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Future farming: protein production for livestock feed in the EU

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Abstract

Climate change can have a negative impact on agricultural production and food security. Vice versa, agricultural practices themselves contribute to climate change because of land, water, and energy use and anthropogenic emissions of greenhouse gasses and waste. The European Green Deal focusses on "transition to a sustainable food system that has a neutral or positive environmental impact, helps mitigate climate change and adapt to its impact, and reverses the loss of biodiversity". Local production of feed proteins in the European Union may result in new agro-ecosystem services that can be integrated to maximize sustainability of agricultural practices. Feed crops with nutritional properties that are both beneficial to functional biodiversity, biocontrol, pollination, and other ecosystem services can be incorporated into livestock diets. However, implementation is hampered by lack of information, embedded habits of specialization, profit maximization priorities, a lack of awareness about the environmental impacts of existing production systems, and a lack of flow of resources and services between the sectors. When economic benefits from investments are not immediately evident, transition can only be successful with government policies that focus on providing knowledge and education, and financial support. To convince agriculturists and agricultural workers to adopt sustainable practices, policy changes are needed with close cooperation between, and support from, all actors involved, including producers, non-governmental and civil society organisations, and the retail industry.

Keywords European Green Deal, Local feed resources, Agricultural integration, Livestock production, Crop production, Ecosystem services

Introduction

It is unequivocal that human influence has warmed the atmosphere, ocean and land [1]. The urgency of addressing unsustainable practices of 'the human enterprise' is well established and manifested [2]. Climate change can have a negative impact on agricultural production and food security. Vice versa, agricultural practices themselves contribute to climate change because of land, water, and energy use and anthropogenic emissions of greenhouse gasses and waste. Trends in EU consumer consumption patterns show a steady increase in the number of vegans, vegetarians, and flexitarians for environmental reasons. In addition, although there is currently still a low level of willingness by consumers to replace meat with insects or cultured meat, they offer a tremendous potential for cheap mass production of protein with a lower environmental impact [3]. Alternatively, consumers who are concerned about the environmental impact of their food choices are willing to pay for

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animal products derived from more sustainable production processes [4]. The European Commission, under the umbrella of the European Green Deal, aims to help mitigate climate change and adapt to its impact, and reverse the loss of biodiversity [5]. This is accomplished through a series of policy initiatives, including the Circular Economy Action Plan that focusses on sustainable resource use, the Biodiversity Strategy for 2030 that aims to restore degraded ecosystems and manage them sustainably addressing the key drivers of biodiversity loss, and the Farm-to-Fork strategy that aims to accelerate the transition to a sustainable food system that has a neutral or positive environmental impact [5]. The policy initiatives include fostering EU-grown plant proteins for food and feed to increase the self-sufficiency of EU protein production and decrease dependency on international imports. A decrease in landscape complexity results in biodiversity loss; instead, mixed cropping systems may increase landscape complexity and protect biodiversity through an increase in habitat diversity [6].

The present perspective focusses on protein production for livestock feed in the European Union. It is directed to stakeholders, and national and EU policy makers in particular. First, we discuss the intensification of livestock and feed production and its impact in a global context. We then discuss protein feed resources in the EU, ecosystem services incorporating legumes, grasses, and non-leguminous forbs, and the implications of EU local protein feed production for land use change. We end the discussion with future directions.

World population growth and intensification of livestock production

On June 11th 1987, World Population Day, the world's population size hit the five billion people mark; the United Nations Population Division projects that the world may be inhabited by over 11 billion people by 2100 [7]. Although the population in some countries is projected to substantially decline (e.g., in central and eastern Europe), other countries are forecasted to witness a doubling, tripling, or even an eightfold increase by 2100 [8]. The number of hungry people worldwide has been slowly rising, but the overall purchasing power of the developing world has increased significantly over the last decades, resulting in increased amounts of food consumed per capita as well as a shift in consumption patterns towards larger amounts of livestock-derived products [9]. In 2018, the average supply of protein of animal origin had grown to 13.1 g per capita per day in Africa, compared to an average of 61.6 g per capita per day in Northern America and Europe [10]. The consumption levels exceed needs in the most developed countries. Following the increase in human population size and consumption per capita, Delgado et al. [11] in 1999 wrote about his vision of livestock to 2020: "A revolution is taking place in global agriculture that has profound implications for human health, livelihoods, and the environment. Population growth, urbanization, and income growth in developing countries are fuelling a massive increase in demand for food of animal origin". This demand is met by an increase in the world production of meat from different livestock (including poultry) species: according to the FAO [12] in 2020, the world's livestock population comprised some 33 billion chickens, 1.5 billion cattle, and 950 million pigs.

In addition to an increase in the world's livestock population numbers, the increase in the world's demand for meat is met by intensification and technological innovation of animal production systems, animal breeding practices that improve production yields per animal, and high-quality animal feeds. A study by Domingues et al. [13] showed that intensification of livestock production in France was brought about by specialization of land use, a reduction in the number of farms from two million in 1938 to half a million in 2010, an increase in stocking rate of approximately 170% in monogastrics and 50% in herbivores, and a fourfold increase in the indicators of mechanisation and labour productivity. In Spain, between 2007 and 2020 alone, the number of pig farms with a maximum of 25 or 1000 fattening pigs declined by 50% and 25%, respectively, while farms with a maximum of 4000 or 6000 fattening pigs increased by nearly 25% and 50%, respectively. When permission is granted, the maximum number can be extended up to 7200 fattening pigs per farm such that one single macro farm with three cycles per year can fatten up to 21,600 pigs per year [14]. Intensification of livestock production has also taken place in many developed regions, closing the yield gap with respect to the production level that can be attained in the developed world [15]. Intensification of animal production is further supported by precision livestock farming (PLF), i.e., 'a management system based on continuous automatic real-time monitoring and control of production/reproduction, animal health and welfare, and the environmental impact of livestock production' [16].

Genetic improvement is key to increased production efficiency of livestock animals. Best Linear Unbiased Prediction (BLUP) for estimation of breeding values, using linear mixed models that use genetic relationships between individuals based on pedigree, along with vast advances in statistics and computing power, have provided animal breeders the tools to implement breeding programs that have resulted in unprecedented genetic improvement of production traits in farm animals over the past decades [17]. Currently, in genomic selection, estimates of the effects of all genotyped Single Nucleotide Polymorphisms (SNPs) across the genome are used to estimate an individual's breeding value, with pedigree-based relationships between animals replaced by genomic relationships. In addition, a wide range of novel -omics methods (e.g., transcriptomics, proteomics, and metabolomics) are now available that can be used to further identify genes that are associated with phenotypic variation of production traits (see Rauw et al. [18] for an overview). Vast genetic improvement is supported by heavy selection in only few selected commercial livestock breeds. Farm animals from highly selected populations require high quality, if not quantity, of feed resources to allow for the expression of genetically improved production traits. This is accomplished by sourcing genetically selected feed crops with high nutritional and commercial value from international markets, including grain, oilmeal, fishmeal and soybean meal [19]. For example, soybean meal is a major ingredient in livestock feeds. It has a high protein content, a suitable amino acid profile, and can be produced year-round [20]. Furthermore, precision livestock feeding can provide each animal with the nutrients required based on individual demand to maximize feed efficiency and nutrient utilization. This is accomplished through automatic data recording devices that estimate the individual nutrient requirements, and automatic feeding systems that provide the adequate amount and precise diet formulation that maximizes the desired production trajectory [21].

Environmental impact of livestock production

A global increase in the number of livestock animals requires an increase in the resources used to grow and feed them. Of all the world's land surface, approximately 71% is 'habitable land'; half of this land is used for agriculture. Currently, pastures used for grazing and land used to grow crops for animal feed account for 77% of agricultural land, thus comprising nearly 30% of the total land surface of the planet [22]. Although the self-sufficiency of protein consumption based on animal-derived products in the EU is very high, this is not the case for plant protein inputs to the EU's animal production industry [23]. The EU, with a production of 2.6 million tonnes of soybeans in 2019–2020, is heavily reliant on imports, mostly from Brazil and Argentina [23, 24], while per year, Brazil with 75 million tonnes and the US with 65 million tonnes account for 85% of global soybean exports for biofuel production, animal feed and food products, followed by Argentina (7.7 M tonnes), Paraguay (5 M tonnes) and Canada (4.4 M tonnes) [25]. Across South-America, direct soybean-driven deforestation reached a total of 3.4 Mha between 2001 and 2016 [26].

Of the global available fresh and accessible runoff water, approximately 35% is used for agriculture. Currently, 38% of crop water consumption is attributable to livestock feed production while grazing involves 29% of total agricultural water consumption, giving cause for serious concern regarding the water implications of our food choices [27]. Furthermore, livestock production requires fossil energy inputs for the production of fertilizers, farm machinery, fuel, irrigation, and pesticides for grain and forage production [28]. For example, Todde et al. [29] estimated that direct energy requirements of a conventional dairy farm located in the south of Italy would amount to an energy consumption of 13,675 kg of diesel, 26,245 kWh of electricity and 115 kg of Liquefied Petroleum Gas (LPG); feed preparation and distribution, and field activities associated to crop cultivation accounted for 39 and 38% of diesel fuel utilization, respectively. Crops genetically selected for high yields and nutritious value require inputs of energy, equipment, fuel, chemicals, and other supplies. Between 1961 and 2014, as global crop production more than tripled, the supply of nitrogen fertilizer increased 955% [30].

The negative implications of intensification of livestock and feed production have been extensively described, regarding losses of nutrients from fertilizers and manures to watercourses and contributions of gases to climate change. Agricultural runoff of nitrates, ammonium, phosphorus compounds, heavy metals, and persistent organic pollutants with water from irrigation and rainfall from farmlands affects the health and security of surface waters and aquatic ecosystems [31]. Since 1750, atmospheric carbon dioxide increased 47%, methane 156% and nitrous oxide 23%, which has unequivocally been caused by human activities [1]. After carbon dioxide, methane is the second-largest driver of climate change. Representing one third of global emissions, livestock production is the largest anthropogenic methane source, mainly coming from enteric fermentation of ruminants and manure management [32]. Livestock animals deposit 70%-95% of nitrogen intake as manure and urine, which results in nitrate leaching from urine, ammonia volatilization, nitrous oxide, nitric oxide, and N_2 emissions [33]. Agriculture is responsible for 60% of anthropogenic nitrous oxide global warming potential [33].

Agricultural production also profoundly impacts diversity of life on earth. Seventy-five percent of the global land surface is significantly altered by multiple human drivers [34]. According to Erb et al. [35], in the hypothetical absence of land use, potential vegetation would store more than double the amount of carbon (currently estimated at $\approx$ 450 Gt [36]), also highlighting the massive effect of land use on biomass stocks. In addition, a decrease in landscape complexity is a main driver of biodiversity loss [37]. Whereas human activities halved the planet's plant biomass, it resulted in a fourfold increase in the total mass of mammals due to the vast increase of the human population and livestock animals. The biomass of humans (≈ 0.06 Gt C) and that of cattle and pigs (≈ 0.1 Gt C) far surpass that of wild mammals (≈ 0.007 Gt C), while the biomass of domestic poultry (≈ 0.005 Gt C) surpasses that of wild birds (≈ 0.002 Gt C) [36]. Livestock production is an important contributor to global biodiversity loss due to land use changes for grazing and feed production. For example, land-use change to livestock grazing includes removal of biomass, trampling, replacement of wild animals by livestock, and conversion of rangelands into crop land to provide for a substantial part of feed in mixed and industrial production systems [38]. The production of soybean in Brazil, and in particular in the Atlantic Forest ecoregion, has resulted in biodiversity damage to mammals, birds, amphibians, reptiles and plants [39]. In addition, human agricultural practices themselves are inherently based on low biodiversity. Of the world's 148 large terrestrial mammalian herbivores and omnivores, only 14 were domesticated, while of about 200.000 wild species of higher plants, only about 100 yielded valuable domesticates [40].

Protein feed resources in the EU

Yield-centric intensification and specialization of animal production systems have historically led to spatial segregation of crop and livestock production [41]. This is particularly pronounced for high quality protein crops in the European Union (in particular Western European countries) that are, for a significant part, imported from other continents. In the EU, cereals, maize, and oilseed rape in the north, and maize and sunflower in the south cover 92% of the arable land area [41]. Soya beans in particular, however, are imported into the EU, because the area of farmland dedicated to legume production in the EU is only ~ 2% of total arable land [42, 43]. In 2011, the European Parliament adopted a motion to deal with the unsustainability of this heavy dependency of the EU to soybean meal imports [44]. The motion recognized a long list of benefits of European-grown protein crops: economic benefits for farmers and the feed industry; assimilation and fixation of nitrogen in the soil and a reduction of synthetic nitrogen fertiliser use and greenhouse gas emissions; reduction in CO_2 emissions and ozone production, more balanced nutrient storage, reduced soil acidification, enhanced disease resistance, reduced propagation of weeds, better soil structure, less use of herbicides and plant protection treatments, lower energy consumption, greater biodiversity, and assisting pollination when protein crops are introduced into crop rotation; better water management substantially reducing the run-off of nutrients into groundwater in mixed cropping systems; and adaption to European climatic conditions stabilising and enhancing agricultural biodiversity within the production system. This was supported by the Policy Department on Structural and Cohesion Policies, which in 2013 provided, in response to a request by the European Parliament's Committee on Agriculture and Rural Development, an overview of the development and environmental effects of protein crop production in Europe. It suggested nine policy options for supporting protein crops, including encouragement of on-farm crop diversification measures, classification of legume-cropped areas as ecological focus areas, regional and coupled support schemes for protein crops, increased support for organic farming, promotion of legumes via agri-environment schemes, strengthening of climate protection policies following from reduced greenhouse gas emissions and increased carbon sequestration in soil, policies on the use of nutrients (nitrogen fertilizers) in agriculture, support of producer initiatives for networking and knowledge dissemination, and investment into research, breeding, and technical progress. They concluded that "increasing the production of protein crops would be an important contribution to the sustainable development of European agricultural and food systems", with complementary multiple positive environmental and resource-conserving effects operating at field, farm, regional and global levels [45]. In addition, in 2013, a Focus Group on Protein Crops, set up by the European Innovation Partnership in Agriculture, analysed the feed production potential of European grown soy-beans, rapeseed, sunflower, lupin, pea, faba beans, alfalfa and clover. They concluded that European protein crops have a long way to go before being competitive with imported feeds, but "this can be stimulated through different aspects of innovation, including technical innovations on agronomy (variety choice, fertilization, disease control, water use, crop mixtures, environmental effects and rotational aspects) and breeding (focusing on drought resistance, climate adaptability, disease resistance, protein content and reduction in anti-nutritional factors)" [46].

Reintroduction of protein feed production to the European Union does not necessarily mean full recoupling of (traditional) crop and livestock systems. Instead, territorial integrated crop and livestock systems can exchange crop and livestock products among farmers at a regional level [41]. Local production of feed proteins in the European Union may result in new agro-ecosystem services that can be integrated to maximize sustainability of agricultural practices. For example, localization of feed production "offers an array of economic, environmental, and social benefits, such as a reduced amount of energy used in their transport, improved economic viability of local farms and their communities, and decreased safety risks associated with decentralized production" [47]. In an approach called 'ecostacking', benefits obtained from ecosystem services in a cropping system are maximized by stacking the beneficial services of functional biodiversity, biocontrol, pollination, and other ecosystem services in an additive or synergistic manner [48]. Ecosystem services to the crop can be improved by techniques such as cover crops and crop rotation, incorporating legumes, grasses, and non-leguminous forbs [48].

Grain legumes, grasses, and non-leguminous forbs

As an example, in Spain, local protein plants that can be used in animal feeds include peas, lupine, common vetch, Narbon vetch, bitter vetch, carob, red vetchling, fenugreek, and black chickpeas. These varieties may reach a high production potential due to their adaptation to the local edaphoclimatic conditions of Spanish soils, and their resistance to disease and the Mediterranean climate [49]. Legume species have additional benefits to sustainable agriculture when they are used in intercropping and as a break crop in crop rotation. Legume crops are generally perceived to be less competitive and less profitable than cereals, however, crop rotations with grain legumes may offer increased gross margins [43, 50]. Crop rotation is as old as the Egyptians, Greeks and Romans, who realized that the production of a single type of crop in one zone eventually depleted the soil of nutrients, reducing yields [51]. However, to date, maximum production yields are reached with simplified cropping systems combined with the use of mineral fertilizers and chemical crop-protection products for weeds, pests and disease control, in particular over the past decades with the introduction of precision agriculture. Conventional fertilizers, and in particular chemically produced nitrogen fertilizers, are very energy-intensive to produce, while losses of nutrients to water courses leads to freshwater eutrophication. Instead, leguminous crops have the ability to fix atmospheric nitrogen through symbiosis with rhizobia bacteria in their roots, bringing nitrogen into the soil, thereby reducing the need for nitrogen fertilizers [52]. Furthermore, crop rotation incorporating legumes improves land phosphorus uptake and use efficiency, reduces the risk of root diseases, and reduces pesticide use [43, 53]. Additional economic benefits of legume crop rotation follow from better time partitioning of farm labour resulting in more efficient use of machine and manpower, cost savings for tillage because of improved soil structure, and higher potential selling price of grain legumes [43, 50]. Implementation of a wide variety of legume crops in agricultural crop production systems conserves and enhances agrobiodiversity that is critical for sustainable agriculture and food security [54]. Likewise, several legume traits enhance local biodiversity on farmed land, including that of soil organisms, plants, invertebrates, pollinators, mammals, and birds [55]. For example, mass-flowering aids flower-feeding insects including bee-pollinators, nitrogen fixation aids soil organisms as well as higher trophic levels by providing high-quality nutrients, and legume-based cover aids maintenance of a greater range of rare plant species [55]. Also, certain bird species, like the little bustard (Tetrax tetrax), prefer legume species in their habitat selection [56].

Currently, European (research) interest into legume crops is mainly dedicated to only a small number of available legume species, including pea, clover, faba bean, and common vetch [52]. Although local leguminous crops may produce acceptable to high yields, local varieties are generally not able to compete against highly genetically selected and commercialized crops. Indeed, with the exception of peas, genetic selection has been minimal or inexistent for local varieties [49]. To establish the value of local varieties as feed crops, is it needed to assess their resilience and ecosystem service value, and to identify and quantify their nutrient value, bioactive components, and anti-nutritional factors. Furthermore, analysis of genetic diversity plays a pivotal role in conserving and exploiting these genetic resources in breeding programs for genetic improvement in these traits [57]. For example, Narbon vetch is a crop that is well adapted to the Mediterranean climate, and has a reasonably high protein content (between 20 and 30%). However, the presence of the antinutritional sulfur-containing dipeptide γ-glutamyl-S-ethenyl-cysteine (GEC) produces a garlic-like flavour in animal feeds that reduces feed intake and growth rate, and therefore may limit the use of Narbon vetch in animal nutrition. Selection for higher protein and lower GEC content can combine the beneficial agronomical properties of Narbon vetch with its value as a feed crop [58]. Other examples of genetic improvements include genetic selection for improved resilience to environmental stresses, including drought, heat, cold, salinity, flood, submergence and pests [59], but also for enhanced environmental ecosystem function through selection of pollinator friendly varieties with better floral attractiveness and rewards for insects [60].

Over the past 50–100 years, industrialisation and use of artificial fertilizers have enabled winter fodder and pasture on arable lands with enormously increased productivity, however, large numbers of species previously associated with semi-natural grasslands have declined and are now threatened by extinction [61]. For example, adding nitrogen to N-limited grasslands improves crop productivity but decreases biodiversity [62], while there is a clear negative correlation between mowing intensity and plant species richness [63]. During the last decades, with an increased awareness of unsustainable agricultural practices and increased interest in organic grassland farming, non-leguminous forbs (e.g., *Polygonum bistorta* L., *Alchemilla vulgaris* L., and *Cichorium intybus* L.) have become a valued functional group of grassland plants due to their contribution to grassland biodiversity [64]. As reviewed by Lukač et al. [64], depending on the species, non-leguminous forbs have high nutritive value for animal feeds, with high levels of nitrogen compounds, crude protein, energy content, minerals, and condensed tannins that may prevent bloat and parasite burden in grazing animals. For monogastric feeds, green biorefinery concepts are a promising solution for the production of nitrogen-rich protein concentrates from green crops [65]. Sustainable grassland management can help mitigate the negative impacts of modern farming practices and support a range of ecosystem services, including soil health, pollination, natural enemy communities, pest control, cultural services, and biodiversity of plant and animal species, either directly or as source habitats from which pollination and pest control services can spill-over into cropped land [66]. In addition, multispecies swards, which include complementary multiple plant functional groups such as grasses, legumes, and forage forbs, that each bring an agronomic benefit to the sward, can improve resource efficiency, enhance productivity and result in greater nutritive value as well as improved resilience to drought [67, 68]. For example, Hoekstra et al. [69] showed that mixing deep-rooted species with shallow-rooted species increases flexibility in nutrient uptake, resulting in increased drought resistance of biomass production, and that adding legumes to grassland mixtures has a strong favourable effect on the uptake of nitrogen but also of other nutrients in non-legume species.

Land use changes for EU local protein feed production

Local protein feed production in the EU implies land use changes, i.e., allocation of new agricultural land or land reallocation [70]. However, finding suitable land space to implement this is challenging, given the competition between land uses, e.g., diversion of land used to grow food to land used to grow feed, and competition with land required for bioenergy production [71]. Overall, soil productivity in the EU is threatened by soil degradation processes including erosion, organic matter decline, contamination, salinisation, compaction, soil biodiversity loss, landslides, and by activities involving soil sealing (the permanent covering of soil with an impermeable material) and land take (increase in artificial surfaces, like residential areas, manufacturing plants, business centres, and public transport networks) [72]. Regarding the latter two activities, urban land is mostly developed on well drained, fertile and flat areas that are closer to water sources and urban areas, forcing agriculture to move to less productive areas [73]. In addition, historically in Europe, rapid urbanization and rural exodus, agricultural intensification and specialization, and reallocation of agricultural production resulting from the Common Agricultural Policy (CAP) that subsidizes some crops to the detriment of others, and required farmers to leave a proportion of their land out of intensive production ('set-aside policy', obligatory between 1992 and 2008), has led to high agricultural productivity in some areas, but agricultural land abandonment in others [74]. Land abandonment is projected to reach 5.6 million ha, or 3% of agricultural land by 2030, while around 30% of agricultural areas are under at least a moderate risk of abandonment [75, 76]. Resulting from these trends, the agricultural land in the EU has shown an overall steady decline from approximately 2 million km^2 in 1970 to 1.8 million km^2 in 2000 and 1.6 million km^2 in 2020 [77], corresponding to 51%, 46% and 41% of land area, respectively [78]. Because of the diversity of landscape and climatic conditions, there is large variability in agricultural land changes at national levels [79]. Although crop yields have increased over the past century requiring a lower land use per kg product, this may not compensate the overall reductions in the extent of agricultural areas, raising concern for food security [72, 80].

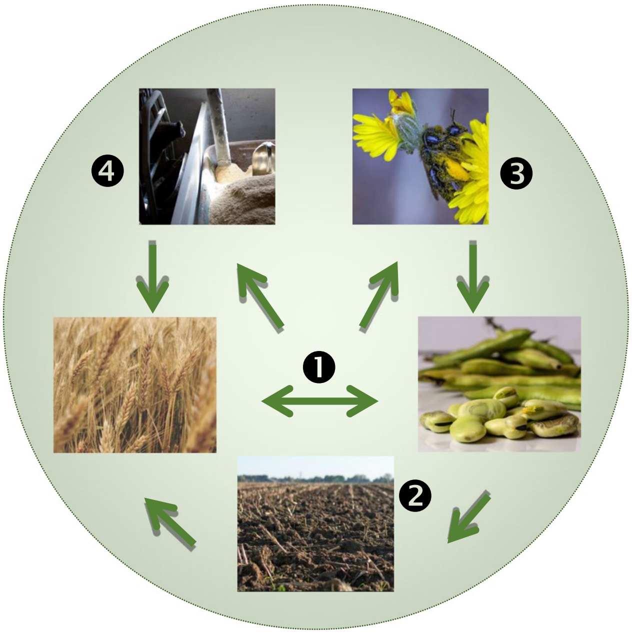
Agricultural production potential in the EU may be improved, and the negative environmental, biological, hydrological, geomorphological, socioeconomic and cultural implications may be reversed by recultivation of abandoned agricultural land [74, 81]. However, land abandonment affects primarily marginal, remote areas with unfavourable climatic or topographic conditions such as mountainous regions [81, 82]. Reviewing literature on different trajectories observed after agricultural abandonment, Fayet et al. [82] found cases reporting reconversion to intensified mono-functional production (cropland or grassland, most frequently in Eastern Europe) but no examples of low-intensive organic farming or sustainable practices. Only a minority of abandoned lands returned to different forms of agricultural uses. Intensified landscape outcomes were mostly found on fertile lands (e.g., former croplands) that are suitable for mechanisation and easily accessible, and they were driven by land management policies that provided (national or CAP) subsidies and programmes for recultivation, and by access to markets [82]. Therefore, for the return of abandoned land to sustainable agricultural practices (e.g., protein feed production) in support of the European Green Deal objectives, specific policy measures are needed to support appropriate land management practices [71].

According to Fayet et al. [71], if abandoned lands are not explicitly integrated in the EU Green Deal policy framework, there is little chance of uptake and opportunities may be missed. In addition, Montanarella and Panagos [83] emphasize that the EU Green Deal has to consistently address soil degradation processes and has to include sustainable soil management practices for restoring soil health and soil functions as a key element in their policy framework.

Land use for local protein feed production also depends on agronomic concepts that include the beneficial impacts of crop rotations on cropping systems, in particular when increased crop yields are achieved from crop rotation [70, 84]. However, there is usually little data available on crop rotations at farm and regional scales [84]. For example, modelling showed that producing protein feeds locally instead of importing them would increase the land needed to produce feed for pig production [70]. However, it would also reduce the estimated total yearly land use per kg of pig carcass because crop rotation results in increased wheat yields [70]. Land required for feed production furthermore depends on livestock feed efficiency, which is a major focus for improvement in selection programs and production systems, it depends on alternative animal diet scenarios, e.g., based on the use of agricultural residues and food waste, and on trends in human consumption patterns towards consumption of meat alternatives [85, 86].

Future directions

For successful integration of ecosystem services of livestock and crop production (see Fig. 1), within the appropriate national or regional ecosystems and in function of desired cropping techniques (e.g., crop rotation, mixed cropping, circular livestock-crop farming) crops need to be identified that are both beneficial to functional biodiversity, biocontrol, pollination, and other ecosystem services, and have nutritional properties that can be incorporated into livestock diets. This requires 1) identification of crop varieties that thrive in the local biophysical environment; 2) evaluation of their production potential and nutrient and anti-nutrient content (and how the latter can be eliminated or reduced); 3) evaluation of the provision of crop and animal ecosystem services; 4) evaluation of the production potential of (local) livestock breeds fed local feed resources; 5) evaluation of the potential to optimize agricultural production systems; and 6) genetic sequencing of local crop and livestock varieties followed by genetic improvement through selection. For example, crops can be selected for improved production potential and nutritional properties, soil improvement capacity, pollinator floral attractiveness, pest control, and climatic resistance. Livestock can be selected for improved robustness to climate change, functional traits, animal welfare, and improved ability to produce on local feed resources. Because livestock productive output of high producing animals requires a high quality of feed resources, feeding feed resources of (as



❶ Crop rotation and mixed cropping systems may increase the yield and gross margins, reduce propagation of weeds, and enhance agrobiodiversity that is critical for sustainable agriculture and food security.
❷ Legume crops can fixate nitrogen in the soil; crops can increase carbon inputs into the soil, reduce soil erosion, alter soil temperature and soil biodiversity, and improve soil structure for crop production.
❸ Mixed crops provide feed and habitats to a wide variety of invertebrate and vertebrate animals enhancing biodiversity. *Vice versa*, biodiversity provides a range of ecosystem services including pollination, natural enemy communities, and pest control.
❹ Pastures used for grazing and land used to grow crops for animal feed account for 77% of agricultural land; therefore, integration of livestock- and crop production is timely.
(Photos mid-right clockwise: G Diaz Estela, J Kroon, J Petersson, WM Rauw, WM Rauw; First three photos from Pexels.com).

Fig. 1 Integration of ecosystem services of livestock- and crop production yet) unimproved local varieties may result in genotype by diet interaction. Therefore, optimizing production efficiency of livestock on local feed may require a different type of animal than those currently selected in intensive high-quality input–output production systems [3].

The overwhelming response to the Climate Change Conference COP26 in 2021 and COP27 in 2022 shows that the young generation in particular demands immediate action, not promises and future commitments. It is clear that there is a great interest in the European Union to improve agricultural sustainability. In December 2019, the European Green Deal was presented by the European Commission as “a roadmap with actions to boost the efficient use of resources by moving to a clean, circular economy and stop climate change, revert biodiversity loss and cut pollution”. These ambitions are supported by a series of policy initiatives, including the Farm-to-Fork strategy (transition to a sustainable food system that has a neutral or positive environmental impact), the Biodiversity Strategy (protect nature, reverse degradation of ecosystems, and halt biodiversity loss), and the Circular Economy Action Plan (design and production for a circular economy) [5]. A circular economic principal of production is based on “grow, make, use, and restore” as opposed to a linear economic principal of “take, make, use, and dispose” [87]. Intensive agriculture and livestock production is mainly linear in structure with high levels of external inputs and the production of agricultural wastes. Although sustainability of production systems can be improved by precision agricultural procedures that minimize inputs and reduce waste, current intensive agriculture is still mostly dependent on external inputs, including agricultural chemicals for crop production and imported feedstuffs for livestock production. In addition, technification of agricultural systems is not available to the entire sector [3]. Instead, the circular bioeconomy aims at minimizing external inputs, as well as minimizing the production of wastes by reutilization within the agricultural production systems (e.g., crop residues and manure) or to produce, e.g., bioenergy [87]; an illustrative example of circular agriculture is given by Rauw et al. [88].

In livestock production, one of the action points is to “examine the EU rules to reduce the dependency on critical feed materials (e.g., soya grown on deforested land) by fostering EU-grown plant proteins as well as alternative feed materials (…)” [89], as outlined in the EU Plant Protein Plan [90]. On 2 December 2021, an agreement was adopted on reform of the common agricultural policy (CAP) that is in effect from 1 January 2023. The CAP 2023–2027 supports transition towards sustainable agriculture, reflecting higher green ambitions that contribute to the targets of the European Green Deal. This includes “the introduction of eco-schemes [with] stronger incentives for climate- and environment-friendly agricultural practices” regarding crop diversification, maintenance of permanent grassland, and ecological focus areas [91]. The new CAP also continues more favourable conditions for the cultivation of legumes. However, in many cases farmers lack information, e.g., on the way they should grow legumes to gain high performance, while value chains do not exist or are poorly organised [43]. According to Garrett et al. [41], deeply embedded habits of specialization, farm income and profit maximization priorities, and a lack of understanding the environmental impacts of existing production systems impedes current agricultural transitions. Similarly, according to Ditzler et al. [52], when it comes to sociotechnical lock-ins in agriculture, regarding crop varieties, market uses, and ecosystem services delivered, choices made decades ago result in self-reinforcement of specialized farms, narrowly focused research and knowledge support agendas, and few dominant industry and market chains. Balázs et al. [92] analyzed how EU-level policies influence the production of legumes in Europe, and they conclude that productivity of legumes in the EU has lagged behind because of a lack of public and private upstream investment in breeding, technological developments, and specialist advice from agricultural extension or advisory services skilled in legume-based crop system management, e.g., with respect to the crop types and management procedures that are needed to reach biodiversity- and/or environmental-protection goals.

Crop and livestock production, ecosystem services, and the value chain, which are mostly independently considered by policy makers, need to be closely integrated for successful flow of resources and services. For example, crop farmers may show interest in growing local feed legumes, however, a secure market is needed where they can sell their product directly to livestock producers or to feeding companies that implement them in livestock diets. Feeding companies may show interest in developing livestock diets based on local legumes (e.g., [93]), however, research is needed that specifies at which level they can be implemented. In addition, a secure supply is needed where crop farmers consistently deliver, and where feeds can consistently be sold to livestock producers. To produce livestock on feeds with local feed resources, producers require a reliable and steady supply of feed and need to be informed on both desirable and undesirable implications on livestock production and health. In addition, when negative economic implications apply, a specialized niche market for livestock products based on, e.g., local feed resources may be required. Retailers may show interest in selling livestock products in a niche market, but, also here, a continuous product supply is desired. European protein food and feed production can be stimulated by extension services backed by research programs, creation of government intervention through policy legislation, alignment of policies for better inclusion of legumes in the agri-food systems, the development of legume-supported value chains, and engagement of all the stakeholders and beneficiaries tackling the entirety of the value chain [92]. Stakeholder involvement is crucial for engagement and commitment, and the development of innovative solutions and action plans. Furthermore, the knowledge and knowledge-gaps, potential benefits, trade-offs and risks of new farming methods need to be evaluated with multi-level and multi-criteria assessment models [94]. When economic benefits from investments are not immediately evident, transition can only be successful with government policies that focus on providing knowledge and education, and financial support, e.g., subsidies and compensation for potential losses. To convince agriculturists and agricultural workers to adopt sustainable practices, policy changes are needed with close cooperation between and support from all actors involved, including producers, non-governmental and civil society organisations (e.g., dealing with citizens' concerns and expectations about biodiversity, climate change, environmental protection, and social justice), and the retail industry.

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