L
Gama medic	*M. rugosa* Desr
Snail medic	*M. scutellata* (L.) Mill
Barrel medic	*M. truncatula* Gaertn
French (pink) serradella	*Ornithopus sativus* Brot
Yellow serradella	*O. compressus* L
Berseem clover	*Trifolium alexandrinum* L
Gland clover	*T. glanduliferum* Bois
Crimson clover	*T. incarnatum* L
Balansa clover	*T. michelianum* L
Persian clover	*T. resupinatum* L
Subclover (subterranean clover)	*T. subterraneum* L
Rose clover	*T. hirtum* All
Arrowleaf clover	*T. vesiculosum* Savi
Common vetch	*Vicia* sativa L
Hairy vetch (woolly-pod vetch)	*V. villosa* Roth
Purple vetch	*V. benghalensis* L
Warm-season legumes	
Butterfly pea	*Clitoria ternatea* L
Townsville stylo	*Stylosanthes humilis* Kunth
Stylo	*S. guianensis* (Aubl.) Sw
Shrubby stylo	*S. scabra* Vogel
Dalrymple vigna	*Vigna luteola* (Jacq.) Benth
Zornia	*Zornia glabra* Desvaux

[a]Species listed by Peoples et al. (2012), Phelan et al. (2015), and Putnam and Orloff (2014)

elsewhere in the world that it has been proposed that it could be present in 30% of all cropland pastures (Julier et al. 2017; Peoples et al. 2019; Phelan et al. 2015; Putnam and Orloff 2014; Smil 1999).

Forage legumes can provide significant amounts of N to agroecosystems via BNF, particular by pure legume swards (Carlsson and Huss-Danell 2014; Gault et al. 1995; Peoples et al. 1998, 2012). This can lead to an accumulation of soil organic C and N (Gault et al. 1995; Guan et al. 2016; Holford 1981), reduce the need for N fertiliser, and improve the productivity of both forage (Finn et al. 2013; Lemaire et al. 1992, 2014) and cereal production systems (Angus and Peoples 2012; Fillery 2001; Peoples and Baldock 2001; Reckling et al. 2022). Reis Ely et al. (2025) recently estimated that around 20 Tg of N may be fixed globally by forage legumes each year based on FAO area data for cultivated pastures (presumed to encompass all agricultural forage systems), modelled regional climatic predictions of net primary productivity and assumptions about legume composition and the relationships between legume DM production and BNF (Carlsson and Huss-Danell 2014; Peoples et al. 2012). Other previous estimates of BNF in agroecosystems suggested that the total annual inputs by forage legumes could vary from 12–30 Tg fixed N because of uncertainties about the legume composition of various forage systems around the world and the appropriate rates of BNF for different legume species (Herridge et al. 2022; Smil 1999).

It the context of this review, it is worth noting that the long-term global trend of increasing specialisation of farming enterprises has led to cereal cropping and livestock production often occurring in different parts of the landscape (Lemaire et al. 2023; Sulc and Tracy 2007; Voisin et al. 2014; Wolfe 2011). Even where cropping and pasture occur on the same farm, each operation may be localised in different areas (Franzluebbers et al. 2011; Lemaire et al. 2015; Rótolo et al. 2011). Consequently, opportunities for wheat or maize to directly benefit from legume-based pastures or forage production systems are currently restricted to those few regions of the world where cereal and animal production are still closely integrated (Lemaire et al. 2015; Wolfe 2011), and where periods of pasture are routinely used to restore soil fertility prior to cropping (Angus and Peoples 2012; Bell et al. 2019).

Legumes as green manure, brown manure, or cover-crops

Before the rapid expansion in the use of N fertilisers for grain cropping in the 1960s, 25–50% of farmed land was generally committed for the purpose of soil fertility regeneration involving legume-based pastures and crops, often with associated livestock grazing to accelerate nutrient cycling (Crews and Peoples 2004; Lemaire et al. 2023). Legume green manures in these systems would be terminated prior to sowing the next cash crop by a combination of mowing, rolling or tillage, and the residues either left as a mulch to smother weeds, or incorporated into the soil with additional

Table 2 Examples of important perennial legume species grown for forage at commercial-scale.[a]

Common name	Scientific name
Cool-season legumes	
Sulla	*Hedysarum coronarium* L
Birdsfoot trefoil	*Lotus corniculatus* L
Lucerne/alfalfa	*Medicago.sativa* L
Sweet clover[b]	*Melilotus officinalis* (L.) Lam
Common sainfoin	*Onobrychis viciifolia* Scop
Caucasian clover	*Trifolium ambiguum* M.Bieb
Strawberry clover	*T. fragiferum* L
Alsike clover	*T. hybridum* L
Red clover	*T. pratense* L
White clover	*T. repens* L
Warm-season legumes	
Pinto peanut	*Arachis pintoi* Krapov
Rhizoma peanut	*A. glabrata* Benth
Centro	*Centrosema pubescens* Benth
Desmanthus (wild tantan)	*Desmanthus virgatus* (L.) Willd
Greenleaf desmodium	*Desmodium intortum* (Mill.) Urb
Silverleaf desmodium	*D. uncinatum* (Jacq.) DC
Siratro	*Macroptilium atropurpureum* (DC.) Urb
Burgundy bean	*M. bracteatum* (Nees & Mart.) Marechal & Bau
Puero (tropical kudzu)	*Pueraria phaseoloides* (Roxb.) Benth

[a]Species listed by Ojiem et al. (2007), Peoples et al. (2012), Phelan et al. (2015), and Putnam and Orloff (2014)

[b]Note: Sweet clover is biennial not a perennial

cultivation. The practice of green manuring using a similar cohort of crop or forage legumes as those discussed above remains a component of organic cereal production (Baddeley et al. 2017).

There is limited use of green manure by smallholder farmers in Asia and Africa as they have such a restricted area to grow food, they are unable to devote land for green manure solely for soil improvement (Giller et al. 2000). Until recently, sacrificing land for green manure also made little economic sense in most conventional wheat or maize cropping systems, as the potential savings in N fertiliser costs in cereal production, rarely justified the prospective income forgone in the preceding green manure year (Swan et al. 2023). However, the evolution of weeds that are resistant to multiple herbicides has forced conventional farmers to periodically include low-input, vigorous legumes in their cropping program that can be either green manured or killed with knock-down herbicide before herbicide-resistant weeds can set viable seed (often described as "brown manure") (Roper et al. 2012; Swan et al 2023; Umbers 2021). On large farms where labour is expensive allocating 10–20% of the farm area to brown manure allows more timely operations elsewhere in the cropping program and sets up a weed-free field with high residual N and water for following cereal or oilseed crops, thereby increasing profit at the farm-scale.

Cover-cropping is a variation of green manuring that is increasingly being used by both organic and conventional farmers (Al-Musawi et al. 2025; Baddeley et al. 2017; Biassoni et al. 2024). In the temperate climatic zones of Europe and North America, the temperature and light conditions after harvest are sufficient to support some plant growth, although not always enough to produce a commercial cash-crop every year (Pitchers et al. 2023). This is where legume cover-crops (also known as catch-crops) can be sown either alone or mixed with non-legumes rather than leaving land as a bare fallow to scavenge soil mineral N and reduce the risk of N losses through erosion, leaching and/or denitrification (Abdalla et al. 2019; Baddeley et al. 2017; Couëdel et al. 2019; Hauggaard-Nielsen et al. 2009; Kaye and Quemada 2017; Li et al. 2015; Plaza-Bonilla et al. 2015). Once the cover-crop is terminated shortly before sowing the next cash-crop, the accumulated biomass essentially becomes a source of green manure. While cover-cropping is a useful strategy in higher rainfall environments, it is a less viable option in drier climates where there is erratic rainfall and summer fallowing is commonly practiced. Under these conditions there are few reliable sowing opportunities, but even if a cover-crop can be successfully sown, the replacement of a fallow by the cover-crop can deplete soil water reserves to such an extent that the following cereal's yield can be reduced (Holman et al. 2018; Hunt et al. 2021; Nielsen et al. 2016; Rose et al. 2022; Siddique et al. 2008). Indeed, meta-analysis suggests that a minimum annual rainfall of around 700 mm may be required to realise sufficient yield benefits from cover-cropping to justify the replacement of fallowing in dryland environments (Garba et al. 2022).

A variation of cover-cropping known as 'relay-cropping' is used on some smallholder farms in Africa whereby a short-duration legume like cowpea might be sown into the maize crop, and the cowpea takes over as the maize matures (Kermah et al. 2019). The dense mat of legume material produced by the helps suppress weeds, stabilise and protect the soil, as well as provide a source of N for the next crop. The concept of sowing either grain or forage legumes into existing, established wheat or maize crops has attracted considerable research attention, especially in temperate environments of Europe and North America, but it is yet to be widely adopted by farmers (Lamichhane et al. 2023).

Although experimental data on BNF by green and brown manures and legume cover-crops and their impacts on cereal productivity are available across different geographic regions and agroecological zones (e.g. Biassoni et al. 2024; De Notaris et al. 2025; Evans et al. 2003; Espinoza et al. 2012; Li et al. 2015; Ojiem et al. 2007; Peoples et al. 2017; Pott et al. 2021; Roper et al. 2012), it is difficult to assess the likely global inputs of BNF or the amounts of legume N that might be returned to cropping soils by such systems. Unlike the detailed production data available for pulses and oilseed legumes, equivalent information on the use of these practices in different countries and their productivity are not captured in FAO statistical databases and are rarely reported in official governmental documentation. As the N inputs and flow-on benefits provided by green and brown manuring or cover-cropping cannot be reliably quantified, discussion in later sections of this review concerning the prospective contributions by legume to the N dynamics of cereal-based cropping systems can only offer a conservative view of the impact.

Legume effects on the productivity and N uptake by cereals

There have been many reviews of cereal productivity following legumes in a cropping sequence (e.g. Al-Musawi et al. 2025; Angus et al. 2015; Cernay et al. 2018; Franke et al. 2018; Kirkegaard et al. 2008; Lasisi and Liu 2023; Ma et al. 2021; Mundare et al. 2025; Peoples and Craswell 1992; Peoples and Herridge 1990; Preissel et al. 2015; Reckling et al. 2022; Ryan et al. 2008; Vanlauwe et al. 2019; Zhao et al. 2022), or when they are grown in direct association with a legume (e.g. Bedoussac et al. 2015; Fletcher et al. 2016; Jensen et al. 2015; Li et al. 2016). It is not our intention to reproduce the detailed analyses of these previous publications in the following section, but rather to provide a brief commentary on the relative effects of the different legume-based systems described above on wheat and maize biomass, grain yield and N uptake across geographic regions.

The effect of legumes on following cereals in a crop sequence

Table 3 summarises the impact of legumes on wheat and maize production and N uptake observed in each of the five main geographic regions of the world when the cereals were grown in the absence of N fertiliser. The average values shown within Table 3 were derived from Table S6 which contains 1,476 site/years of cereal responses to legume pre-crop treatments from experimentation reported in 120 publications from 31 different countries (1,010 grain yield datasets for wheat and durum wheat, 389 for maize, and 77 for barley, oats, rye, sorghum and millet). Two-thirds of all wheat and maize studies used grain legumes as pre-crop treatments, 90% of which investigated the rotational effects of grain legumes on the first cereal crop.

More wheat studies were undertaken in some countries and geographic regions than others, however there appeared to be regional differences in yield responses by the first wheat crop grown after grain legumes (Table 3). Grain yield improvements ranged from + 0.67 t/ha in the variable and low rainfall environments of Oceania (Australia, n = 374) to + 1.35 t/

Table 3 Summary of the range and mean measures of improvements in grain yield, crop dry matter (DM) accumulation and N uptake by the first or subsequent wheat or maize crops grown after legumes in the absence of supplementary N fertiliser in different geographic regions of the world. The preceding legumes had been grown for grain, forage, green (GrM) or brown manure (BrM), and cover-crops (C-cr). The number (n) of site/years of data used to calculate individual mean values are indicated for each parameter.[a]

Geographic region and preceding legume type	Cereal	Increase after legumes								
		Grain yield[b] (t/ha)			Above-ground biomass[c] (t DM/ha)			Crop N uptake[d] (kg N/ha)		
		n	Range	Mean	n	Range	Mean	n	Range	Mean
Asia										
Grain legumes	Wheat	63	0.27–3.33	0.92	19	1.27–1.70	1.52	19	9–24	15 (22)[e]
	Maize	24	0.19–2.21	1.14	21	0.56–3.74	1.95	19	5–26	17 (27)[e]
Forage legumes	Wheat	29	0.50–1.21	0.86	-	-	-[f]	-	-	-[f]
	Maize	3	0.25–0.41	0.33	2	-	1.73	2	-	17 (26)[e]
Legume GrM, BrM or C-cr	Wheat	21	0.06–0.63	0.31	7	0.21–1.06	0.64	11	18–41	27 (41)[e]
	Maize	2	0.73–1.00	0.87	1	-	1.00	1	-	27 (41)[e]
Europe										
Grain legumes	Wheat	130	0.50–2.68	1.35	4	1.47–2.30	1.89	20	12–34	22 (33)[e]
Forage legumes	Wheat	20	1.50–2.78	2.14	-	-	-[f]	20	25–59	42 (63)[e]
Legume GrM, BrM or C-cr	Maize	6	0.90–0.95	0.93	6	1.50–1.93	1.71	6	21–40	31 (46)[e]
Americas										
Grain legumes	Wheat	113	0.16–1.97	0.79	15	0.46–3.18	1.82	63	7–54	28 (43)[e]
	Wheat2	36	0.12–0.19	0.14	15	-	0.30	15	-	5 (8)[e]
	Maize	98	0.82–3.58	2.58	28	-	4.98	34	21–58	36 (55)[e]
Forage legumes	Wheat	2	-	1.47	-	-	-[f]	-	-	-[f]
	Maize	33	-	4.36	-	-	-[f]	-	-	-[f]
Legume GrM, BrM or C-cr	Wheat	56	0.68–2.38	1.53	2	-	3.34	33	21–51	40 (61)[e]
	Maize	109	0.41–3.78	1.43	17	2.64–3.23	2.94	31	14–81	41 (63)[e]
Oceania										
Grain legumes	Wheat	378	0.25–1.12	0.67	89	0.59–2.49	1.71	111	14–38	24 (36)[e]
	Wheat2	55	0.22–0.39	0.39	2	-	0.69	6	12–20	16 (24)[e]
Forage legumes	Wheat	37	0.22–1.65	0.73	10	0.54–3.01	1.78	31	4–44	26 (39)[e]
	Wheat2	16	0.26–1.67	0.74	10	0.48–2.47	1.48	10	7–30	19 (29)[e]
	Wheat3	6	-	1.49	6	-	2.14	6	-	25 (38)[e]
Legume GrM, BrM or C-cr	Wheat	34	0.30–1.83	1.12	30	0.82–4.1	2.48	34	17–66	40 (62)[e]
	Wheat2	4	-	1.20	-	-	-[f]	4	-	45 (68)[e]
Africa										
Grain legumes	Wheat	9	0.26–1.53	0.97	4	-	4.00	4	-	68 (103)[e]
	Maize	114	0.03–2.50	0.91	22	0.85–2.93	1.79	22	11–30	19 (29)[e]
Averaged across all regions										
Grain legumes	Wheat	693		0.94	132		2.19	217		31 (48)[e]
	Wheat2	91		0.27	17		0.50	21		11 (16)[e]
	Maize	236		1.54	71		2.91	75		24 (36)[e]
Forage legumes	Wheat	88		1.30	10		0.45	51		17 (26)[e]
	Wheat2	16		0.74	10		1.48	10		19 (29)[e]
	Wheat3	6		1.49	6		2.14	6		25 (38)[e]
	Maize	36		2.35	2		1.73	2		17 (26)[e]

Table 3 (continued)

Geographic region and preceding legume type	Cereal	Increase after legumes								
		Grain yield[b] (t/ha)			Above-ground biomass[c] (t DM/ha)			Crop N uptake[d] (kg N/ha)		
		n	Range	Mean	n	Range	Mean	n	Range	Mean
Legume GrM, BrM or C-cr	Wheat	112		0.99	40		2.15	79		36 (54)[e]
	Wheat2	4		1.20	-		-[f]	4		45 (69)[e]
	Maize	117		1.08	24		1.88	38		33 (50)[e]

[a]High-level summary of improvements in wheat and maize production or N uptake were collated from multiple experiments presented in Supplementary Information Table S6. Values are presented for the first wheat or maize crop sown after a legume unless followed by the numbers '2' or '3' which indicate the second or third cereal grown following a legume; respectively

[b]Increased grain yield = (cereal yield after a legume) – (cereal yield after a non-legume control). A range is not shown where data were derived from only one study

[c]Increased above-ground dry matter (DM) = (cereal DM after a legume) – (cereal DM after a non-legume control). A range is not shown where data were derived from only one study

[d]Increased N uptake = (cereal N after a legume) – (cereal N after a non-legume control). A range is not shown where data were derived from only one study

[e]Crop N uptake values shown in parentheses represent estimates of total cereal N (above + below-ground N) where above-ground N data have been adjusted to include the additional N assumed to be associated with cereal roots (Khan et al. 2003; Wichern et al. 2008)

[f]No data reported

ha under the more favourable growing conditions of Europe (n = 130; Table 3). The largest European yield response dataset came from Germany (n = 44) which recorded + 1.83 t/ha greater wheat yields following grain legumes (Table S6). The yield responses to a preceding grain legume observed in Australia and Germany represented the equivalent of 31% and 25%; respectively of average wheat yields during 2018–2022 (2.14 t/ha in Australia and 7.35 t/ha in Germany; Table S2), which were comparable to previously reported assessments of mean global % improvements in grain yield after legumes (Mundare et al. 2025; Zhao et al. 2022). Across the complete wheat dataset collated for all five regions grain yields by the first wheat after grain legumes were on average + 0.94 t/ha (n = 693) greater than the unfertilised non-legume-wheat control sequence, above-ground wheat biomass was increased by + 2.19 t DM/ha (n = 132) and N uptake by + 31 kg N/ha (estimated to be + 48 kg N/ha on a whole-plant basis if N associated with wheat roots were included, n = 217; Table 3).

The size of the dataset collated for maize grown after grain legumes was smaller than for wheat (Table 3). Nonetheless, the data suggest that the average yield improvement by the first maize crop was greater in the Americas (+ 2.58 t/ha, n = 98) than either Asia (+ 1.14 t/ha, n = 24) or Africa (+ 0.91 t/ha, n = 114). When assessed across the complete maize dataset, the average response to a preceding grain legume was + 1.54 t/ha additional grain (n = 236), + 2.91 t DM/ha increase in the accumulation of above-ground biomass (n = 71) and + 24 kg N/ha greater N uptake (+ 36 kg N/ha on a whole-plant basis, n = 75; Table 3).

Although far fewer comparisons have been reported, cereal grain yields and/or crop N uptake appeared to often be greater after forage legumes, green/brown manure or cover-crops than following grain legumes (Tables 3 and S6). This conclusion is supported by various studies which found that 20–40 kg fertiliser-N/ha was frequently required to be applied to rainfed wheat or maize grown in cereal-cereal sequences to achieve the equivalent yield improvements observed when grown in the absence of fertiliser-N after grain legumes, compared to 50–125 kg fertiliser-N/ha where forage legumes, green manure or cover-crops had been used (Bruulsema and Christie 1987; De Notaris et al. 2025; Ledgard and Giller 1995; Lengwati et al. 2020; Miller et al. 2003; Peoples and Craswell 1992; Peoples and Herridge 1990; Siddique et al. 2008).

Based on the data from eight direct experimental comparisons undertaken in North America and Australia, the improvements in yield and N accumulation by the second cereal crop grown after grain legumes were on average around 60% of the response observed in the first cereal cropping year (Table S6) (Angus et al. 2015). Previous studies have concluded that the benefits of grain legumes rarely persist into a third subsequent crop unless a series of dry seasons preserve the legacies of high soil mineral N and low disease through the crop sequence (Angus et al. 2015; Kirkegaard and Ryan 2014). In contrast, the available data suggest that responses by the second cereal following legume-based forage systems or green manures may not decline to the extent observed after grain legumes and that enhanced cereal productivity can persist into a third cereal cropping year in the case of forage legumes (Table S6) (Angus and Peoples 2012; Evans et al. 2003; Reckling et al. 2022; Ta and Faris 1990).

The rotational benefits can be affected by the legume species grown and vary between and within experiments, and across geographic regions (Tables 3 and S6) (Al-Musawi et al. 2025; Angus et al. 2015; Chalk 1998; Kirkegaard et al. 2008; La Menza et al. 2025; Peoples and Craswell 1992; St Luce et al. 2015). For example, maize yields after either soybean grain crops or lucerne and red clover forage in long-term Canadian experimentation exceeded that of an unfertilised maize monoculture on 31 occasions over the 33-year study, with improvements in maize yield ranging from 0.6–4.9 t/ha (mean + 2.6 t/ha across all years) after soybean and 1.8–8.8 t/ha (mean + 4.4 t/ha) after forage legumes (Liang et al. 2025). Factors that have been identified as influencing cereal responsiveness to a preceding legume included:

(i) The productivity of the preceding grain legume and the amount of residual N returned to the soil (Aslam et al. 2003; Asseng et al. 1998; Giller et al. 2000; Peoples et al 2017; Seymour et al. 2012; Vanlauwe et al. 2019),
(ii) The productivity and/or legume composition of the preceding pasture, green manure or cover-crop (De Notaris et al. 2025; Harris et al. 2006; La Menza et al. 2025; Liang et al. 2025; Moore and Grace 1998; Peoples et al. 2017), and the timing of the termination of the legume system prior to cropping (Angus et al. 2000; Dear et al. 2004; Gan et al. 2016; La Menza et al. 2025),
(iii) Availability of soil N and other soil nutrients such as phosphorus (P) and/or potassium (K) (Angus et al. 2015; Duncan et al. 2018; Giller and Cadisch 1995; Schut and van Ittersum 2025),
(iv) Fallow weed management and in-crop weed infestations (Hunt et al. 2021; Swan et al. 2023; Wittwer et al. 2017), and
(v) Differences in the duration of the fallow period, and the climatic conditions experienced during the fallow and cereal growing-season (Holman et al. 2018; Kirkegaard et al. 2008; La Menza et al. 2025; Liang et al. 2025; Miller et al. 2003; Moore and Grace 1998; Peoples et al. 2017; Ryan et al. 2008; Vanlauwe et al. 2019; Zentner et al. 2001).

The effect of legumes on intercropped cereals

Intercropping wheat or maize with legumes frequently results in improved stability in the productivity of both cereal and legume crops (Raseduzzaman and Jensen 2017), increased cereal uptake of N per plant and higher cereal grain protein contents than when the cereal is grown as a sole crop (Bedoussac et al. 2015; Fletcher et al. 2016; Jensen et al. 2020; Li et al. 2024; Rerkasem et al. 1988; Xiao et al. 2018). It has widely been speculated that legumes contribute to the N nutrition of cereals in intercropping and mixed cropping systems via the direct transfer of legume N to cereals growing in the immediate proximity. Many different above- and below-ground mechanisms have been proposed that might conceivably facilitate such transfer (Table 4). Various ^{15}N-based technologies have been deployed in an attempt study these potential pathways for legume N (Chalk et al. 2014; Hupe et al. 2025; Ingraffia et al. 2021; Peoples et al. 2015; Xiao et al. 2004). However, the interpretation of data can be complex and controversial as in reality N transfer is probably occurring in all directions; from legume to legume, from legume to cereal, and from cereal to cereal (Carlsson and Huss-Danell 2014; Chalk 1998; Hupe et al. 2025).

Often it has been assumed that any transferred legume N was predominantly fixed N with a ^{15}N value identical to atmospheric N_2 despite the absence of any compelling scientific evidence to support such a

Table 4 Potential mechanisms by which cereals in intercropping systems could either obtain N transferred from neighbouring legumes or accumulate more biomass N via other means.[a]

Pathway	Rate of transfer	Likely importance
Above-ground		
Decomposition & mineralisation of fallen senesced leaves	Slow	Minor short-term
Foliar leachates	Rapid	Minor
Foliar release of ammonia gas	Rapid	Minor
Improved light interception	-	Major (?)[b]
Increased biomass due to reduced cereal foliar disease	-	Potentially major[c]
Below-ground		
Turnover & mineralisation of senesced roots & nodules	Rapid (?)[b]	Major (?)[b]
N-compounds released from the nodulated roots	Rapid (?)[b]	Minor (?)[b]
Transfer between roots interconnected via mycorrhizal hyphae	Rapid	Minor (?)[b]
Root or nodule herbivory	Rapid (?)[b]	Major (?)[b]
Increased root growth due to reduced cereal root disease	-	Major (?)[bc]
Faster rate of cereal root growth than the legume	-	Major
Reduced weed competition for water & nutrients	-	Potentially major[c]
Poorer competition for soil mineral N by legume roots	-	Major

[a]Adapted from information provided by Bedoussac et al. (2015), Hauggaard-Nielsen et al. (2001), Ingraffia et al. (2021), Corre-Hellou et al. (2006), Ledgard and Giller (1995), Peoples et al. (2015), Siddique et al. (2008), Zang et al. (2015)

[b]A question-mark indicates that the relative importance of a proposed pathway is either unknown, or there is no scientific consensus

[c]The relative impact will be related to the extent to which intercropping suppresses weeds and/or reduces the severity of cereal disease. This can be influenced by whether the preceding crop had been a cereal or not, environmental conditions prior to, or during, the growing-season and farmer management practices (Hunt et al. 2021; Kirkegaard and Ryan 2014)

notion (Ledgard and Giller 1995). In truth, the identity and isotopic signatures of prospective transferred compounds are rarely if ever known, so it is impossible to accurately quantify how much legume N may be directly contributing to N nutrition of a companion cereal (Chalk et al. 2014; Peoples et al. 2015). Consequently, there are many inconsistencies and contradictions reported in the literature and the significance of many of the potential pathways of N transfer in intercropping systems listed in Table 4 remain uncertain (Ledgard and Giller 1995; Peoples et al. 2015).

While it is anticipated that N derived from forage legumes would be transferred to neighbouring grasses and herbs in mixed pasture swards over several years (especially if the pastures were grazed) (Ledgard and Giller 1995; Lemaire et al. 2023), any transfer of N from an intercropped legume to a cereal either via below-ground pathways or from fallen leaves is unlikely to play a major role within a single growing-season (Giller et al. 2000; Ledgard and Giller 1995; Peoples and Herridge 1990; Zang et al. 2015).

The observed increased biomass and N uptake by the intercropped cereal component compared to sole cereal crops could result from improved light inception, different patterns in the rates and maximum depth of root growth or plant water and nutrient uptake over the growing-season by each intercropped species, a suppression of competition with weeds for water and nutrients, or a lower incidence of cereal disease (Table 4) (Bedoussac et al. 2015; Corre-Hellou et al. 2006; Hauggaard-Nielsen et al. 2001; Lithourgidis et al. 2011; Siddique et al. 2008). However, it is also possible that the greater access and assimilation of plant-available soil N by individual cereal plants in intercrops occurs because the intraspecific root competition between neighbouring cereals for N in a pure cereal crop is greater than interspecific competition between the cereal and legume roots in an intercrop mix (Table 4) (Jensen et al. 2020; Ladha et al. 2022; Peoples et al. 2009a; Xiao et al. 2018). Reports of higher %Ndfa of intercropped legumes than when grown in pure stands (Bedoussac et al. 2015; Corre-Hellou et al. 2006; Giller et al. 2000; Hauggaard-Nielsen et al. 2001; Jensen et al. 2015; Li et al. 2009; Li et al. 2024; Rerkasem et al. 1988) are also consistent with cereals scavenging more soil mineral N (and fertiliser N) than the legume intercrop (Chalk 1998; Jensen et al. 2020; Herridge et al. 1995; Peoples et al. 1995c). Therefore, the improved N yields under intercropping are most likely derived from a greater access to, and uptake of, soil and fertiliser N by the cereal, and an enhanced BNF by the legume than achieved by either of the corresponding sole crops.

Legumes in major cereal producing countries and their N dynamics

The world's five most important grain legume producing countries (India, Brazil, USA, Argentina and China; Tables S4 and S5) are also major cereal producers. Consequently, it should not be surprising that pulse and oilseed legumes grown by the 15 countries responsible for most of the global wheat and maize also represented 72% of the total area of grain legumes (181 Mha), 84% of the annual grain harvested (416 Tg) and 89% of the total N_2 fixed globally (32.2 Tg fixed N: 7.1 Tg fixed N by pulses and 29.0 Tg fixed N by legume oilseeds; Tables 5, 6, S7 and S8). However, the average rates of total BNF calculated across all grain legumes varied greatly between individual countries and ranged from as little as 55 kg fixed N/ha in Pakistan to as much as 308 kg N fixed N/ha in Brazil (Table 6). This was related to differences in the mix of legume crops grown, their productivity, and relative reliance upon N_2 fixation for growth (Tables 5, 6, S7 and S8) (Herridge et al. 2022; Peoples et al. 2021).

Each tonne of legume grain contains between 30 and 65 kg N depending upon the species (Ludemann et al. 2024; Palmero et al. 2022; Salvagiotti et al. 2008; Sayaz et al. 2004). Out of the total 45.3 Tg N accumulated by grain legumes in the major wheat and

Table 5 Comparisons of estimates of the total annual amounts of N derived from biological N_2 fixation (BNF), the net inputs of fixed N and amounts of legume N remaining after grain harvest in above-ground vegetative residues and nodulated roots of pulses and oilseed legumes grown in major wheat and maize producing countries during 2018–2022. Countries are ranked in order of declining combined areas of wheat and maize production

Country	Total BNF over the growing season[a] (Tg fixed N)		Net inputs of fixed N after grain harvest[b] (Tg fixed N)		Legume residual N after grain harvest[c] (Tg residual N)	
	All Pulses	Both Oilseeds	All Pulses	Both Oilseeds	All Pulses	Both Oilseeds
China	0.34	2.33	0.17	0.55	0.34	2.02
USA	0.14	7.00	0.05	0.46	0.18	4.93
India	2.50	1.93	1.68	0.78	3.11	2.00
Russian Federation	0.26	0.29	0.12	–0.01	0.27	0.37
Brazil	0.13	12.33	0.03	2.65	0.25	5.37
Argentina	0.05	3.12	0.02	0.36	0.08	2.36
Ukraine	0.04	0.18	0.01	–0.03	0.02	0.21
Australia	0.22	< 0.01	0.12	< 0.01	0.27	< 0.01
Canada	0.41	0.42	0.19	0.04	0.46	0.31
Pakistan	0.07	0.01	0.05	0.01	0.10	0.01
Mexico	0.08	0.03	0.04	0.01	0.14	0.03
France	0.06	0.02	0.02	< 0.01	0.06	0.02
Indonesia	0.01	0.08	0.01	0.03	0.02	0.08
Germany	0.04	< 0.01	0.02	–0.01	0.03	< 0.01
South Africa	< 0.01	0.12	< 0.01	0.03	< 0.01	0.11
15-country total	4.35	27.86	2.53	4.87	5.33	17.82
World	7.14	29.01	3.91	6.38	8.70	21.68

[a]Total BNF values for individual grain legume species were calculated from data presented in Table S7 and represent the sum of numbers provided in Table S8. Values have been adjusted to include estimates of BNF associated with the nodulated roots (Herridge et al. 2022; Khan et al. 2003; Unkovich et al. 2010; Wichern et al. 2008)

[b]Net inputs of fixed N = (Total BNF) – (Grain N removed). Values are the sum of data presented in Table S9

[c]Residual legume N = (Total crop N) – (Grain N removed). Values are the sum of data presented in Table S9

Table 6 Comparisons of total amounts of N derived from biological N_2 fixation (BNF), net inputs of BNF and amounts of residual legume N remaining after grain harvest by all legume crops grown in major wheat and maize producing countries to the N offtake in wheat and maize grain, and the amounts of N fertiliser applied. Legume data for each country are presented as estimates determined for the total area of grain legumes 'at the time of grain harvest', and as a revised likely returns of N for only 'legume residues in rotation with wheat and maize' during 2018–2022. Values in parentheses represent legume N data re-calculated as kg N/ha

Country	Total estimates all grain legumes at the time of grain harvest[a]				Revised estimates for legumes grown in rotation with wheat & maize[b]			Wheat & maize[a]	
	Legume area (Mha)	**Total BNF** (Tg fixed N)	**Net input of BNF** (Tg fixed N)	**Residual legume N** (Tg N)	**Legume area** (Mha)	**Net input of BNF** (Tg fixed N)	**Residual legume N** (Tg N)	**Grain N offtake** (Tg N)	**Fertiliser-N supply** (Tg N)
China	16.31	2.67 (164)	0.72 (45)	2.36 (145)	14.68[c]	0.50 (34)	1.70 (116)	6.95	13.05
USA	35.69	7.14 (200)	0.51 (14)	5.11 (143)	35.69	0.51 (14)	5.11 (143)	6.73	6.42
India	50.44	4.43 (88)	2.46 (49)	5.11 (101)	45.40[c]	1.51 (33)	3.23 (71)	2.60	4.39
Russia	5.10	0.55 (106)	0.11 (22)	0.64 (128)	5.10	0.11 (22)	0.65 (128)	1.88	1.24
Brazil	40.47	12.46 (308)	2.68 (66)	5.62 (139)	39.47	2.61 (66)	5.48 (139)	1.70	1.39
Argentina	17.48	3.17 (182)	0.38 (22)	2.44 (140)	17.48	0.38 (22)	2.44 (140)	1.28	0.80
Ukraine	1.85	0.22 (118)	−0.02 (−4)	0.23 (41)	1.85	−0.02 (−4)	0.23 (41)	1.07	1.20
Australia	2.25	0.22 (100)	0.12 (53)	0.27 (120)	1.60[c]	0.08 (52)	0.19 (118)	0.49	0.45
Canada	5.64	0.83 (145)	0.23 (40)	0.77 (137)	5.64	0.23 (40)	0.77 (137)	0.85	1.02
Pakistan	1.35	0.08 (55)	0.06 (41)	0.11 (77)	1.22[c]	0.04 (33)	0.05 (41)	0.65	1.60
Mexico	1.87	0.11 (64)	0.05 (23)	0.17 (88)	1.87	0.05 (23)	0.17 (88)	0.50	0.92
France	0.51	0.08 (137)	0.02 (33)	0.08 (137)	0.51	0.02 (33)	0.07 (137)	0.92	0.97
Indonesia	0.81	0.09 (111)	0.04 (47)	0.10 (136)	0.73[c]	0.03 (41)	0.07 (96)	0.34	0.45
Germany	0.22	0.04 (181)	0.01 (68)	0.03 (182)	0.22	0.01 (68)	0.04 (182)	0.50	0.48
South Africa	0.91	0.12 (140)	0.03 (33)	0.11 (121)	0.91	0.03 (32)	0.11 (116)	0.26	0.31
15-country total	180.9	32.21	7.40	23.15	172.37	6.09	20.31	26.72	34.69

[a]Derived from data presented in Tables 5, S2, S3, S7–S9

[b]The revised estimates of likely returns net inputs of fixed N and residual legume N in each country were based on the estimated proportion of the grain legume area grown in wheat- and maize-cropping systems. Values also took into consideration whether it was common farmer practice to either retain residues in the field, remove legume stubble to feed animals and for other purposes, or graze stubble with livestock as outlined in the text

[c]Countries where grain legume area was modified

maize producing countries, 23.1 Tg N was estimated to be removed at harvest (Table S8). Estimates of BNF were greater than the amounts of grain N harvested for all legume crops except soybean in Europe (Tables 5 and S9) which derives a lower proportion of N for growth from N_2 fixation (%Ndfa of 44% on average based on data collated from Austria, France, Germany, Greece, Poland, Romania and Switzerland, n = 52) compared to soybean grown elsewhere in the world (61–78%; Peoples et al. 2021).

The net inputs of fixed N play a key role in determining the rate of depletion of the soil N reserves over time and affect the organic N fertility of cropping soils (Anglade et al. 2015; Angus and Peoples 2012; Palmero et al. 2022; Peoples and Craswell 1992; Vanluawe et al. 2019). However, it is likely that the amount of N remaining in legume residues at the end of a growing-season will be a more important source of N contributing to soil mineral N status and the rotational benefits for following crops (Peoples et al. 2017; Vanlauwe et al. 2019). The N removed in grain represented around half of the total amount of N accumulated by pulses and oilseed legume crops (Table S8). The estimated amounts of N remaining in the above-ground legume vegetative residues and nodulated roots at the time of grain harvest in the 15 main wheat and maize producing countries corresponded to 23.2 Tg N (Tables 6 and S9).

We do not wish to imply that comparisons of the area of grain legumes against the combined areas of wheat and maize for each country presented in Fig. 8 provide a quantitative guide to the extent of grain legume-wheat or grain legume-maize rotations, but they do represent a useful benchmark to assess the maximum extent to which legumes currently contribute to cereal productivity. Review of the values presented in Fig. 8 indicated that < 10% of the wheat and maize produced in some countries could be in rotation with legumes, while in other countries, potentially the entire wheat and maize crop could be grown after a grain legume. This is considered in more detail below for each of the major cereal-producing countries.

Asia: During 2018–2022, either India or China, or both, featured in the top three countries for all pulse crops except common bean and cowpea (Table S4). Furthermore, India and China were also the top two producing countries for groundnut (Table S5), and the fifth and fourth largest producers of soybean (FAOSTAT 2025; Herridge et al. 2022). Consequently, large areas of grain legumes were grown in both India (50.4 Mha), and China (16.3 Mha; Fig. 8, Table S7). The importance of legumes as a source of protein in the largely vegetarian Indian diet was particularly evident in India's production data for pulses (24.8 Tg grain/year, ~27% of global pulse harvest) and groundnut (9.3 Tg grain/year, 18% of global harvest) (Tables S4-S6). Not surprisingly, substantial amounts of BNF by pulses (2.5 Tg fixed N/year) and soybean and groundnut (1.93 Tg fixed N/year) were calculated to occur in India and predominantly by faba bean (0.13 Tg fixed N/year) and oilseed legumes (2.33 Tg fixed N/year) in China (Tables 5, 6 and S8). Net inputs of BNF at the time of grain harvest represented 2.46 Tg fixed N/year in India (equivalent to 49 kg fixed N/ha) and 0.72 Tg fixed N/year in China (45 kg fixed N/ha), with 5.11 and 2.36 Tg N/year; respectively remaining in post-harvest residues (101 and 145 kg N/ha; Tables 7 and S9). By contrast, pulses and oilseed legumes were relatively minor crops in both Pakistan and Indonesia annually producing only 0.7 and 1.3 Tg legume grain from 1.3 and 0.8 Mha (Fig. 8, Table S7). Consequently, total BNF in Pakistan (predominantly from pulses) and Indonesia (largely by groundnut) represented < 0.1 Tg fixed N/year (equivalent to 55 and 111 kg fixed N/ha, respectively; Tables 5, 6 and S8). This resulted in low estimated annual net inputs of fixed N (0.06 and 0.04 Tg fixed N) and returns of residual legume N (0.1 and 0.11 Tg N/year). Although, when expressed on a per ha basis, the values calculated for Pakistan and Indonesia (41 and 47 kg fixed N/ha, 77 and 136 kg residual N/ha; respectively) were not too dissimilar to levels achieved in either India

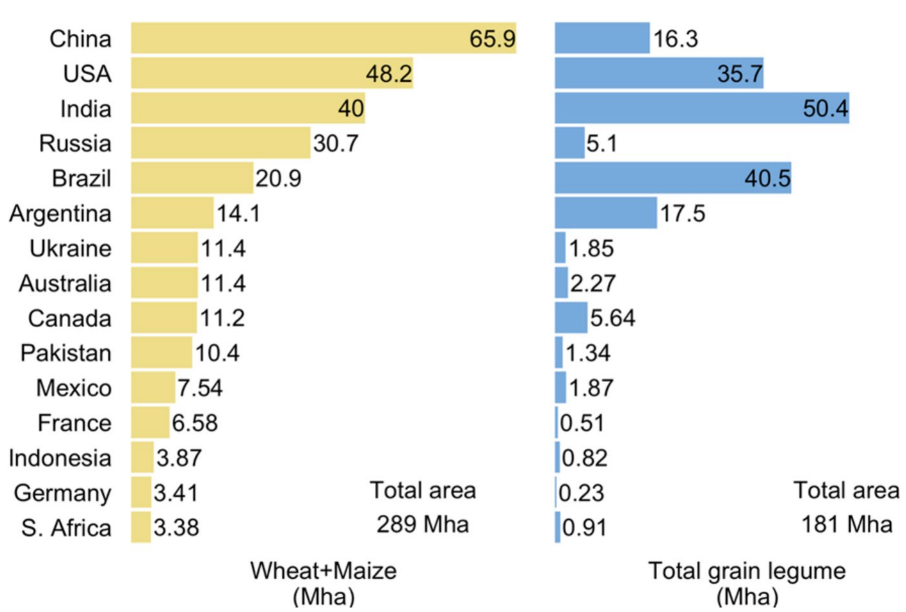

Fig. 8 Comparisons of the areas of cereals and grain legume harvested in 15 major wheat and maize producing countries. Countries are ranked in order of declining combined areas of wheat and maize production (FAOSTAT 2025; further details provided in Tables S2, S3 and S7)

Table 7 Estimates of net inputs of biological N_2 fixation (BNF) and the amounts of residual legume N remaining after grain harvest expressed as a percentage of either the N offtake in wheat and maize grain or the amounts of N fertiliser applied by 15 major wheat and maize producing countries during 2018–2022.[a]

Country	Net inputs of BNF by legumes grown in rotation with wheat & maize		Residual N of legumes grown in rotation with wheat & maize	
	Cereal grain N (%)	N Fertiliser (%)	Cereal grain N(%)	N Fertiliser (%)
China	7	4	24	14
USA	8	8	76	88
India	58	34	124	81
Russia	6	9	35	58
Brazil	154	188	322	434
Argentina	30	48	191	336
Ukraine	0	0	21	21
Australia	16	18	39	46
Canada	27	23	91	83
Pakistan	6	3	8	3
Mexico	10	5	34	20
France	2	2	8	8
Indonesia	9	7	21	17
Germany	2	2	8	9
South Africa	12	10	42	39

[a]Calculated from data presented in Tables 6

or China (49 and 41 kg fixed N/ha, 101 and 145 kg residual N/ha; Tables 6 and S9).

In addition to growing large quantities of wheat and maize, all four Asian countries are also major rice producers (FAOSTAT 2025). While short-duration crops such as green gram or black gram may be planted between two rice crops in parts of Asia (Hobbs and Osmanzai 2011; Singh et al. 2009; Thwe et al. 2019), around 90% of grain legumes in China, India, Pakistan and Indonesia tend to be grown in rainfed (upland) areas in closer association with wheat and/or maize, rather than in rotation with lowland (flooded) rice (Ladha et al. 2022; Yao et al. 2025; Zhang et al. 2025; Zhao et al. 2022).

Grain legumes are often cultivated during the winter (Rabi) season in India, and theoretically all the wheat and maize (combined area 40 Mha) grown in the following monsoon (Kharif) season (Ladha et al. 2022; Singh et al. 2009), could be grown after a legume even if only 90% of the total grain legume area (45.4 Mha) was considered (Fig. 8, Table S7). The situation in China, Pakistan and Indonesia was starkly different to India since the areas of wheat and maize dwarfed that of grain legumes and the major areas of cereal production did not necessarily always closely overlap that of legumes (USDA 2025), so that < 20% of these cereals might follow a preceding legume crop in the other three Asian countries (Fig. 8, Table S7).

The agricultural systems of Asia are dominated by smallholder farms of < 2 ha in area (Valbuena et al. 2012; Zou and Mishra 2024). Intercropping is a common feature on many smallholder farms in Asia (e.g. maize is frequently intercropped with faba bean in the southern provinces of China or soybean in South Asia, while wheat is often intercropped with pulses in South Asia; Hobbs and Osmanzai 2011; Maskey et al. 2001; Pala et al. 1994) which would assist the productivity of the accompanying cereal. But how much wheat or maize grown in rotation with legumes benefited from the net returns of BNF and residue N would depend on how legume stubbles were managed post-harvest. In smallholder mixed crop–livestock systems, the protein-rich vegetative remains of groundnut and pulses are critical sources of livestock feed, especially in low production environments, and farmers generally prioritise the removal of legume stubble and haulms (stalks, stems) after grain harvest for animal fodder, fuel, or sale to other farmers (Aslam et al. 2003; Herridge et al. 2019; Hobbs and Osmanzai 2011; Shah et al. 2003; Valbuena et al. 2012). On-farm data from Pakistan suggest that the return of up to 50 kg fixed N/ha in vegetative residue can be foregone in such situations, and only the N associated with, or derived from, the nodulated roots remain (Aslam et al. 2003; Peoples et al. 2002; Shah et al. 2003). Assuming the below-ground allocation of N in many grain legumes represents around 30% of the total crop N accumulated prior to grain harvest (Herridge et al. 2022; Khan et al. 2003; Unkovich et al. 2010; Wichern et al. 2008), this below-ground pool could represent on average about 60% of the potential residual N remaining post-harvest. However, on larger-scale farming enterprises where livestock are not prevalent, or where conservation agriculture is promoted with incentives, residue retention will be more common. For example, on farms greater than a few hectares in the North China Plain and

North-eastern China soybean residues are usually pulverised at harvest and either left on the ground or incorporated into the soil using machinery (Li et al., pers. comm.).

In recognition of the profound variations in Asian cropping systems, the net inputs of fixed N and residual N determined at the time of grain harvest for China, India, Pakistan and Indonesia shown in Table 6 have been adjusted to ascertain a more 'likely' discounted returns of BNF and legume N for the prospective benefit of following wheat or maize. These calculations have assumed that only 90% of grain legumes were grown in wheat and maize production systems, that all the N left after soybean harvest was generally retained, but because of the common farmer practice of removing legume stubble, just 60% of the residual N from groundnut and pulses presented in Tables 5 and S9 remained. As a result, the net inputs of BNF were reduced to 33–34 kg fixed N/ha in India, China and Pakistan, and 41 kg fixed N/ha in Indonesia. The derived estimates of the likely returns of residual legume N in wheat and maize cropping systems in India (3.23 Tg N, 71 kg N/ha) were not too dissimilar from the combined amounts of N calculated to be removed in the annual Indian wheat and maize grain harvest (2.60 Tg N/year, 65 kg N/ha), but residual legume N in China (1.70 Tg N/year), Pakistan (0.05 Tg N/year), and Indonesia (0.07 Tg N/year) was considerably lower than the N harvested in cereal grain (6.95, 0.65 and 0.34 Tg N/year; respectively; Tables 6, S2 and S3; FAOSTAT 2025). In all four countries the returns of legume N were much smaller than fertiliser-N currently applied to wheat and maize (Fig. 2, Table 6).

Europe: The areas of legumes grown in Europe have been variable and strongly influenced by policy interventions (Kuhlman et al. 2017; Magrini et al. 2016; Mahmood et al. 2018; Watson et al. 2017). Areas of grain legumes increased between 1980 and 1992, due to the awareness of protein dependency of Europe on the USA which had banned soybean export in 1973. Yet a subsequent shift in the Common Agricultural Policy in 1992 resulted in a decline in legume area (Magrini et al. 2016; Mahmood et al. 2018). While both forage and grain legumes play relatively minor role in European agriculture (Figs. 4–7 and Table S7), areas have increased slightly since 2013 due to the greening and eco-schemes within the common agricultural policy and other factors (Voisin et al. 2014; Watson et al. 2017; Zander et al. 2016). Nonetheless, major wheat producers such as the Ukraine and France still only grew 20–30% of the area of field pea they did two to three decades ago (FAOSTAT 2025).

Pure forage legume stands represent < 5% of the total forage area (Julier et al. 2017) and grain legumes are grown on average across < 2% of the total arable land, although there are marked differences between individual European countries (Kuhlman et al. 2017; Mahmood et al. 2018; Watson et al. 2017). For example, only 1–2% of cropping sequences, representing 1% or less of the arable land in Germany, Denmark and the Netherlands contained grain legumes, whereas 13–17% of cropping sequences involved grain legumes on 5–7% of arable land in Italy and Lithuania (Kuhlman et al. 2017; Stoddard 2017; Watson et al. 2017). However, significantly larger areas of pulses, legume forages and cover-crops are grown on European organic farms than suggested by these national statistics which are dominated by conventional systems (Barbieri et al. 2017; Yan et al. 2025).

European farming is dominated by cereals and collectively Europe contributes 34% and 11% of the annual global grain production for wheat and maize; respectively (Fig. 1). Europe produces around 11% of the annual global pulse production (Fig. 4a) which is dominated by field pea (40% of total European pulse production) and faba bean (30%; Fig. 5). Soybean is climatically adapted across Europe from the Mediterranean to the Baltic Sea due to progress in breeding and changes in climate; areas sown to soybean have increased in Europe in recent years (Guilpart et al. 2022; Nendel et al. 2023). Production of minor crops such as chickpea and lentil are increasing as adaption options to climate change and in response to expanding markets as more European consumers adopt diets based on plant-based sources of protein. Currently the areas of grain legumes grown in the four European countries producing the most wheat and maize grain represent the equivalent of only 7–8% (France and Germany) or 16–17% (Russian Federation and Ukraine) of the areas sown to wheat and maize (Fig. 8).

Grain legumes are usually grown after cereals and are then followed by cereals (commonly winter wheat) or, to a lesser extent, canola (oilseed rape, rapeseed; *Brassica napus* subsp. napus L.) to take advantage of the positive pre-crop effects (Preissel et al. 2015; Reckling et al. 2020). The N fertilisation of cereals following grain legumes can be reduced on average by 23–31 kg N/ha (Preissel et al. 2015), and grain yields of unfertilised cereal crops can be up to 2.7 t/ha higher (+1.35 t/ha on average) than where the preceding crop had been a non-legume (Table 3). When grain legumes are followed by spring-sown cereals such as oats, cover-crops are generally grown after early harvested field pea to mitigate the risk of N losses (Plaza-Bonilla et al. 2015). Maize tends only to be grown after late harvested legume crops such as soybean or a cover-crop. Field pea and faba bean are the most adapted grain legumes grown across Europe and are used as either spring or autumn sown crops (Jensen et al. 2010). In parts of Southern and Eastern Europe, soybeans are grown in relatively short rotations with maize and/or sunflower (*Helianthus annuus* L.), often under irrigation (Notz et al. 2023).

There is usually a period of several years between growing legume crops, although this period can be much longer if the fungal disease Aphanomyces root rot, caused by *Aphanomyces euteiches* Drechsier, occurs. This pathogen, which can develop in wet/saturated soils, can lead to substantial yield losses in field peas, lentil and other legumes, and field pea can no longer be grown on some French farms because dormant Aphanomyces oospores can survive in soil for over ten years (Moussart et al. 2008; Pfender and Hagedorn 1983). Because of the cross infectivity of some root-infecting diseases across different legume species it is generally recommended that legume crops should be grown only once every four to six years to avoid the build-up of other soil-borne root and stem rot diseases such as *Fusarium*, *Pythium*, *Phoma*, or *Sclerotinia*, (Jensen et al. 2010; Monti et al. 1994).

Forage legumes in arable systems (excluding permanent grassland) are either grown as sole crops (mainly lucerne) or in mixtures with grasses (red clover or white clover). These can be established in either spring, summer or autumn after seedbed preparation or be undersown in cereals. The latter is a well-established practice in organic farming. Forage legumes are usually grown for 2–4 years, and the residual N is generally much greater than achieved by grain legumes. The timing of the termination of the forage ley is crucial in determining N availability to the following crops. Cereals with a high market-value are commonly the first crops grown after a forage ley. In long-term experiments in Sweden, perennial grass-clover mixtures have been demonstrated to increase soil organic C and to improve grain productivity and the yield stability of following cereals compared to a system without forage leys (Bergkvist and Båth 2015; Persson et al. 2008; Reckling et al. 2022).

Legume cover-crops are used on European farms before spring sown cereals to increase soil organic C, provide ground cover and to control weeds. However, cover-crop effects on cereals can be variable and appear to be influenced by the farming system in which they are used (Table S6). For example, Wittwer et al. (2017) demonstrated that grain yields following cover-crops were highest in organic systems with reduced tillage (+24%), intermediate in organic systems with tillage (+13%) and conventional systems with no tillage (+8%), and lowest in conventional systems with tillage (+2%). The uncertainty in crop response after cover-crops may explain in part why farmers using cover-cropping practices may not always reduce N fertilisation rates.

Despite the total areas of grain legumes being relatively small, the total amounts of N_2 fixed across the four largest European wheat and maize producing countries were large when expressed on a per ha basis (106–181 kg fixed N/ha; Table 6). But the patterns of BNF were somewhat different. Nitrogen fixation by pulses dominated in France and Germany, contributions of BNF by pulses and soybean were similar in the Russian Federation, but BNF by pulses was dwarfed by soybean in Ukraine due to the small areas of pulses grown (0.34 Mha) compared to soybean (1.51 Mha; Tables 5 and S7). When net inputs of BNF were calculated, Ukraine was the only country with a calculated negative net balance because of the presumed low N_2 fixation (Peoples et al. 2021) and the large amounts of N removed in soybean grain (Tables 5, 6 and S8). The calculated return of legume residual N in Ukraine (41 kg N/ha) was also considerably lower than the other three countries on a per ha basis (128–182 kg N/ha; Table 6). However, the amounts of legume residual N returned to cropping soils were much smaller (0.04–0.65 Tg N/year) than either cereal grain N offtake (0.50–1.88 TgN/year) or the amounts of fertiliser-N applied to wheat and maize in each country (0.48–1.24 TgN/year; Table 6).

Americas: North American grain legume production during 2018–2022 was dominated by the USA (35.69 Mha), with a smaller area in Canada (5.64

Mha; Fig. 8 and Table S7). Close to 95% (33.8 Mha) of the total legume cropping area in the USA was occupied by soybean, with groundnut (0.59 Mha), common bean (0.52 Mha), and field pea (0.37 Mha) being the other main crops (Table S7). In the case of Canada, soybean represented 40% of the total legume area (2.21 Mha) and pulses the remaining 60% (principally lentil on 1.62 Mha and field pea with 1.54 Mha; Table S7). Trends in N_2 fixation by these various legume crops mirrored the relative areas grown, so that almost all the fixed N was derived from soybean (6.87 of a total 7.14 Tg fixed N/year) in the USA, with soybean (0.42 Tg fixed N/year) and pulses (0.40 Tg fixed N/year) being close to half each in Canada (Tables 5, 6 and S8).

The most common rotation system in North America is soybean-maize on around 80% of the 'Corn Belt' in the Mid-West region of the USA which produces about two-thirds of the US maize, and much of the Canadian soybean and maize production areas of southern Ontario (FAOSTAT 2025; Fischer et al. 2014; Ladha et al. 2022; USDA 2025). However, on US dairy farms and in southern Canada, maize may also be grown in longer-term rotations with lucerne or other perennial forage species (Russelle et al. 2007; Sulc and Tracy 2007).

Legumes do not feature as prominently in wheat production as in maize systems in the USA (Maaz et al. 2018), especially for winter wheat grown on the central Great Plains (spanning Texas, Oklahoma, Kansas, Nebraska, Colorado and Montana) which represents one of the largest regions of wheat monoculture in the world (Fischer et al. 2014; Massigoge et al. 2024). By contrast the most common cropping systems for wheat or malt barley in the main wheat production areas of Alberta, Saskatchewan and Manitoba on the Canadian Northern Great Plains consist of two-year rotations of either canola-cereal or pulse-cereal involving lentil, field pea, or chickpea (Ladha et al. 2022; Strydhorst and Liu 2023; USDA 2025; Wang et al. 2025). This has been a direct outcome of declining areas of summer fallowing, an increased use of summer annual crops, and the adoption of reduced tillage and stubble retention practices by Canadian farmers (Awada et al. 2014).

Only a small area of Mexico in Central America is used for legumes with common bean being the most widely grown crop (Fig. 8 and Table S7). However, the poor N_2 fixation capacity by common bean (Palmero et al. 2022; Peoples et al. 2009a, 2021) meant it contributed just half the country's BNF (0.06 Tg fixed N/year), despite being grown on 80% of the area (1.5 of a total 1.87 Mha; Tables 5, 6 and S8). Mexican farming systems are very different and more complex than its northern neighbours. Maize plays an integral role in Mexican cuisine and is cultivated under diverse agro-climatic and socio-economic conditions, which results in heterogeneous production systems. These include small-scale traditional, low yielding (1–2 t grain/ha) 'milpa' intercropping mixtures in the rainfed areas of central and southern regions involving native maize landraces planted in conjunction with squash (*Cucurbita* spp.) and either common bean, runner bean, faba bean, or field pea depending upon the district (Sosa-Cabrera and González-Amaro 2022). But there are also areas of large-scale, high-yielding (up to 9–10 t grain/ha) irrigated hybrid maize in the north (Juárez-Hernández et al. 2019). There are two maize planting seasons, summer (about 70% of production, around 90% of which is rainfed) and winter (30% of the crop, 60% of which is irrigated; USDA 2025). The small areas of wheat (0.6 Mha; FAOSTAT 2025) are primarily concentrated in the north-western states of Mexico and rely heavily on irrigation and N fertiliser to achieve grain yields of 5.7 t/ha (FAOSTAT 2025; Fischer et al. 2014).

It is difficult to confirm the fate of legume residues across all the different cereal production systems used in North and Central America, but since conservation tillage and stubble retention practices are now used on over 44 Mha of the cropland in the USA and close to 22 Mha in Canada, and are reported to be increasingly common in Mexico (Classen et al. 2018; Kassam et al. 2022; Martínez-Cruz et al. 2019), the calculations in Table 6 have assumed that for the most part all legume residues remain in the field in all three countries. Accordingly, the annual net inputs of fixed N into cropping soils represented 0.51 Tg fixed N for the USA, 0.23 Tg fixed N for Canada, and 0.05 Tg fixed N for Mexico (Table 6). The much lower rates of net inputs of fixed N in the USA (14 kg fixed N/ha) compared to Canada (40 kg fixed N/ha) or Mexico (23 kg fixed N/ha) was a result of the large areas of soybean grown in the USA and the high rates of N removal in soybean grain relative to the dependence of North American soybean on BNF (Tables S7 and S8) (Palmero et al. 2022; Peoples et al. 2021;

Salvagiotti et al. 2008). The calculated returns of residual legume N in the USA (5.11 Tg N/year, 143 kg N/ha) and Canada (0.77 Tg N/year, 137 kg N/ha; Table 6) were approaching the annual amounts of fertiliser-N consumed in cereal cropping each year and the rates applied to maize in the USA (5.24 Tg N/year, 158 kg N/ha; Table S3) and wheat in the case of Canada (0.83 Tg N/year, 85 kg N/ha; Table S2). But was somewhat lower than total fertiliser-N use when the fertiliser also applied to wheat in the USA (1.18 Tg N/year, 78 kg N/ha) and maize in Canada (0.19 Tg N/year, 129 kg N/ha) were considered (Tables 6 and S2; IFA 2022). Residual legume N in Mexico (0.17 Tg N/year, 88 kg N/ha) was also less than the combined amounts of N supplied by fertiliser to support both maize (0.86 Tg N/year, 123 kg N/ha), and wheat production (0.06 Tg N/year, 113 kg N/ha; Tables 6 and S3; IFA 2022).

Notable features of South American agriculture have been the widespread adoption of conservation agriculture and stubble retention (now covering almost 70% of cropland; Kassam et al. 2022) and the rapid expansion in maize and soybean cropping resulting in a doubling in the areas planted to both crops in Brazil and Argentina since the year 2000 (FAOSTAT 2025). The average increase in areas sown to soybean during the five years 2018–2022 of 1.53 Mha each year meant that Brazil has now overtaken the USA to become the world's largest soybean producer (Tables S5 and S7; FAOSTAT 2025). Soybean was grown on 94% (37.6 Mha) of the area planted to grain legumes in Brazil during 2018–2022 and was responsible for 96% of the total BNF (12.29 Tg fixed N/year), with common bean (2.6 Mha and 0.13 Tg fixed N/year) and groundnut (0.18 Mha and 0.04 Tg fixed N/year) being the very distant second and third most important legume crops (Tables 5, 6, S7 and S8). Since the total area of all grain legumes (40.5 Mha) was twice the combined area of maize (18.4 Mha) and wheat (2.5 Mha; FAOSTAT 2025), it is possible that legumes always preceded both cereal crops (Fig. 8, Tables S3 and S7).

There are two maize cropping periods in Brazil. The first maize crop (one-quarter of Brazil's total production) is sown between October to the end of December and is often intercropped with common bean, while > 90% of the second maize crop (three-quarters of total production) is planted after soybean in January–February in the central-south region of Brazil, primarily in the State of Mato Grosso which produces 47% of Brazil's maize and 28% of the soybean (Ladha et al. 2022; USDA 2025). Soybean is also an important rotational crop for wheat in the southern Brazilian States of Paraná and Rio Grande do Sul that produce 24% of Brazil's soybean, and 83% of the wheat (Ladha et al. 2022; USDA 2025). Since no-tillage practices are now used across 43 Mha in Brazil, it was assumed all stubble in the main soybean and cereal production areas would generally be retained in the field after harvest (Fuentes-Llanillo et al. 2021; Kassam et al. 2022).

The derived estimates of the likely returns of BNF and residual N for following maize or wheat crops presented in Table 6 have been adjusted to account for the major soybean growing areas in the Mato Grosso where soybean is double-cropped to cotton (*Gossypium hirsutum* L.) (i.e. cotton sown immediately after soybean in the same calendar year) in addition to being grown prior to maize (Hampf et al. 2020). Based on crop rotation data obtained from commercial cotton farms the calculations have assumed soybean was grown before two-thirds of the total 1.5 Mha sown to cotton during 2018–2002 (dos Santos et al. 2020; FAOSTAT 2025; USDA 2025). This resulted in only a small reduction in the estimates of the net contributions of BNF from 2.68 to 2.61 Tg fixed N/year (equivalent to 66 kg fixed N/ha; Tables 6, S3 and S7) because of the large total areas of soybean and the high reliance of Brazilian soybean upon BNF for growth (78%; Peoples et al. 2021). Estimates of legume residual N also changed slightly from 5.62 to 5.48 Tg N/year (139 kg N/ha; Tables 6 and S7). These amounts of legume N returned to cropping soils greatly exceeded both the annual amount of fertiliser-N used and the average rates of applied to maize (1.25 Tg N/year, 68 kg N/ha) or wheat (0.14 Tg N/year, 55 kg N/ha) as well as the N removed in maize and wheat grain (1.55 Tg N/year, 85 kg N/ha and 0.14 Tg N/year, 57 kg N/ha; respectively; Fig. 2, Tables 6 and S2; FAOSTAT 2025; IFA 2022).

In Argentina, crop rotations are dominated by soybean, maize and winter cereals, the latter representing 28% of total 28 Mha of arable land cropped each year (de Abelleyra et al. 2024; FAOSTAT 2025). Soil types and weather conditions in some areas under agriculture in Argentina are suitable for double-cropping (especially in the Pampean region), but the sowing and harvest of a single grain crop per year is the most widespread system. Wheat (6.3 Mha, 2018–2022; FAOSTAT 2025) and other cool-season cereals were planted on more than 95% of the winter cropping area, with only very small areas of field peas, chickpeas and lentils (0.21 Mha; Table S7). By contrast, grain legumes occupied about 60% of the total area devoted to summer crops, > 90% of which was soybean (16.4 Mha) with groundnut and common beans representing the balance (0.88 Mha; Table S7). Much of the remaining 40% of the summer cropping area was allocated to maize (7.8 Mha; Table S3) or other warm-season cereals. In some regions maize may be grown as a double-crop after cool-season pulses, but elsewhere maize was usually sown after a long winter-bare fallow period following the previous summer growing-season's soybean crop (Biassoni et al. 2024).

A 2018 farming survey (INDEC 2021) indicated that pastures occupied around 7.5 Mha of which 25% were identified as being legume-based (mainly lucerne and annual clovers, melilotus, or hairy vetch). Measures of BNF in pure legume swards in Argentina indicate 100–200 kg N/ha could be fixed each year (Enrico et al. 2020; Racca et al. 2001), but there is little quantitative data to indicate what proportion of these pastures might be in rotation with cereals. Winter cover-crops were reported to be used on 1.2 Mha, the most important of which included oats, rye, and hairy vetch. Hairy vetch tends to be planted primarily before maize and its net N contribution to maize has been estimated to represent in the order of 30–40 kg N/ha (Biassoni et al. 2024).

Comparisons of the total areas sown to grain legumes (17.5 Mha) or wheat and maize (14.1 Mha) in Argentina indicated that potentially both cereals could follow a preceding legume crop (Fig. 8). Total BNF by grain legumes was calculated as 3.17 Tg fixed N/year (182 kg N/ha; Table 6). Since all grain legume residues tend to remain in the field for the benefit of following crops (Biassoni et al. 2024), the estimated net contributions of 0.38 Tg fixed N/year (22 kg fixed N/ha) and 2.44 Tg residual legume N/year (140 kg N/ha; Table 6) represented valuable inputs to cereal cropping soils. This might explain the relatively modest 0.38 Tg fertiliser-N/year supplied to maize (49 kg N/ha) and 0.42 Tg N/year applied to wheat in Argentina (66 kg N/ha) (Enrico et al. 2020) compared to the rates of N fertiliser utilised in other of the major cereal producing countries (Fig. 2, Tables S2 and S3; IFA 2022). However, some have argued that N fertiliser rates for maize and wheat could be too low and may be contributing to on-farm yield gaps (Aramburu Merlos et al. 2015; Correndo et al. 2021).

Oceania: Maize has always been a very minor irrigated crop in Australia grown on < 0.10 Mha (FAOSTAT 2025). By contrast, wheat is Australia's largest grain crop and was grown on 10–13 Mha (11.31 Mha average) of the 22–24 Mha of the land used annually for grain cropping during 2018–2022 (Fig. 8 and Table S2; ABARE 2024). During this same period Australia was one of the three largest global producers of chickpea (from 0.26–1.1 Mha, 0.57 Mha average), lentil (0.42–0.58 Mha, 0.46 Mha) and lupin (0.48–0.66 Mha, 0.57 Mha) with the total area planted to grain legumes ranging from 1.6–2.6 Mha (2.25 Mha average; Fig. 8, Tables S4 and S7; FAOSTAT 2025).

In Australia, it is also necessary to consider the potential rotational contributions from forage legumes in addition to grain legumes (Angus and Grace 2017; Angus and Peoples 2012; Fillery 2001). Despite a long-term trend of declining areas of pasture nationally, pasture remains a common feature of most grain production areas (Bell et al. 2019; Kirkegaard et al. 2011; Umbers 2021). Around 50% of Australia's grain farms are described as mixed-farming enterprises involving both grain and livestock production (11,600 farms designated as 'cereal-sheep' or 'cereal-beef cattle' operations of a total 22,700 wheat producers; ABARE 2024; Bell et al. 2019). The basis of mixed-farming relies on alternating phases of pastures grown in rotation with grain crops (often described as 'ley-farming') (Bell et al. 2019; Kirkegaard et al. 2011; Peoples et al. 2012; Swan et al. 2014). Based on Australian farm production statistics (ABARE 2024) and past national surveys of pasture type and distribution (Donald 2012; Pearson et al. 1997) it has been estimated that 30.5 Mha of the 46.6 Mha managed ('improved') pastures were legume-based of which 7.6 Mha (25%) may be returned to cropping with 1.9 Mha of cropped area being re-sown to pasture each year (Angus and Grace 2017; Herridge 2022). It is difficult to compare areas of forage legumes to wheat such as those presented for grain legumes in Fig. 8. Wheat is grown on these mixed-farms on diverse soil types (from high clay content soils with high water holding capacities, to shallow soils with major sub-soil physicochemical constraints to root growth, and deep sandy soils with low water holding capacity) and a range of contrasting agro-climatic regions (sub-tropical, summer-dominant rainfall environments, temperate uniform precipitation patterns, and winter-dominant rainfall Mediterranean-type climatic zones) receiving anywhere between 250 and 700 mm long-term average annual rainfall (Barton et al. 2022; Bell et al. 2019; Harries et al. 2015; Kirkegaard et al. 2011; Maaz et al. 2018). This results in considerable regional variation in:

(i) The proportion of grain-only farms and mixed-farms (Bell et al. 2019; Umbers 2021),
(ii) On-farm botanical composition of pastures (i.e. % of total foliage DM derived from legumes vs grasses and forbes) (Angus and Peoples 2012; Hackney et al. 2019; Swan et al. 2014) and the effect this has on BNF and potential rotational benefits (Bowman et al. 2004; Harris et al. 2006; Peoples et al. 1998, 2004, 2012),
(iii) Duration of the pasture phase (1–5 years) (Angus and Peoples 2012; Bell et al. 2019; Hunt et al. 2021),
(iv) Percentage of farmland utilised for cropping each year (43–69%) (Harries et al. 2015; Hunt et al. 2021; Umbers 2021), and
(v) The length of the cropping phase before returning to pasture (Bell et al. 2019; Hunt et al. 2021; Umbers 2021).

Each of these factors can also be influenced by fluctuations in commodity prices and the relative value of grain and livestock products, all of which greatly complicates any computations and general conclusions (Angus and Peoples 2012; Bell et al. 2019; Kirkegaard et al. 2011).

Nonetheless, it is still possible to obtain a high-level comparison of the relative roles BNF by either forage or grain legumes play in the annual N-balance of Australian mixed farms and cereal-based cropping systems. Inputs of BNF by Australian legume-based pastures have been estimated to be 3.0–3.2 Tg fixed N/year, but potentially only 25% of this amount (0.75–0.8 Tg N/year) might be fixed in the year immediately prior to the resumption of a cropping phase (Angus and Grace 2017; Herridge 2022). This compares to total BNF by all pulses grown in Australia of 0.22 Tg fixed N/year (100 kg fixed N/ha; Table 6). Based on estimates of the amounts of N harvested in grain and the total (above-ground + below-ground) N accumulated by the various mix of legume crops grown in Australia presented in Table S8, 30% of the crop N was removed in grain and 70% remained in residues or incorporated into soil pools after grain harvest. This was somewhat different than the 50:50 global average but reflects the large contribution of chickpea to the Australian dataset, which typically allocates a much higher proportion of total plant N to nodules and roots than most other grain legumes (Herridge et al. 2022; Khan et al. 2003; Unkovich et al. 2010). The net input of BNF at grain harvest was estimated to be 0.12 Tg fixed N/year (53 kg fixed N/ha) with 0.27 Tg residual legume N/year (120 kg N/ha; Tables 3, 5, 6, S8 and S9).

To ascertain a more realistic estimate of the likely contributions of grain legumes to wheat within the context of Australian farming systems, it is also necessary to consider other important grain crops grown in the Australian grain-belt such as (ranked in declining area harvested in 2022) canola (4.4 Mha), barley (3.8 Mha), oats (0.8 Mha), and sorghum (0.7 Mha; ABARE 2024). Of these crops, canola would be the most probable alternative to wheat to be sown immediately after a grain legume (Hunt et al. 2021; Jensen et al. 2010; Umbers 2021). Given the relative areas of wheat and canola, it has been assumed for the calculations that 30% (0.65 Mha) of the grain legumes may have preceded canola and 70% (1.6 Mha) occurred before wheat. Stubble tends to be retained intact until sowing the next crop on around 60% of the Australian grain-production area, but on mixed-farms post-harvest residues can be grazed by livestock (Hunt et al. 2016; Thomas et al. 2020; Umbers 2021). While the prevalence of grazing of crop stubble varies across grain-producing regions, national surveys of farmers suggest up to 15% of the crop area could be grazed (Umbers 2021). This usually occurs in the higher rainfall areas with the large-seeded crops such faba bean and lupin which tend to have heavier stubble loads than other pulses. In these situations, sheep are introduced to the field primarily to utilise any legume grain lost during the harvesting process and to lightly graze the stubble (Thomas et al. 2020).

To undertake a full assessment of the likely net returns of BNF and residual N prior to wheat, it was necessary to estimate how much of the legume stubble N remaining on 15% (0.24 Mha) of the presumed 1.6 Mha grown before wheat that was consumed, excreted and subsequently lost from the soil:plant system as outlined in Table S10. The amounts of N calculated to be lost from grazed legume stubble were very small (0.0003 Tg fixed N/ha, equivalent to 1.5 kg fixed N/grazed ha, and 0.0008 Tg above-ground residue N/year, or 3.3 kg N/grazed ha; Table S10) and represented < 0.5% reduction in the derived estimates of the net inputs of fixed N and grain legume residue N (Tables 6). The final values represented 0.084 Tg fixed N/year (52 kg N/ha) and 0.189 Tg residue N/year (118 kg N/ha) by grain legumes were less than the annual applications of fertiliser-N (0.44 Tg N/year, 39 kg N/ha) to the Australian wheat crop (Fig. 2, Tables 6 and S2). However, this does not include contributions of BNF and organic N by legume-based pastures to wheat grown in mixed-farming systems (Angus and Peoples 2012; Angus and Grace 2017; Fillery 2001; Herridge 2022).

Africa: Across most of the African sub-tropics/tropics, smallholder mixed crop-livestock systems contribute to the livelihood of over half of the population and are responsible for producing much of the staple food and animal products (Valbuena et al 2012). The (sub)-tropical climates that prevail over much of the African continent preclude large-scale production of rain-fed wheat, which is confined largely to North Africa and the highlands of Ethiopia. Ethiopia produces by far the most wheat of any country in Africa (6 Tg grain/year from 2.1 Mha; Tadesse et al. 2022), much of it in rotation with the cool-season legumes; chickpea, faba bean, field pea and lentil. The spike in prices and disruption of trade caused by the Ukraine war led to a major push for wheat self-sufficiency by the Ethiopian government (Sida et al. 2025). The benefits of legume rotations on boosting wheat production have been demonstrated under experimental conditions (Table S6), but free-ranging livestock graze legume stubble during the long dry winter, meaning that little above-ground residues remain.

Maize is the major staple cereal across much of Africa, accounting for 19–35% of total land area cultivated for agriculture in central, eastern and southern Africa (Acevedo-Siaca and Goldsmith 2020), but few countries are self-sufficient (van Ittersum et al. 2025). Poor and declining soil fertility, the lack of widespread fertiliser use, and erratic rainfall frequently constrain maize yields (Kermah et al. 2017; Sanchez 2002; Vanlauwe et al. 2019), and production has increased in pace with population growth largely due to an expansion of the area of cropland (Giller et al. 2021). Many regions of sub-Saharan Africa plant continuous maize during both the short and long rainy seasons (Acevedo-Siaca and Goldsmith 2020). However, grain legumes are used by smallholder farmers in some areas as intercrops or relay-crops in maize systems to mitigate the risk of complete crop failure of monocrops (Kermah et al. 2017, 2019), and Vanlauwe et al. (2019) has estimated that between 15–18% of the land may be cropped with grain legumes across sub-Saharan Africa (excluding South Africa). The lack of reliable crop statistics makes it difficult to accurately estimate the contributions of legumes to the N economy of smallholder farming systems, but there is undoubtedly great potential to increase the area under legumes.

The situation is somewhat different in South Africa, which is the only African country which qualifies for the 'league tables' in terms of production volumes. Smallholder farming is still important for the food security of millions, but around 30,000 large-scale commercial farms were responsible for generating the bulk (> 90%) of the South Africa's agricultural production (Mathinya et al. 2022).

Wheat is a relatively minor crop in South Africa (2 Tg grain/year from 0.53 Mha), with 50% of the production occurring in the Mediterranean, winter-cropping region of the Western Cape (FAOSTAT 2025; USDA 2025). Conservation agricultural practices are widespread in this area (Strauss et al. 2021). Wheat is mostly rotated with canola as there are no major legume cash-crops in the farming system. Some farmers grow annual medics or a mix of species that include a legume as cover-crops and forage, but the areas are small (Matthews et al. 2025).

Maize is the main crop of South Africa in terms of area cultivated and production (14. 8 Tg grain/year from 2.85 Mha, representing > 25% of the total agricultural area), grown in the summer cropping region in the eastern half of the country (Table S3; Acevedo-Siaca and Goldsmith 2020). Over 80% of the annual maize production is rainfed (USDA 2025). Local adapted soybean varieties, farmers learning to grow the crop, and expansion of processing capacity resulted in a large increase in yield and areas of soybean grown from < 0.2 Mha in 2008 to > 1 Mha in 2023 in the same cropping region as maize (FAOSTAT 2025; USDA 2025). This has drastically changed maize-based systems. Previously, farmers struggled to grow a profitable crop other than maize, but now maize often follows soybean with two-thirds or more of both soybean and maize grain production occurring in the Free State and Mpumalanga Provinces. While conservation agriculture is now used on 1.6 Mha of South African cropland (Kassam et al. 2022), this is adopted in only small pockets of the summer cropping area. Nonetheless, farmers in this region generally plough less, and leave more residues in the field, than in the past to curb wind and water erosion. While farmers with large cropping areas tend to specialise in crops, many others do have ruminant livestock. Possibly 75% of soybean fields (equivalent to 0.59 Mha during 2018–2022; Table S7) might be grazed by cattle and/or sheep after harvest in the dry winter. To ensure the soil is not left bare and vulnerable, animals are usually managed so that they eat no more than about half the crop stubble.

A comparison of the areas grown to wheat and maize with that of all grain legumes suggest that over 25% of either of these two cereals could be grown after legumes (Fig. 8). Re-calculations of cropping ratios based solely on the areas of soybean and maize comes to the same conclusion. Legume crops grown in maize-based systems in addition to soybean would include common bean (0.05 Mha), groundnut (0.04 Mha) and cowpea (0.01 Mha; Table S7). However, in terms of area and BNF the contributions by these three crops were small (< 0.01 Tg fixed N/year) compared to the 0.79 Mha of soybean (0.12 Tg fixed N/year, 152 kg N/ha; Table S8). The only other legume of note is lucerne, a valuable cash-crop harvested for hay under irrigation, but it occupies only a small fraction of the total arable land in South Africa.

Across all legume crops grown in South Africa, the net inputs of fixed N were determined at the time of grain harvest represented 0.03 Tg fixed N/year (equivalent to 33 kg fixed N/ha) with 0.11 Tg N/year in legume residues (Tables 5, 6, S7–S9). To determine likely returns of BNF and residual N, the consumption, excretion and loss of urinary N from the 0.59 Mha where soybean stubble was grazed needed to be considered (Table S10). The amounts of stubble N estimated to be lost from urine patches during grazing were calculated to be equivalent to 0.001 Tg fixed N/year (1.7 kg fixed N/ha) and 0.004 Tg N/year (6.4 kg N/ha grazed; Table S10) and resulted in the reduction of the net inputs of fixed N and legume residue N by just 4% (Table 6). The final derived estimate of residual legume N (0.11 Tg N/year, 116 kg N/ha) which would primarily be returned to maize-based cropping systems, was lower than the amount of N removed in maize grain (0.24 Tg N/year) or the fertiliser-N supplied (0.29 Tg N/year), but comparable to rates of N removed in grain (82 kg N/ha) and the average rates of N fertiliser applied on a per ha basis (100 kg N/ha; Fig. 2, Table S3).

Discussion

The analyses of legume N-dynamics undertaken here for each of the 15 major wheat and maize producing countries have focused primarily on BNF and residual organic N by grain legumes. This is because legume cropping is presently the only form of legume land use where the detailed quantitative data on the area and productivity for individual pulses and oilseed legumes are available on a country-by-country basis in FAOSTAT (2025) that are necessary to undertake the required calculations. From this perspective, any conclusions drawn from Tables 6 and 7 comparing the returns of legume N to applications of fertiliser-N will represent conservative assessments of the relative value of inputs of legume N for wheat and maize production.

That said, there were a few overarching observations. Firstly, estimates of BNF by grain legumes were found to be greater than the amounts of N removed in harvested legume grain in all 15 countries except the Ukraine (Table 6). In other words, assuming no major post-harvest losses of N, grain legumes generally added to, rather than depleted, the N reserves of cereal cropping soils. The other main observation was that Brazil was the only country where net inputs of fixed N exceeded cereal grain N offtake and fertiliser-N supply, although the amount of residual legume N remaining after grain legumes either approached or surpassed cereal N demand in USA, India, Brazil, Argentina and Canada (Tables 6 and 7). Across the other ten countries, there were substantial shortfalls in the estimated annual amounts of legume residue N, especially in Pakistan, France and Germany where returns of legume N to cereal cropping soils represented < 10% the N harvested in wheat and maize grain N or applied as fertiliser (Table 7).

Given that the 15 countries producing the bulk of the world's wheat and maize grain also consume over 80% of the total N fertiliser applied to those two crops (Tables S2 and S3), the frequency of legumes in cereal-based cropping systems will need to increase in all the major cereal producing countries except Brazil and Argentina before legumes can make any meaningful global impact in reducing applications of fertiliser-N in future cereals systems (Figs. 2 and 8, Tables 6 and 7). The size of this challenge is illustrated in the data in Table 8 which shows the degree to which the areas of grain legumes would need to be expanded to redress the present imbalance between legume and fertiliser sources of N to meet cereal N demand. These values have been derived from calculations of the shortfalls in the amounts of legume N returned to cereal cropping soils by assuming the increased legume areas consisted of the identical mix of legume crops currently grown in each country using the similar agronomic and stubble management practices as present, with the same rates of residual legume N return depicted in Table 6. The additional residual legume N achieved from a 10–32% increase in legume areas grown in India, USA and Canada was calculated to be sufficient to match current cereal N offtake and/or fertiliser-N supply, and possibly a doubling of the area of grain legumes might be necessary in the Russian Federation and Australia (Table 8). This conceivably could be achieved through fallow replacement, intercropping or the substitution of legumes in the place of minor small grain crops. However, in the case of the three to seven-fold increase in

Table 8 Estimates of how much the area of legumes would need to be expanded in the future for returns of residual legume N to match current wheat and maize grain N demand or the amounts of N fertiliser applied by the 15 major wheat and maize producing countries. The additional legume area values are expressed in terms of Mha and as a percentage of the average areas grown in each country during the five-year period 2018–2022.[a]

Country	Cereal grain N offtake			N Fertiliser supply		
	Current shortfall[b]	Additional legume area required[c]		Current shortfall[b]	Additional legume area required[c]	
	(Tg N)	(Mha)	(% increase)	(Tg N)	(Mha)	(% increase)
China	5.25	45.2	**277%**	11.35	97.8	**600%**
USA	1.62	11.3	**32%**	1.31	9.2	**26%**
India	nil	-	-	1.16	16.3	**32%**
Russian Federation	1.23	9.6	**188%**	0.59	4.6	**90%**
Brazil	nil	-	-	nil	-	-
Argentina	nil	-	-	nil	-	-
Ukraine	0.84	20.5	**1107%**	0.97	23.7	**1279%**
Australia	0.30[d]	2.5	**113%**	0.26[d]	2.2	**98%**
Canada	0.08	0.6	**10%**	0.25	1.8	**32%**
Pakistan	0.60	14.6	**1084%**	1.55	37.8	**2800%**
Mexico	0.33	3.7	**200%**	0.75	8.5	**456%**
France	0.85	6.2	**1217%**	0.90	6.6	**1288%**
Indonesia	0.27	2.8	**347%**	0.38	4.0	**490%**
Germany	0.46	2.5	**1149%**	0.44	2.4	**1099%**
South Africa	0.15	1.3	**142%**	0.20	1.7	**189%**

[a]Calculated from data presented in Table 6

[b]**Shortfall in N = (Grain N offtake - Residual legume N) or (Fertiliser-N supply - Residual legume N)**

[c]Increased legume areas were calculated from the shortfall in N and the country-specific legume residue N kg N/ha values shown in Table 6 assuming a similar mix of legume species currently grown under the same agronomic and stubble management practices. A 'nil-value' indicates that legume residual N exceeded grain N demand or fertiliser-N supply

[d]Australian values represent overestimates as the contributions of residual N from forage legumes in mixed-farming systems have not been included in the calculations. It is likely that N remaining after legume-based pastures would be more than sufficient to meet the N short-fall following grain legumes.

grain legume area needed in South Africa, Indonesia, Mexico and China, and the 12 to almost 30-fold greater area of legumes required in France, Germany, Ukraine or Pakistan (Table 8) any meaningful attempt to redress the current imbalance would entail a reduction in cereal area.

Conclusions

Our review of literature confirmed that in the absence of supplementary N fertiliser, wheat and maize grain yields, biomass, and N uptake are all higher in the first cereal grown following legumes compared to where the preceding crop had been a non-legume, irrespective of the legume's end use, geographic region or climate (Table 3). Improvements in productivity and crop N-dynamics were also observed in the second cereal crop, albeit smaller than demonstrated in the first cereal, and there was evidence that legume rotational effects can persist into the third cereal cropping year after legume-based forage systems (Tables 3 and S6) (Evans et al. 2003; Reckling et al. 2022; Ta and Faris 1990). However, integration of legumes into cereal cropping systems will need to be substantially increased in most countries before such benefits can be exploited to reduce the dependence of cereal production on synthetic N. To achieve this, it will be necessary to reverse the policy and trade-related decisions and shifts in consumer dietary preferences responsible for the long-term stagnation or decline in the global areas of some pulse species (Fig. S1), and the decreased use of grain and forage legumes in Europe and elsewhere in the world (Jensen et al. 2010; Kuhlman et al. 2017; Magrini et al. 2016; Mahmood et al. 2018; Peoples et al. 2019; Siddique et al. 2012; Voisin et al. 2014; Watson et al. 2017). It is equally important to understand the changes in commodity prices/market-driven opportunities and the genetic improvements that contributed to the global expansion in areas of oilseed legumes (Fig. S1) and large increases in areas of pulses grown in Australia (lentil and chickpea) and Canada (lentil and field pea) between the 1990s and early 2020s (FAOSTAT 2025; Maaz et al. 2018).

Economic disincentives such as year-to-year variability in grain yield and prices, restricted market access, and lack of adequate policy support are frequently identified as factors that hinder legume adoption (Maaz et al. 2018; Magrini et al. 2016; Preissel et al. 2015; Zander et al. 2016). This is despite evidence that cropping systems that include legumes can provide greater financial stability and improve profit from a multiple-year and whole farm perspective (Mahmood et al. 2018; Massigoge et al. 2024; Miller et al. 2015; Notz et al. 2023; Peoples et al. 1995c; Swan et al. 2023; Tzemi et la. 2025; Zentner et al. 2001). Better access to market information, effective value chain integration, and supportive policies will be important before more farmers can be persuaded to grow more legumes.

Farmers often report that they are reluctant to adopt legumes as they perceive them as risky crops because of sensitivity to abiotic stresses, poor competitive ability with weeds, and susceptibility to diseases and insect pests which all place constraints on productivity (Table 9) (Johansen et al. 1994; Mahmood et al. 2018; Peoples et al. 2009a; Siddique et al. 2012; Swan et al. 2023; Stoddard 2017). Weeds, pathogens and insect pests not only limit the frequency with which legumes can be used within a rotation (Jensen et al. 2010; Monti et al. 1994) but can also contribute to the dis-adoption of legumes if production risk becomes too great and the management costs prohibitive (Harries et al. 2015; Maaz et al. 2018; Seymour et al. 2012; Wery and Ahlawat 2008).

In the short- to medium-term it will be necessary to identify what agricultural practices need to be adapted and expanded to alleviate or reduce the risks (and costs) of legume production and lower interannual variability in legume yield (e.g. intercropping: Bedoussac et al. 2015; Raseduzzaman and Jensen 2017), with the aim of optimising the rotational benefits (Gan et al. 2016; Maaz et al. 2018; Pala et al. 1994; Solh et al. 1994). But in the longer-term increased breeding efforts will be required to accelerate genetic progress in generating better yielding cultivars that are more competitive with weeds, have high capacity for BNF, and greater resistance to disease attack and insect predation (Herridge and Danso 1995; Nboyine et al. 2024; Ojiewo et al. 2019). In addition, global changes in climate also need to be considered. Increasing temperatures, more frequent extreme events (heat shock and frost) and increased rainfall variability can all exacerbate environmental restraints to legume cultivation. Thus, to ensure the future success of legume-cereal rotations, breeding efforts need to include the development of legume

Table 9 Various abiotic and biotic factors that have been identified as important constraints to the productivity of legumes and the inputs of BNF in farmers' fields.[a]

Region & Country	Legume system	Primary factors identified
South Asia		
Pakistan	Cool-season crops	Rainfall, nutrition, weeds
	Warm-season crops	Fertiliser N, no inoculation, insect pests, disease
Nepal	Cool-season crops	Rainfall, nutrition, disease, weeds, plant density
	Warm-season crops	Total soil N, available P, weeds
South-East Asia		
Thailand	Warm-season crops	Planting time, rainfall, available P, weeds
Vietnam	Warm-season crops	Soil pH, available P, plant density
West Asia		
Syria	Cool-season crops	Rainfall, nutrition, insect pests, disease
Europe		
Denmark	Cool-season crops	Waterlogging, weeds
France	Cool-season crops	Soil conditions at sowing, frost, disease, weeds, insects, lodging
	Warm-season crops	High temperatures, drought, weeds
Germany	Cool-season crops	Rainfall, nutrition, disease, insect pests, weeds, nodulation
	Warm-season crops	Rainfall & temperature, nutrition, weeds, nodulation, irrigation
	Forage systems	% Legume in forage mixtures, cutting frequency
Oceania		
Australia	Cool-season crops	Rainfall, fallow length, soil pH, no inoculation, cropping history, weeds
	Warm-season crops	Tillage, fallow length, water availability, cropping history, disease
	Pasture	Soil pH & nutrient constraints, % legume, grazing management
Africa		
South Africa	Warm-season crops	Nutrition, water availability, inoculation, cropping history, weeds
Zimbabwe	Warm-season crops	Nutrition, insects, poor seed quality, plant density

[a]After Corre-Hellou and Crozat (2005), Giller et al. (2000), Goward et al. (2016), Hackney et al. 2019; Maskey et al. (2001), Omari et al. (2025), Peoples and Herridge (2000), Peoples et al. (1995b, 2002, 2009a), Reckling et al. (2020), Schwenke et al. (1998), Voisin et al. (2014)

varieties with climate-resilient traits such as improved tolerance to temperature extremes and greater water use efficiency (Siddique et al. 2012; Vadez et al. 2012). The evaluation of underexploited minor legume crops and forages for possible further domestication to provide alternatives to the major legume species now being grown could be an additional complementary strategy (Chongtham et al. 2021; Giller and Cadisch 1995; Peoples et al. 2014, 2019; Sprent and James 2009).

The deployment of any new elite varieties or the introduction of legume species to new areas will need to be accompanied by the development of agronomic management practices specific to the new germplasm to achieve the desired increased yield potential in farmers' fields. It will also be important to expand the options available to facilitate integration of legumes into farming systems. Strategies to overcome the logistical obstacles that currently prevents intercropping and relay cropping from becoming more widely adopted need to be developed (Fletcher et al. 2016; Lamichhane et al. 2023), along with the identification of suitable environments and management practices for legumes to either replace fallow or for legume-based pastures and livestock to be reconnected with cereal cropping (Abdalla et al. 2019; de Faccio Carvalho et al. 2021; Gan et al. 2016; Garba et al. 2022; Holman et al. 2018; Lemaire et al. 2015; Pala et al. 1994).

Expanding the areas of legumes and the frequency with which they are used in a cropping sequence are only part of the solution. For example, in India where areas of grain legumes already greatly exceed those of cereals, the prospects to further increase areas of legume cropping may be limited (Fig. 8). Yet the growth and grain yields of pulses in India and elsewhere in the world are poor and BNF is well below potential (Tables 6 and S7) (Ojiewo et al. 2019; Peoples et al. 2019). Existing knowledge and improved crop agronomy could be used to address current on-farm yield gaps to raise the level of pulse productivity (Table 9) (Crews and Peoples 2004; Giller and Cadisch 1995; Peoples et al. 2002; Schut and van Ittersum 2025; Siddique et al. 2012). This should in turn increase BNF (Anglade et al. 2015; Espinoza et al. 2012; Maskey et al. 2001; Palmero et al. 2022; Unkovich et al. 2010) and enhance both the amounts of residual legume N and the rotational benefits for following cereals (Seymour et al. 2012; Vanlauwe et al. 2019). While improvements in soil mineral N, cereal N uptake and yield can still occur when the preceding legume's vegetative residues are removed or grazed (Table S6) (Aslam et al. 2003; Evans et al 2003; Giller et al. 2000), greater benefits are also likely to accrue if these residues can be retained (Giller and Cadisch 1995; Shah et al. 2003).

Before such changes in farming practices can be achieved a better understanding is required of the social and economic framework within which farmers operate in different wheat and maize producing countries, and the complexity of the decision-making involved in prioritising the allocation of land and resources across multiple crops and enterprises within a systems context (Keatinge et al. 1994; Kirkegaard et al. 2011; Mathinya et al. 2022; Peoples et al. 2019; Wery and Ahlawat 2008). Farmer engagement will be critical to identify the main barriers to the uptake of improved legume varieties or adoption of better agronomic practices (Giller et al. 2000; Maaz et al. 2018; Mahmood et al. 2018; Siddique et al. 2012), and in the co-development of practical, scalable solutions to current production constraints (Table 9) in conjunction with researchers and extension agencies (Akpo et al. 2021; Keatinge et al. 1994; Pala et al. 1994; Schut and van Ittersum 2025). To successfully foster sustainable, legume-integrated cereal systems, such initiatives will need the support of stakeholders such as small and medium enterprises (SMEs), food manufacturers, non-government organisations (NGOs), policymakers, and consumers to develop a viable value chain for legume products (Kuhlman et al. 2017; Mahmood et al. 2018; Peoples et al. 2019; van Berkum and de Steenhuijsen Piters 2025).

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Data availability All datasets generated and analysed during the preparation of the manuscript are provided in the Supplementary Information.

Declarations

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