The Biology of Legumes and Their Agronomic, Economic, and Social Impact

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Abstract Intensive agriculture and meat-based westernized diets have brought a heavy environmental burden to the planet. Legumes, or pulses, are members of the large Fabaceae (*Leguminosae*) family, which comprise about 5% of all plant species. They are ancient crops whose popularity both for farmers and consumers has gone

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through several stages of acceptance, and in recent years, legumes have regained their luster. This is due to a global understanding that: (1) farming systems need to promote biodiversity, (2) biological nitrogen fixation is an important tool to reduce the application of external chemical inputs, namely in the form of nitrogen fertilizers, and that (3) plant-based foods have fewer adverse environmental effects per unit weight, per serving, per unit of energy, or per protein weight than do animal source foods, across various environmental indicators. Legumes play a key role in answering these three global challenges and are pivotal actors in the diversification and sustainable intensification of agriculture, particularly in light of new and urgent challenges such as climate change. In this chapter, we showcase the importance of legumes as contemporary agents of change, whose impacts start in the field, but then branch out into competitive global economies, modernized societies, and ultimately, improved food security and human health.

Keywords Biodiversity · Biological nitrogen fixation · Nutrition and health · Pulses · Sustainability

1 Introduction

The word legume comes from the Latin word *legumen* which can be translated to "seeds harvested in pods." In many parts of the world, such as in Canada, Bangladesh, or India, the world pulse is used when referring to legume grains, especially those with a low content in fat. Legumes or pulses have accompanied farmers since the Neolithic revolution, the very onset of farming practices of mankind. Pea (*Pisum sativum*), lentil (*Lens culinaris*), chickpea (*Cicer arietinum*), and bitter vetch (*Vicia ervilia*) belong to the "Big Eight," that package of "founder crops" which have been domesticated in the Fertile Crescent during the 10th and 9th millennia BCE (Asouti and Fuller 2013). Legumes were domesticated alongside grasses as early as 10,000 years ago (Hancock 2012). Among the earliest legume crops were chickpea, garden pea, and lentil (Sprent 2009; Hancock 2012; Smýkal et al. 2015). The domestication of other important legumes followed later on in different regions of the world, for example, soybean in east Asia (Sedivy et al. 2017), Azuki bean (*Vigna angularis*) in west Asia (Lee 2012), or common bean (*Phaseolus vulgaris*) in Mesoamerica (Lopez et al. 2013). The cultivation of soybean [*Glycine max* (L.) Merrill] dates from China in around 2500 BCE, being now spread throughout the world mostly due to its elevated protein content of the seeds that can reach almost 40%. Despite its particular worldwide importance, soybean is heavily reliant on inoculation to bring it into profitable use in non-native countries like Brazil (Alves et al. 2003).

It is thought that the introduction of legumes into cropping systems in Europe (before the tenth century) enabled an improvement in soil quality and provided nourishment to populations, relieving famine and improving overall population growth.

More than 820 million people have insufficient food and many more consume low-quality diets that cause micronutrient deficiencies. This has contributed to a substantial rise in the incidence of diet-related noncommunicable diseases. All legumes offer a high level of protein in above- and belowground biomass, particularly in grains, in comparison to other crops such as cereals. They are self-supporters of nitrogen fertilization through atmospheric nitrogen fixation in root nodules in symbiosis with soil bacteria from the families *Rhizobium*, *Bradyrhizobium,* and others. The genetic regulation of these processes has been intensively investigated and various forward- and reverse-genetic approaches have identified nearly 200 genes required for symbiotic nitrogen fixation in legumes (Roy et al. 2019).

In times with low availability of meat, pulses—legumes with predominant grain usage—provided a valuable source of proteins for the human diet. The biblical tale of Esau who sold his birthright to his younger brother Jacob for the price of a lentil stew illustrates the estimation of the pulses in early societies. In the past, meat was often unavailable to common people, i.e., for the majority of ancient societies. Pulses, therefore, were a sufficient alternative to meat for a healthy and whole food diet. The traditional Milpa cropping system, a combination of maize, beans, and squash, is a good example for the integration of legumes in sustainable cropping systems and in the whole food human diet (Altieri et al. 2011). It integrates physiological and morphological benefits of crops, including pulses, at the field, and offers a balanced food composition for human consumption with beans as the main provider of protein. The Milpa system originated from Mesoamerica and has spread to many tropical and subtropical regions across the world because of its benefits. Meanwhile, it can be considered a model for innovative cropping systems today and in the future.

In the middle of the twentieth century, pulses disappeared more and more from the menu in the industrial countries and as well from cropping systems at the same time. Pulses were considered to be an old-fashioned food, with nonnutritive compounds such as lectins, alkaloids, saponins, or phytates (Muzquiz et al. 2012), with lengthy time-consuming preparation methods and some causing intestinal irritations. Finally, meat was available to all social classes. There are additionally some agricultural challenges of legume growing: they have lower yields and lower economic value in comparison to cereals. For example, a farmer in temperate Europe (France, Germany, Poland) can achieve a yield of 4.8–7.6 t ha^{-1} winter wheat and only 2.7–3.5 t ha^{-1} dry pea (FAO Stat 2019).

Recently, there seems to be a return to the value of pulses. Concerns about ecological impacts of meat production, ethical concerns in terms of animal welfare, and considerations for human health (Chai et al. 2019; Hagmann et al. 2019) have promoted an interest in a more sustainable plant-based food production, with legumes as a substantial contributor. In times of public discussions about the loss of biodiversity, sustainable agriculture, and climate change, a renaissance of legumes in agricultural systems seems a reasonable and promising way to design the future of our planet.

2 The Biology of Legumes

2.1 Taxonomy and Morphology

The Earth currently has almost 400,000 species of plants. About 5% of plant species are members of the large plant family Fabaceae (*Leguminosae*) which produce their protein-rich seeds within simple dehiscent dry fruits botanically known as legumes (commonly known as pods). The Fabaceae family includes 770 genera and nearly 20,000 worldwide distributed species (LPWG 2017). The Fabaceae evolved to have root systems that enable symbiotic relationships with various species of soil bacteria that are capable of fixing atmospheric nitrogen, thereby providing a basic biological source of nitrogenous compounds such as proteins and their biochemical derivatives. Legume species are very diverse and are adapted to almost all terrestrial ecosystems in the form of trees, shrubs, vines, and annual herbs. Legume flowers characteristically have five petals that have evolved to a wide range of characteristic sizes, shapes, and colors. Legume species can be self-pollinating, cross-pollinating or both. The traditional classification of *Fabaceae* into the three subfamilies, *Caesalpinioideae*, *Mimosoideae*, and *Papilionoideae*, has been revised by The Legume Phylogeny Working Group (LPWG 2017) and Sprent et al. (2017). A new subfamily classification presented by LPWG (2017) divides the Leguminosae into six subfamilies: *Detarioideae* (84 genera; ca. 760 species; Pantropical), *Cercidoideae* (12 genera; ca. 335 species; Pantropical, *Cercis* warm temperate), *Duparquetioideae* (1 genus; 1 species; West and West-central Africa), *Dialioideae* (17 genera; ca. 85 species; Pantropical), *Caesalpinioideae* (148 genera; ca. 4400 species; Pantropical, some temperate), and *Papilionoideae* (503 genera; ca 14,000 species; cosmopolitan). The previous subfamily *Mimosoideae* has been incorporated into the Caesalpinioideae as the mimosoid clade. Species from *the Detarioideae, Cercidoideae, Duparquetioideae,* and *Dialioideae* are all non-nodulators. Nodulation has been confirmed in only eight genera in the *Caesalpinioideae* sensu stricto subfamily. Most, but not all mimosoids and papilionoids can nodulate (Sprent et al. 2017).

The *Caesalpinoideae* subfamily is highly variable, mostly trees and shrubs with zygomorphic asymmetrical flowers. The mimosoid clade are adapted to tropical and subtropical climates and exist mostly in the form of trees and shrubs. Their flowers are symmetric with valvate petals and have large numbers of prominent stamens. The *Papilionoideae* is the largest, most widely adapted and diverse legume subfamily. Their floral morphology (standard, wings, and keel petals) is demonstrated by that of the widely known species (bean, pea, and soybean) that have edible pods and seeds used in food systems as vegetables and dry seeds. The members of this ecologically diverse group include trees, shrubs, and herbs.

2.2 Nodulation

Legumes form symbiotic relationships with nitrogen-fixing bacteria (rhizobia), most of which belong to the genera *Rhizobium*, *Bradyrhizobium*, *Mesorhizobium*, *Ensifer* (Sinorhizobium), and *Azorhizobium* in the Alphaproteobacteria (Denison and Okano 2003; Tampakaki et al. 2017a, b; Ferguson et al. 2019) and in the genera *Paraburkholderia*, *Cupriavidus,* and *Trinickia* in the Betaproteobacteria (Gyaneshwar et al. 2011; Estrada-de los Santos et al. 2018). The infection of roots by rhizobia results in the formation on roots (and occasionally stems) of unique organs called nodules (Ferguson et al. 2013) in which the biological nitrogen fixation process takes place (Ferguson et al. 2019). In this process, the bacterial enzyme nitrogenase catalyzes the reduction of atmospheric N_2 to ammonia (Howard and Rees 1996), which is a plant-available N form.

The nodulation process in many, but not all, legumes follows root infection by efficient compatible rhizobia strains. The root infection causes the curling of the root hairs that entrap the rhizobia and then, after the formation of infection threads through these structures, the bacteria enter the root cells (Peleg-Grossman et al. 2007; Fournier et al. 2015). According to Oldroyd and Downie (2008), the induction of cortical cell divisions is necessary for the nodule's morphogenesis. The bacteria within the nodule cells are a differentiated symbiotic form of rhizobia called bacteroids. Each bacteroid is surrounded by the symbiosome (or peribacteroid) membrane (Denison and Okano 2003; Peleg-Grossman et al. 2007). In the initiation of the rhizobia-legume symbiosis, several compounds (e.g., Nod factors and flavonoids) are implicated. Nod factors are lipochitooligosaccharides secreted by rhizobia that are involved in the initiation of cell divisions in the cortex, which leads to root hair curling and the formation of infection threads (Ibáñez and Fabra 2011; Murray 2011). Flavonoids produced by legume roots activate NodD proteins and consequently the expression of the Nod genes that are implicated in the synthesis of Nod factors (del Cerro et al. 2017).

Taken together, this chemical cross-talk between the rhizobia and the host legume allows the latter to impose a degree of stringency on which bacteria can enter and form a symbiotic nodule, but as it is based on nod genes rather than *nif* genes, it cannot guarantee that the symbiosis will be effective, and hence compatible, but "cheating" rhizobia are considered to be a significant problem for nodulated legumes (Sprent et al. 2017).

Oxygen plays a significant role in nitrogen fixation because an adequate supply of oxygen in the nodules is needed by bacteroids for respiration (Denison and Okano 2003). See review by Minchin et al. (2008). It is also important to point out that the nitrogen fixation process is characterized by high energy (ATP) demands (Rutten and Poole 2019), because the reduction of 1 molecule of N_2 to ammonia utilizes at least 16 molecules of ATP (Maier 2004). These energy requirements are covered by the respiration of bacteroids (Miller et al. 1988), but sufficient transport of carbohydrates to the roots is needed to maintain sufficiently high respiration rates. Nevertheless, excessive oxygen concentrations can inactivate the nitrogenase (Denison and Okano 2003), and thus the protein leghaemoglobin (Lb) is also an important component of the nodules, as it acts as an oxygen carrier that facilitates a controlled flux of oxygen to the nitrogen-fixing bacteroids (Denison and Okano 2003). Furthermore, Lb protects nitrogenase from being inactivated by free oxygen, while the Lb-bound oxygen is accessible to bacteroids (Abdelmajid et al. 2008; Rutten and Poole 2019). The internal red-pink color of the nodules is due to the presence of leghaemoglobin (Rejili et al. 2012). Abdelmajid et al. (2008) linked higher nitrogen fixation capacity with a higher accumulation of leghaemoglobin in the nodules.

3 Agronomic Impact

3.1 Nitrogen Supply via Biological Nitrogen Fixation (BNF)

Over the past decades, the excessive application of inorganic nitrogen fertilizers has resulted in groundwater contamination with nitrates (Lv et al. 2019). Groundwater pollution via leaching of these pollutants (NO_3^-) is one of the most serious environmental problems and is positively related to high nitrogen fertilization rates (Vinod et al. 2015; Zheng et al. 2019). Thus, to reduce the groundwater pollution with nitrates, it is important to reduce the excess application of inorganic fertilizers in agricultural fields and/or to apply organic nitrogen sources such as compost or manure. The use of legumes as green manures or the inclusion of legumes in crop rotation systems is alternative to inorganic nitrogen fertilizers that can contribute to higher crop yields and improved soil quality (Castro et al. 2017; Ntatsi et al. 2018).

Biological N fixation by legumes (e.g., faba bean, lentil, pea, chickpea, alfalfa, red clover etc.) ranges from 21 to 389 kg ha^{-1} (Table 1) (Cazzato et al. 2012; Nimmo et al. 2013; Büchi et al. 2015; Hossain et al. 2016; Snapp et al. 2017; Akter et al. 2018; da Silva Júnior et al. 2018; Dhamala et al. 2018; Ntatsi et al. 2018; Pampana et al. 2018; Ntatsi et al. 2019).

The N_2-fixation capacity of legumes (e.g., the proportion of N derived from the atmosphere [%Ndfa] and biomass productivity) is mainly dependent on plant species, genotypes, symbiotic bacteria (e.g., *Rhizobium* spp.) strains, and environmental conditions (Büchi et al. 2015; Hossain et al. 2016; Akter et al. 2018; Ntatsi et al. 2018; Benjelloun et al. 2019; Ntatsi et al. 2019).

Despite the fact that legumes contribute to nitrogen enrichment of soil BNF, it is worth mentioning that their over-frequent use of these plant species can also lead to nitrate leaching (De Notaris et al. 2018; Hansen et al. 2019). Thus, it is important to optimize the use of legumes (e.g., appropriate crop rotation sequences, mixtures of legumes, and nonlegumes) in order to reduce the risk of nitrate leaching (Hansen et al. 2019; Rakotovololona et al. 2019).

Table 1 Biological nitrogen fixation (BNF) capacity (kg ha^{-1}) of commonly cultivated legumes

Common name	Scientific name	BNF (kg ha^{-1})	Cultivation area	References
Faba bean	*Vicia faba* L.	118.6–311	Greece, Italy	Ntatsi et al. (2018), Pampana et al. (2018)
Pea	*Pisum sativum* L.	36.6–125.3	Canada, Greece	Hossain et al. (2016), Ntatsi et al. (2019)
Common vetch	*Vicia sativa* L.	107–131	Switzerland	Büchi et al. (2015)
Grass pea	*Lathyrus sativus* L.	101–149	Switzerland	Büchi et al. (2015)
White lupin	*Lupinus albus* L.	53.1–64.1	Italy	Cazzato et al. (2012)
Chickpea	*Cicer arietinum* L.	21.0–103.6	Canada	Hossain et al. (2016)
Lentil	*Lens culinaris* Med.	23.0–86.8	Switzerland, Canada	Büchi et al. (2015), Hossain et al. (2016)
Common bean	*Phaseolus vulgaris* L.	16.3–71.9	Canada	Akter et al. (2018)
Cowpea	*Vigna unguiculata* (L.) Walp.	36–75	Brazil	da Silva Júnior et al. (2018)
Soybean	*Glycine max* (L.) Merr.	90–95	USA	Snapp et al. (2017)
Alfalfa	*Medicago sativa* L.	103–209	Canada, China	Nimmo et al. (2013)
Egyptian clover	*Trifolium alexandrinum* L.	35–59	Switzerland	Büchi et al. (2015)
Red clover	*Trifolium pretense* L.	35.4–389	Denmark, USA	Snapp et al. (2017), Dhamala et al. (2018)

3.2 *Pre-crop Benefits Through a Combination of Residual Nitrogen and Break-Crop Effects*

Legume cropping, including rotation, intercropping, green manure, and legume-enriched pastures, shows significant advantages over nonlegume systems in terms of fertilizer use and hence emissions of the greenhouse gases CO_2 and N_2O (Jensen and Hauggaard-Nielsen 2003). Grain and forage legumes, by virtue of their symbiosis with N_2-fixing bacteria, can reduce the need for N fertilizer application. If legume cropping becomes more widely adopted, this could reduce the demand for manufactured fertilizer (Jensen et al. 2012). In terms of soil N inputs from BNF, an approximate value of 9 kg N mineralized per ton of stubble may be possible for grain legume crops, with higher transfer values being recorded for forage legume systems—15 to 20 kg N per tonne (Peoples et al. 2004, 2009, 2017). Typical rates of BNF for grain and forage legumes are between 100 and 200 kg shoot N ha^{-1} per year or growing season (Peoples et al. 2019).

Reduced fertilizer usage associated with legume cropping is only suitable after the successful establishment of the root-nodule symbiosis, adequate levels of BNF, and appropriate crop management practices to maintain N_2 fixation. This may involve inoculation of plants with appropriate strains of rhizobia to improve nitrogen fixation, carrying a cost in terms of energy and GHG emissions, and careful monitoring of soil N. Liming of soils is important too in maintaining N_2 fixation, N_2 fixation having the potential to acidify unbuffered soils and hence inhibit nitrogenase activity. This acidifying activity has the potential also to mineralize inorganic phosphate and reduce the requirement for P fertilizer addition (Williams et al. 2017).

Skowronska and Filipek (2014), in their review of life cycle analysis studies on fertilizer manufacture, provide illustrative data on the extent of GHG savings possible through reduced fertilizer production. Depending on the type of N fertilizer, the combined GHG cost of production, packaging, and delivery ranges from 1.9 to 6.3 kg CO_2e (carbon dioxide equivalent) kg^{-1} fertilizer The GHG cost for P fertilizer is considerably less, 0.6–1.66 kg CO_2e kg^{-1} fertilizer, with manufacture of calcium carbonate for soil amendment accounting for 0.15 kg CO_2e kg^{-1} (Skowronska and Filipek (2014).

Calculation of the reduction in field GHG emissions possible with legume cropping is problematic given the wide variance in data available due to differing crops, soils, climate, management, and most significantly the type of measurement and the time course of measurements employed. Using values averaged across 67–71 site-years of data, Peoples et al. (2019) report an overall reduction in N_2O emissions for legume crops compared with N fertilized crops and pastures of approximately 59%, assuming N_2O emissions of 0.47 t CO_{2e} ha^{-1} for legume crops and 1.16 t CO_{2e} ha^{-1} for N fertilized crops and pastures.

3.3 Increased Crop Diversification and Biodiversity

Modern intensive agricultural systems are relatively simplified, focussing on a small number of crop species, often in monocultures, and reliant on mineral fertilizers and chemical crop protection to maximize their productivity. Heterogeneous crop systems, however, can show improved production efficiency, yield stability, and resilience to environmental stresses. Legume crops have great potential for optimizing these benefits, whether by increasing the diversity of crops within the crop rotation sequence or as components of crop species mixtures. The positive contribution of legumes to diversification arises directly from legume-specific traits and indirectly from their reduced reliance on agronomic inputs. This is underpinned primarily by the ability of legumes to fix atmospheric nitrogen into nitrogen-rich organic compounds—as well as their capacity to capitalize on generating a symbiotic- or facilitative-microbiome in the rhizosphere (Chen et al. 2019).

Nonlegume crops show up to 30% greater biomass production in a legume-supported rotation: the benefit of BNF is estimated to be maximal when grain and forage legume crops are present in half of the years of the crop sequence (Iannetta et al. 2016). Despite this, grain legume production in Europe is falling (Magrini et al. 2016) and is characterized by only a few legume crop species, which has constrained progress in legume crop improvement. There are ample opportunities to diversify the range of legume crops and take advantage of adaptive traits in of orphan legume species to improve, for example, their resilience to biotic and abiotic stresses (Cullis and Kunert 2017). By enhancing soil nutrient supply and function, legumes can promote nutrient acquisition by nonleguminous plants growing in a species mixture. Legume crops exhibit multiple traits that complement or facilitate the growth of nonlegume species, leading to more efficient use of resources. This allows greater productivity and profitability per unit land area to be achieved with intercropping compared with monocultures (Martin-Guay et al. 2018). Floral resource provision in legume-supported mixtures, along with increased canopy and root system heterogeneity, and reduced reliance on agronomic inputs, can promote the abundance and activity of beneficial organisms, which facilitate ecosystem services such as pollination, nutrient cycling, and suppression of pests, diseases, and weeds (Everwand et al. 2017).

4 Economic Impact

Understanding the economics of legume systems requires an analysis of the factors influencing the equilibrium between supply (farmers) and demand (consumers) and the interlinkages along the supply chain, while assessing the impact of any shocks to the system on other aspects such as trade and environment. As is the case of any other agricultural industry, but even more so due to their benefits to the public good (European Parliament 2013), changes to the equilibrium between the supply and demand of legumes translates into wider long-term effects, and as such, an analysis of legume production (e.g., assessment of farm profitability) is incomplete and potentially incorrect if not coordinated with an analysis of demand, and of the corresponding ripples on trade, environment, and health.

The economics of legumes in the European Union (EU) shows a production trend closely correlated to the different types of subsidies and payments linked to the Common Agricultural Policy (CAP) reforms, and the global market prices for fertilisers (Fig. 1). Linked to similar factors affecting livestock production, feed demand mirrors production trends for dry pulses (only starting in the 1980s in the case of beans). Imports mirror the demand for processing in the case of soybeans, and mirror the production trends for peas and, respectively, lentils, lupins and other pulses, while showing an opposite trend to the domestic production of beans (following the rise in the 1980s in its use for feed and food).

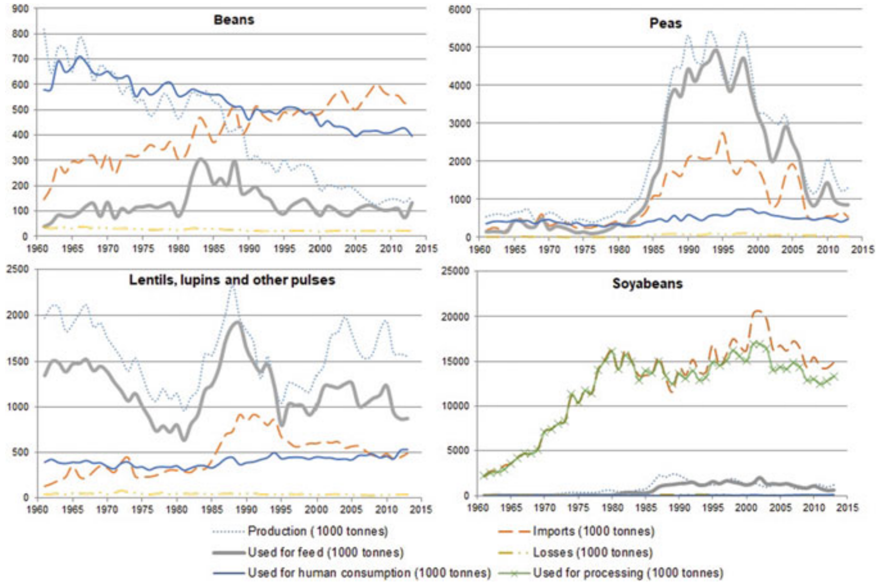

Fig. 1 Legumes production and imports, uses and losses in the European Union. *Source* Own creation based on FAOSTAT data (extracted November 2019)

The cultivation of dry pulses (i.e., grain legumes except soybeans) in EU countries is significantly more frequent in: regions with higher receipt of voluntary coupled CAP support to protein crops; regions with higher shares of organic farming; regions with a more important role of legume consumption in regional diets; regions with relatively deep soils and; regions displaying lower competition for land use with sunflower. Livestock density and share of irrigable agricultural areas are significantly negatively correlated with the share of dry pulses. Up to a certain temperature sum maximum, also higher temperature sums seem to be beneficial for the cultivation of dry pulses. In contrast to dry pulses, regional soybean shares in the arable area are positively correlated with a region's distance to the next main port and with the share of irrigable agricultural area. Agglomeration and spillover effects may matter (i.e., farms located in the neighborhood of dry legume producers are also more likely to commence cultivation of dry legumes; regions with a high share of dry pulses tend to be close to each other), as in the case of dry pulses where a significant spatial lag coefficient was found. Such effects, however, are likely to be effective on a spatial scale smaller than the regional level. Potentially significant causal factors, which have not been tested due to poor data availability, that may be positively linked to legume production include proximity to processing facilities and trading companies and access to extension services and regional networks and training programs (Oré Barrios et al. 2020). Other factors well acknowledged in the literature (European Parliament 2013) with positive causal effects on the cultivation of legumes are market factors, i.e., producer prices for outputs (pulses) and inputs (nitrogen fertilisers).

The economic circumstances of farms cultivating legumes are linked to some of the factors mentioned above, e.g., larger organic farms show higher profitability. There are also indirect economic benefits of legume cultivation such as the lower cost of agricultural inputs (nitrogen and tillage cost saving) and yield effects on other crops (e.g., cereals included in the rotation). While profits and the economic sustainability of the farm are necessary, they may not always be sufficient and farmers' decision-making may be influenced by noneconomic factors, such as their perceptions of how what they create affects other issues beyond the farm gate, such as the environment and human health.

Similarly, consumers' choices may be influenced by environmental and health concerns as opposed to purely economic reasons and assessing the weight of the different attributes of choice would help predict sustainable changes in shopping habits and subsequent consumption patterns. A study on the own-price elasticities of legumes shows that consumer's demand can only change significantly if factors other than price are considered, such as provision of targeted campaigns and better communication of legumes' health and environmental benefits, better availability of healthy convenience foods, access to information on cooking, and easy recipes (Akaichi 2019).

As represented in Fig. 1, while the consumption trend for beans has been in a stable decrease, the consumption of peas, lentils, lupins, and other dry pulses shows a gentle but steady increase, likely correlated to a slow change in consumer diets reflecting a healthier pattern.

While slow, changes in consumption patterns to include more legumes are apparent and need to be translated into production patterns. The current EU demand for legumes is met partly by domestic production, partly by imports (Fig. 1) and equilibrium analysis is necessary to assess the sustainability of the whole sector when faced with shocks such as price fluctuations in the context of higher dependency on imports, or changes in environmental policies leading to stronger incentives to EU producers and thus a larger share of the demand being met by local production.

5 Social Impact

5.1 Nutrition and Food Security

Food insecurity is a reality for millions of people and households, especially in poor and developing countries (FAO 2019). Recent data reveals that over 2 billion people around the world do not have regular access to safe, nutritious and sufficient food, including eight percent of the population in Northern America and Europe (FAO 2019). Indeed, more than 820 million people in the world were still hungry in 2018. Such living conditions increase the risk of malnutrition and ultimately impair the health of populations (FAO 2019). It is recognized that lack of protein-energy intake, as well as micronutrient deficiencies, are major undernutrition triggers, both frequently associated with more severe food insecurity states (FAO 2019; Webb et al. 2018). Grain legumes could be part of the solution for these problems; however, over time they have been significantly depreciated within human diets, and legume crops are yet greatly under-cultivated (Foyer et al. 2016). In fact, legumes are relatively invisible actors of our food system.

A 2015 Joint Research Center policy foresight assessing the role of EU policies for global food security called for a "Common Food Systems Policy," but failed to even mention protein crops, pulses, or legumes (Maggio et al. 2015). Whereas unique agro-ecological benefits of legumes are gaining more recognition and are slowly being acknowledged in food policy debates, their impact is still at the small-scale of home-grown legume production and consumption. Nevertheless, a recent public food procurement mandate in Portugal (Graça et al. 2018) successfully increased home-grown legume consumption. On the large scale, only the cultivation of non-GMO soybean for feed has increased in Italy, Germany, France, and Poland due to multiple support policies. In other geographical frameworks, such as Canada, cost-benefit analyses have revealed the positive impact of legume consumption (100 g cooked legumes/day by 50% of the population) in combination with a low glycaemic index or high fiber diet on healthcare costs. In addition, human productivity costs (reductions of roughly $370 million Canadian dollars), particularly related with cardiovascular disease and type 2 diabetes (Abdullah et al. 2017), have driven the 2019 Canada's Food Guide to emphasize plant-based protein foods within the "protein foods" group. Beans and lentils have been placed at the top of the list, before nuts and other seeds and animal protein products (meat, poultry, fish, eggs, and dairy foods) (https://food-guide.canada.ca/en/).

Historically, food and agricultural policy often lagged behind nutrition science, though more recently this position has started to change. Legumes may already be leading a green food revolution (Tenkouano 2011), because they have been identified as critical to provide nutrients and balanced diets and provide nutritional security with minimal use of resources, as well as to facilitate social-eating when cultivated in small areas within backyards or home-, school- and community-gardens (Keatinge et al. 2012). Their high protein content (17–30%) (Boye et al. 2010) associated with relevant nutritional richness (Marinangeli et al. 2017), turns grain legumes into better affordable nutritive options, comparatively to more expensive animal-based protein food sources, such as meat or dairy products, which may be less achievable among food insecure contexts. Legumes are also important food sources of slowly digested complex carbohydrates (~50–65%) (Havemeier et al. 2017) and fiber (~30/100 g, with low glycaemic index; dry weight) (Tosh and Yada 2010), as well as minerals (Grela and Samoli 2017) like magnesium, iron, potassium, phosphorus or zinc and several complex B vitamins (Mudryj et al. 2014), namely B1, B6, and B9. On the other hand, they possess low energy density in terms of fat (1.3 kcal/g cooked), providing mostly mono- and polyunsaturated fats (Grela and Samoli 2017).

Grain legumes are also relevant dietary sources of health-protective bioactive compounds (Singh et al. 2016). Last but not least, grain legumes hold versatile technological and cooking properties providing excellent opportunities among food industry to be used in the production of several convenience value-added food products, like flours, snacks, infant, or sports foods (Asif et al. 2013). The possibility to store grain legumes for long periods of time without altering their nutritional value results in one of their best features helping minimize food waste and therefore food insecurity. Although diet is the most apparent link by which agro-food systems affect our health, the role of legumes to provide solutions to the double burden of inadequate dietary intake (undernutrition) and excess food intake (overnutrition) in an unequal world is not widely considered or understood. Still, there seems to be a consensus on a sustainable and nutrient-rich plant-based diet (ovo-lacto-vegetarian and pescetarian) that may provide optimal synergy between nutrition health and environmental sustainability (Springmann et al. 2016; van Dooren et al. 2017). Indeed, markets for plant protein and fiber-based diets are rapidly growing (Logatcheva and van Galen 2015). However, without appropriate and careful reframing, public health improvement and environmental sustainability arguments in favor of a diet-change will not be enough to engage stakeholders and beneficiaries (c.f. de Boer and Aiking 2017) and to achieve a paradigm shift (Mason and Lang 2017).

5.2 Mitigating Effect on Climate Change

The food habits of the 7.7 billion people who inhabit our planet have been threatening all life domains, with extremely worrying expression at the climate change level (Macdiarmid and Whybrow 2019). Animal-based foods are a significant component of food production worldwide and meat or meat products are major dietary protein sources, especially across more westernized countries (Willett et al. 2019). Nevertheless, livestock production accounts for considerably high amounts of total greenhouse gas (GHG) emissions and other pollutants, together with increasing demands for scarce water resources and the promotion of soil erosion (Godfray et al. 2018). If such production and consumer patterns persist, it is expected that by 2050, there will be a 50–80% increase in GHG emissions and a ~13–66% expansion in land used for crop production (Clark et al. 2019), both associated with increased threats to biodiversity (Tilman et al. 2017).

Globally, this will also translate into ~15% more water use, as well as ~50% and ~100% more nitrogen and phosphorous fertilizer use, respectively (Clark et al. 2019). According to the literature, the production of plant-based foods has the lowest environmental impact, achieving for example 25–150 times less GHG emissions than ruminants produce for meat production (Clark et al. 2019). As such, a dietary shift toward more plant-based diets, providing more eco-friendly protein food sources, is being suggested (Willett et al. 2019). Grain legumes have caught the public's attention over the past few years, being considered as nutritious animal food alternatives and highlighted for their key role within sustainable food production systems (Calles et al. 2019b). Among several important features, the atmospheric nitrogen fixation capacity of legumes reduces the need for chemical fertilizer use during crop cultivation, helping reduce GHG production, like carbon dioxide (CO_2) and nitrous oxide

(N_2O). In fact, it appears that by substituting meat with grain legumes could lead to a reduction of up to 74% in GHG emissions, enabling the achievement of the 2020 target for the US (Harwatt et al. 2017).

Grain legume crops are also able to release high-quality organic matter into the soil and facilitate nutrient circulation in the soil, as well as promote water retention minimizing fossil energy inputs in the agricultural food production chain (Stagnari et al. 2017). Indeed, the water footprint per gram of protein for grain legumes seems 1.5 times smaller than for milk, eggs and chicken meat (Mekonnen and Hoekstra 2012). When beef production is considered, such difference becomes six times less, again in favor of grain legumes (Mekonnen and Hoekstra 2012). It is possible then that the increase in production and consumption of grain legumes could be a cornerstone to ensure food and nutritional security, in light of ongoing global climate change (Willett et al. 2019).

Trying to empower this message, the United Nations declared 2016 as the International Year of Pulses (Calles et al. 2019a). In the same year, the slogan for the celebration of the World Food Day was "Climate is changing. Food and agriculture must too" (FAO 2016). Since then, grain legumes have been in the spotlight across worldwide climate change mitigation strategies (Willett et al. 2019). Likewise, a recent World Bank report states that fruits, vegetables, and legume-based products should be supported at the expense of cereals, palm oil, and sugar, while the subsidies and price support mechanisms for unhealthy ingredients should be abandoned. However, to find pathways to more sustainable agro-food systems and innovative policy solutions, greater civil society engagement and more effective public-sector research and education efforts are required (Abarca-Gómez et al. 2017).

5.3 Cultural Valorisation

Traditional food products are naturally linked with local resources and cultural heritage of involved territories. Indeed, gastronomy and several cultural practices related to food represent a distinctive element between different populations. All over the world, it is possible to find a high number of traditional dishes containing grain legumes prepared and cooked in different ways and with unique organoleptic properties, combinations that people easily associate with comfort, societal wellness, and festive food (Polak et al. 2015). In this regard, FAO's Information Network on Post-harvest Operations maintains an updated database of more than 850 recipes from more than 50 countries, where not only the traditional recipes are preserved for posterity but also less common ingredients are presented and promoted (FAO 2015).

Cooking with pulses offers several advantages that go from their affordability for family budgets (food security asset as previously mentioned), their long shelf-life where nutritional value is preserved throughout, to their important organoleptic versatility where savory yet subtle tastes enable their harmonious inclusion in a wide range of cuisines and flavor profiles. Kidney beans, black beans, pigeon peas, chickpeas, and lentils are featured regularly in legume recipes supporting their popularity for cuisine management and making these grain legumes a staple of many diets. Such high versatility enables their inclusion in all types of servings, including entrees, soup bases, side dishes, salads, stews, and desserts (Figueira et al. 2019).

Across the globe, consumption of traditional legume foods is popular in Brazil (black beans with rice) (FAO 2015), in India (dhal, pappadums) (Appel 2005; Misra 2011), in Mexico (refried kidney beans or chili) (FAO 2015) in Middle Eastern countries (hummus, falafel, nakee, bajelah, fasolia) (Kamboj and Nanda 2018; Alalwan et al. 2017), and in Mediterranean countries (navy bean soup, bean stew "feijoada," fave bianche) (Lăcătușu et al. 2019; Renna et al. 2015). In addition, legume flours are traditionally incorporated into many different foods either as batter for vegetables (onions, leeks, aubergine) or as ingredients for savory snacks, that when combined with fried whole grain legumes (Alalwan et al. 2017), may be consumed as a mid-morning or a mid-afternoon meal.

New foods using grain legumes are emerging on the market and may be an interesting alternative to increase their consumption; nevertheless, efforts need to continue to be made in order to promote traditional dishes and associated nutritional value. A balance between old and new is undoubtedly the most favorable means to preserve the heritage and health of a population.

5.4 Increasing the Social Acceptance of Legumes

More and more, populations should be aware of the impact of their choices, namely dietary choices, on the planet's sustainability. The grain legumes should be considered as good options even though these foods continue to be unpopular, especially in developed countries (Perignon et al. 2017). Some misconceptions related to their consumption and subsequent gastrointestinal problems or presumed impact on weight gain, the time needed for their soaking and cooking, and the perceived lack of appealing preparations certainly contribute to their scarce utilization. The promotion of legumes should start among children for several reasons: this food group is unpopular among children and, consequently, their consumption is scarce at this age; dietary changes are easily implemented among children, since their food habits are not so fixed and evidence suggests that early food patterns tend to be maintained throughout life. On the other hand, the issues related to a "healthy planet" are motivating targets for children (Sadegholvad et al. 2017; Smith et al. 2016).

Taste modulation starts very early in the lifecycle and grain legumes could be gradually introduced as early as the eighths or ninth month of life (Fewtrell et al. 2017). However, since the insertion of the child within the family diet is crucial, it is important that these foods are offered regularly and the parents also eat them. Their inclusion in school meals is also fundamental, inclusively as a partial substitute of animal protein. Schools are the ideal place to widely spread concepts regarding nutritional and ecological benefits of legumes, having as major targets the children and their relatives (Smith et al. 2016). Issues related with the practicability of grain legume cooking could be easily overlapped with canned alternatives or even with pre-preparation and freezing in portions. Innovative foods containing grain legumes and ready-to-eat options are also a good solution.

6 Conclusions

Our global society faces several challenges that are negatively impacting the health of our planet, our people, and our agricultural economies. Increases in atmospheric CO_2 and other greenhouse gases are altering our climate in ways that are straining our food systems. Our growing human population is worsening our ability to meet food security and nutrition needs. And various production and processing costs are limiting the economic potential of different players in our food value chain. While legume crops cannot solve all of these issues, we have attempted to show how an expanded utilization of legumes in our food production systems could supply a number of benefits to mitigate these problems.

Our future challenge, then, is to scale up the use of legumes in a way that achieves the most social, economic, and environmental benefits. This will require a change in society's acceptance of legumes and a willingness to divert some cereal-based or meat-based production systems to legume systems and primarily to grain legumes. Fortunately, the benefits gained from legumes are highly integrated and complementary, providing clear value to all members of the legume supply chain (producers, food industry, and consumers). This should facilitate increased acceptance, but a concerted effort among agronomists, nutritionists, environmentalists, and others will be needed to educate and promote the societal benefits of legumes. A reshaping of public and policy maker's opinions will be critical to ensure that legumes are elevated to a new level in our global food network.

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