

Review: Make ruminants green again – how can sustainable intensification and agroecology converge for a better future?

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Livestock farming systems provide multiple benefits to humans: protein-rich diets that contribute to food security, employment and rural economies, capital stock and draught power in many developing countries and cultural landscape all around the world. Despite these positive contributions to society, livestock is also the centre of many controversies as regards to its environmental impacts, animal welfare and health outcomes related to excessive meat consumption. Here, we review the potentials of sustainable intensification (SI) and agroecology (AE) in the design of sustainable ruminant farming systems. We analyse the two frameworks in a historical perspective and show that they are underpinned by different values and worldviews about food consumption patterns, the role of technology and our relationship with nature. Proponents of SI see the increase in animal protein demand as inevitable and therefore aim at increasing production from existing farmland to limit further encroachment into remaining natural ecosystems. Sustainable intensification can thus be seen as an efficiency-oriented framework that benefits from all forms of technological development. Proponents of AE appear more open to dietary shifts towards less animal protein consumption to rebalance the whole food system. Agroecology promotes system redesign, benefits from functional diversity and aims at providing regulating and cultural services. We analyse the main criticisms of the two frameworks: Is SI sustainable? How much can AE contribute to feeding the world? Indeed, in SI, social justice has long lacked attention notably with respect to resource allocation within and between generations. It is only recently that some of its proponents have indicated that there is room to include more diversified systems and food-system transformation perspectives and to build socially fair governance systems. As no space is available for agricultural land expansion in many areas, agroecological approaches that emphasise the importance of local production should also focus more on yield increases from agricultural land. Our view is that new technologies and strict certifications offer opportunities for scaling-up agroecological systems. We stress that the key issue for making digital science part of the agroecological transition is that it remains at a low cost and is thus accessible to smallholder farmers. We conclude that SI and AE could converge for a better future by adopting transformative approaches in the search for ecologically benign, socially fair and economically viable ruminant farming systems.

Keywords: ecosystem services, efficiency, food systems, redesign, sustainability

Implications

There are different futures for ruminant farming systems as regards to production scenarios, climate mitigation measures and food consumption trends. Sustainable intensification (SI) and agroecology (AE) are two frameworks that aim to design more sustainable systems. Here, we analyse them in a historical perspective and discuss how they have been applied to temperate and tropical ruminant systems. Although underpinned by different values pertaining to food consumption patterns, social equity, the role of technology and our relationship with nature, our view is that we should not

be locked into a single approach, as SI and AE could converge for a better future.

Introduction

Livestock is a major component of rural economies, cultures and landscapes around the world. It provides multiple benefits such as the provision of protein-rich food from inedible resources, resulting in farm income and contributing to food security and employment. For instance, livestock products provide 22% of the dietary energy and 50% of protein consumption in Europe. The livestock sector contributes €130 billion annually to the European economy and creates employment for almost 30 million people (Animal Task Force,

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2013). In developing countries, livestock is important as capital stock. Cattle and buffaloes contribute to agricultural activities through draught power, utilise roughages and crop residues that are inedible by humans, and concentrate nutrients in manure for organic fertilisation. The cultural importance of livestock is reflected in the high status that is attached to cattle ownership. Herbivore farming systems also have 'secondary' effects or positive externalities such as contributions to landscape heritage, gastronomy and tourism in European grassland-based landscapes, South-American pampas and Mongolian steppes. Grassland-based landscapes and High Nature Value farmland are important for biodiversity conservation and provide key regulating and cultural services (Rodríguez-Ortega *et al.*, 2014). Despite these positive contributions to society, livestock is also the centre of many controversies as regards to its environmental impacts, including land conversion and degradation. Livestock requires a large amount of feed resources (they use one-third of total cereal production and 8% of human water use; Makkar, 2018). Agricultural land-use to meet the demands for animal products has been noted as the main cause of deforestation; the most recent research shows that approximately two-thirds of the cleared areas in the Brazilian Amazon were converted to pastures (Guéneau, 2018). Livestock account for 14.5% of total greenhouse gas (GHG) emissions (Gerber *et al.*, 2013), which makes the livestock sector a major contributor to climate change. Beef and dairy cattle contribute most to emissions, representing 65% of sector emissions, followed by buffaloes (*Bubalus bubalis*: 8.7%) and small ruminants (6.7%). Grassland-based systems, however, also contribute to carbon sequestration and thus were identified as a key option for mitigating climate change at the United Nation Climate Change Conference that was held in Paris in 2015. Finally, the whole livestock farming sector is currently facing changes in socio-cultural values related to animal welfare and knowledge of food origin.

Total demand for livestock products is expected to increase at a global scale (Campbell *et al.*, 2014). Most of the increase in livestock feed demand will occur in developing countries, which already face many food security challenges (Makkar, 2018) and most of the land-use-related biodiversity impacts (Chaudhary and Kastner, 2016). Therefore, continued exploration of possibilities for increasing livestock production while decreasing the pressure on ecosystems is needed. There are different ways to achieve livestock farming sustainability that include notions or frameworks such as ecological or SI of agriculture, circular economy, industrial ecology, AE and organic farming. There is an ongoing debate whether land for nature and that for production should be segregated (land sparing) or integrated on the same area (land sharing). The first option calls for increasing the production of animal proteins from existing farmland, without further encroachment into remaining natural ecosystems, as many agricultural lands are assumed to not reach their full production potential (Foley *et al.*, 2011; zu Ermgassen *et al.*, 2018). This is the basis of SI that aims to spare land for

nature, as most remaining potentially cultivatable land is beneath tropical forests, where conversion to agriculture is highly undesirable. This option implies that biodiversity in agroecosystems is functionally negligible (Tscharrntke *et al.*, 2012). An alternative option promotes a range of context-specific ecosystem-based principles that stimulate natural processes to reduce dependence on chemical inputs and cut production costs. This is the basis of AE that can be seen as part of a land sharing approach with functional links with ecosystem services (Tittonell, 2014) and assigns equal importance to food production and ecosystem integrity (Dumont *et al.*, 2013).

Sustainable intensification and AE are thus two frameworks that promote ways to reconcile natural resource management and food production in the long term and under climate uncertainty. They have been seen as complementary steps away from industrial systems towards the necessary transition of agricultural and livestock production systems (Tscharrntke *et al.*, 2012; Dumont *et al.*, 2013; Smith, 2013; Gordon *et al.*, 2017; Makkar, 2018). However, other authors have stated that although SI is a step in the right direction, it mainly conforms to the current neoliberal agricultural model (Guéneau, 2018), and AE cannot co-exist alongside the aggressive expansion of industrial agriculture, genetically modified organisms and agrofuels (Altieri *et al.*, 2017). According to Fouilleux *et al.* (2017), it is not necessary to endorse productionist agricultural models to feed the world's population. Agroecology would thus not need to be combined with any other approaches (Altieri *et al.*, 2017). Our aim here is not to enter this type of controversy but rather to review the potentials of SI and AE to design sustainable ruminant systems. In the first two sections, we analyse SI and AE in an historical perspective, which reveals that SI is an efficiency-oriented perspective, while AE promotes system re-conception. Comparing SI and AE highlights a different role of nature in the design of agricultural and livestock farming systems (Tittonell, 2014). We also analyse the main criticisms of these frameworks: is SI sustainable? How much can AE contribute to feeding the world? In the final section, we summarise how SI and AE are underpinned by different values and worldviews (i.e., a structuring system of meaning informing how humans interpret the world; Cayre *et al.*, 2018) about food consumption patterns and the role of technology. However, we agree with Foley *et al.* (2011) that we should not be locked into a single approach, which leads us to discuss how SI and AE could converge for a better future.

Sustainable intensification

Historical perspective

The term 'sustainable intensification' originated from development efforts that aimed to increase the productivity of sub-Saharan agriculture in the 1990s (Pretty, 1997). It was used in the context of increasing production from existing agricultural land in ways that lower environmental impact

and do not lead to further land conversion or loss of 'undisturbed' natural ecosystems (Campbell *et al.*, 2014). In the SI framework, changes in land-use intensity (higher yields, multiple cropping seasons, higher livestock stocking density) are accompanied by changes in the levels of biophysical and socioeconomic inputs to the land (e.g., labour, feed resources or capital). There are a number of illustrations showing that SI can have huge effects on domestic food budgets, social infrastructure, business development and the well-being of both the rural and urban populations (Pretty *et al.* 2011). Proponents of SI originally emphasised the importance of using local knowledge and developing agricultural methods suited to local conditions. Participation of smallholder farmers was considered crucial for the development of more productive technologies (Pretty, 1997). A wide range of bottom-up, integrated technologies was therefore used to conserve water and soils and to manage nutrient flows and pests. However, the term remained loosely defined, so that SI was subsequently firmly embraced by the industry and by a number of international organisations (Food and Agriculture Organisation (FAO), 2010; Campbell *et al.*, 2014) for whom an increase in food demand is an inevitable response to population growth and dietary shifts towards more animal proteins.

In a recent assessment of the concept of SI, many implementers of this framework indicated there is no clear difference between SI and 'traditional' intensification and modernisation practices (Petersen and Snapp, 2015). In practice, SI has long been 'narrowly' focused on production and has been criticised for lacking engagement with the key social principles of sustainability (Loos *et al.*, 2014). According to these authors, focusing on the need to increase food production reflects a fundamental misunderstanding of the primary causes of food insecurity, that is, poverty and political and structural problems. Issues such as equity, access to food and food distribution would thus need to be prioritised before increases in production can improve food security. Recently, the SI framework has been more broadly conceived in a way that addresses dietary issues and improves equity of access to food. In this perspective, Garnett *et al.* (2013) do not consider SI as a 'business-as-usual' food production with 'marginal' improvements in sustainability, but rather as a rethinking of a food system that reduces its environmental footprint supports rural economies and enhances human nutrition and animal welfare. Improvements in animal diets could for instance benefit animal welfare. However, there are potentially negative effects related to (i) more confined environments that affect the ability of the animals to express their natural behaviour and (ii) the risk of more animal health problems due to breeding for higher yields and growth rates (Röös *et al.*, 2017; Huber, 2018).

Sustainable intensification as an efficiency-oriented perspective

One priority of SI is to close yield gaps (i.e. the difference between the actual and attainable yield on the basis of the

genetic potential and optimal production conditions without yield limiting and reducing factors) to produce more food while using less land. Rao *et al.* (2015) discussed that the SI of forage-based systems is based on several intensification processes, including genetic intensification, that is, the deployment of productive livestock breeds, and the development and use of grass and legume cultivars selected because of their higher biomass production, nutritive value and persistence relative to native grasses. One key to the successful intensification of tropical forage-based systems is the adequate selection of fodder species, for instance, leucaena (*Leucaena leucocephala*, Lam.), a nitrogen-fixing shrub that can serve as the backbone of the system. Sustainable intensification of tropical forage-based systems is likely to increase their productivity (zu Ermgassen *et al.*, 2018) while providing regulating ecosystem services, including a contribution to soil fertility, limitation of erosion, and climate regulation via CO₂ sequestration. Integration of forage systems within cropping systems should enhance the coupling of carbon (C) and nitrogen (N) cycles in grasslands, cover-crops, and ley-farming systems, thus reducing the presence of reactive N in the soils and consequently, the risk of nitrate leaching and nitrous oxide emissions to the atmosphere (Lemaire *et al.*, 2014). A large part of grass-based biomass and crop residues can be used for feeding ruminants. Genetic intensification of animals has frequently led to the use of high-yielding breeds. As an example, dairy producers in many places around the world view Holstein Friesian cattle as the ultimate cow for their farm to show their competence as dairy farmers. However, these animals are very dependent on controlled and optimal conditions; they can be vulnerable to climate change and are little adapted to feed on roughages (Phocas *et al.*, 2016). As a consequence, production levels are often far below the attainable yield.

The search for increased efficiency requires precise adjustment of the diets of individual animals to their requirements. Precision livestock farming, by recording herbage biomass and quality and animal physiological and behavioural traits, offers new possibilities to efficiently monitor and manage highly productive livestock systems. According to Campbell *et al.* (2014), SI and climate smart agriculture are highly complementary, with SI being an essential lever for decreasing GHG emissions per unit of product (Röös *et al.*, 2017). This efficiency-oriented perspective is in line with the logic of substituting cereals and soybean meal in ruminant diets with human-inedible resources. Crop residues such as culled Brussels sprouts, waste tomatoes and carrot pulp after juice extraction are used to supplement grazing animals or forages in areas where intensive vegetable production is common. Another innovative option consists of producing insects from food wastes and then using the insects as protein sources for livestock, including dairy cows (Stamer, 2015). Other human-inedible feed resources can be used, mainly for dry cows, growing heifers and small ruminants, including dried distillers grains with solubles, palm kernel cake or spineless cactus (Makkar, 2018).

Is sustainable intensification sustainable?

Within the SI framework, the focus on improving resource use efficiency may, however, not necessarily lead to a reduction in the environmental footprint. This was observed in the Brazilian Amazon region, where more efficient agricultural systems were seen as profitable to farmers, which resulted in the expansion of the cultivated area and further deforestation (Lambin and Meyfroidt, 2011). The most efficient systems are not necessarily the most sustainable. Rodríguez-Ortega *et al.* (2017) compared three Mediterranean sheep farming systems by applying the emergy methodology that is based on the amount of direct and indirect materials and energy sources embodied in final products. Lamb meat production was 1.9 and 1.3 times more intensive and efficient, respectively, in a partially integrated mixed system than in a pasture-based sheep system but 5.1 times less sustainable as a result of lower self-sufficiency and renewability. One problem of crop-livestock systems that sell meat and cereal crops is that animals and crops frequently do not ecologically complement each other (Altieri *et al.*, 2017). As a consequence, farmers keep on buying external chemical inputs. Conversely, in a suckler-cow farm network of the Charolais-area, organic farmers grow crops on farm to feed the cows and efficiently exploit the diversity of feed resources. These farms had the lowest GHG emissions and non-renewable energy consumption per ha, the lowest operational costs and the highest net income per worker (Veysset *et al.*, 2014).

The definition of sustainability within the SI framework largely addresses the reduction of harmful effects, while little attention has been paid to producing positive environmental outcomes such as increasing the supply of clean water and the stocks of natural resources including fertile soils. Moreover, the focus is essentially utilitarian, that is, reducing harmful effects is done to ensure continuing agricultural production while remaining within 'planetary boundaries'. According to Struik and Kuyper (2017), the words 'sustainable' and 'intensification' are often not assigned equal weight. For instance, the Irish grassland-based dairy system developed according to the principles of SI causes biodiversity losses (Sullivan *et al.*, 2010). The Food and Agriculture Organisation has advocated using an ecosystem services approach for SI (FAO, 2010). Given the classical trade-off between food production on the one side and many regulating and cultural services on the other, it is difficult to enhance all ecosystem services simultaneously. According to Smith (2013), SI should thus be regarded as a 'guiding principle in decisions about land-use, rather than as an end-point'. By interpreting SI as an inevitable response to population growth and the search for global food security, it is also only after productivity concerns are covered that most environmental and social issues are addressed. This limits the emergence of converging and transformative solutions that jointly account for productive and environmental issues and that meet the expectations of all types of stakeholders (Howe *et al.*, 2014). Solutions are thus mostly sub-optimal for the environmental and social dimensions. For instance, Thorlakson *et al.* (2018) recently

analysed how 449 companies in the food, textile and wood-products sectors have adopted voluntary practices to improve the environmental and/or social management of their suppliers' activities. Half of these companies use some form of sustainable sourcing practices. However, these practices are limited in scope, with 71% covering only one or a few input materials, one quarter applying to only a single product line, and many primarily focusing on labour rights and compliance with national laws.

Agroecology*Historical perspective*

The term 'agroecology' can be traced back to the 1930s and has been used to denote a scientific discipline, a set of agricultural practices, and a social movement that promotes culturally sensitive, socially fair and economically viable farming systems (Wezel *et al.*, 2009). Until the 1960s, AE was only referred to as a scientific discipline. From the 1970s, AE gradually emerged as a movement in line with environmental movements that went against industrial agriculture creating greater specialisation and intensification. As a scientific discipline, AE applies ecological theory to the design and management of sustainable agroecosystems (Altieri, 2002; Wezel *et al.*, 2009) or of the entire food system (Francis *et al.*, 2003). It aims to stimulate natural processes to design agricultural systems that are weakly artificialised, productive, environmentally friendly and less dependent on chemical inputs. As a movement, AE counts thousands of researchers and practitioners, mainly in Latin America, where it does not work through any standard or certification system (Tittonell, 2014). It promotes traditional farming systems that sustain year-round yields through the use of agrobiodiversity. Diverse plant species and genetic resources and optimal interactions between system components (including between crops and livestock) are used to enhance agroecosystem functions rather than to introduce chemical inputs. Agroecology also promotes food sovereignty, local autonomy, and community control of land, water and genetic resources (Altieri *et al.*, 2017). Farmer-to-farmer networks play a key role in the extension process and dissemination of knowledge (Rosset *et al.*, 2011).

Despite the recent surge in the academic literature on AE, livestock farming systems have scarcely been considered in most agroecological thinking until recently. Disconnectedness from the land is probably the main problem threatening the sustainability of livestock farming. On the basis of a study conducted by Altieri (2002), who identified the key ecological processes to be optimised in agricultural systems, Dumont *et al.* (2013) proposed five principles as a guideline to implement site-specific combinations of agroecological practices in livestock farming systems: (i) achieve integrated animal health management, (ii) decrease the external inputs needed for production, (iii) decrease pollution by optimising the metabolic functioning of farming systems, (iv) enhance functional diversity within livestock farming systems to strengthen their resilience, and (v) preserve biological diversity by adapting

management at farm and landscape scales. The application of these principles was shown to generate environmental and economic benefits that were quantified across a broad range of ruminant, pig, poultry, aquaculture, and integrated crop-livestock systems. The extent to which the five principles were mobilised differed between production systems and their degree of intensification (Dumont *et al.*, 2013; 2017).

Agroecology promotes system redesign and can lead to win-wins between production and environmental goals

Agroecology promotes system redesign and questions production goals. Within the French CIVAM network (Centres d'Initiatives pour Valoriser l'Agriculture et le Milieu rural), the target goal was to create added value from dairy production without always maximising outputs per animal or per unit area. This led to an increase in the use of grazed herbage at the expense of maize silage, as well as a reduction in the use of concentrate feeds. Limiting pesticides and insecticides through more complex crop rotations and an increase in grassland area at the farm level had various direct and indirect benefits on soils, water and biodiversity. Grasslands comprised a large proportion of grass–legume mixtures, and the grazing season was extended into late autumn and winter. Herd management was tailored to adapt animal requirements to resources by grouping calving periods. Inputs, feed costs and mechanisation costs were lower than in conventional systems from the same area. In spite of slightly lower milk production (-13%), the gross margin was higher (+26%). Greenhouse gas emissions were similar between the two systems, that is, 1.1 kg CO₂-eq/l but accounting for carbon sequestration in permanent grasslands and hedgerows led to a 14% reduction of net GHG emissions in the CIVAM compared with conventional dairy farms of the same area (0.87 v. 1.02 kg CO₂-eq/l; Duru and Therond, 2015).

One strength of agroecological systems lies in their self-sufficiency, which, through interacting with their environment and the recycling of on-farm wastes, can produce part of the resources needed for production. Self-sufficiency reduces dependency on erratic market prices but increases dependency on climatic conditions, for instance, summer droughts that can drastically reduce grassland biomass production. The potential of all-forage diets still needs to be demonstrated for productive dairy cattle breeds with high nutrient requirements. An example is the lower ovarian cyclicity during early lactation, which results in poor the reproductive performance of Holstein-Friesian and Montbéliarde cows in low-input systems, in spite of spring calving that aims to optimise grassland utilisation (Pires *et al.*, 2015). Use of animal genotypes adapted to their environmental conditions, and access to pasture so that animals express their natural behaviour are essential principles of AE (Dumont *et al.*, 2013; 2014), and are assumed to guarantee animal welfare. Beef cattle, dairy cattle, sheep and dairy goat farmers in agroecological systems did not establish strong priorities among breeding goals (i.e., between feed efficiency, animal health, reproduction, docility, product quality,

etc.), but rather searched for animals with 'balanced' characteristics that are classically referred to as being 'robust' (Phocas *et al.*, 2016).

High productivity levels can be achieved in tropical and Mediterranean silvopastoral systems that are based on highly diverse feed resources. In a Colombian dairy system, a tree-rich matrix allowed an increased stocking rate and increased milk production by 130% (Murgueitio *et al.*, 2011) while completely eliminating the use of chemical fertilisers and contributing to climate regulation via the maintenance of soil organic matter and complex soil food webs. In tropical silvopastoral systems, the presence of trees within pastures benefits cattle welfare through less exposure to stressful climatic conditions and might increase milk yield (Paciullo *et al.*, 2014). Observations in Latin America have emphasised that enhancing tree species diversity and structural complexity could increase system resilience after a hurricane (Altieri *et al.*, 2017). An increased number of bee species in silvopastoral systems increased coffee production by an average of 5% (Cardoso and Mendes, 2014). As trees mature, they also provide ecological corridors that connect wildlife-friendly habitats. In addition, trees provide timber and firewood materials to farmers, roots and bark for medicinal uses, green forage and pods for livestock, and fruits and honey for human consumption (Murgueitio *et al.*, 2011). Overall, win-win solutions are the result of collective decisions rather than situations where only individual interests and power relations prevail; this has been shown in various temperate and tropical environments (Groot *et al.*, 2010; Carmona-Torres *et al.*, 2011; Howe *et al.*, 2014).

How much can agroecology contribute to feeding the world?

One of the main criticisms of AE is that the productivity of agroecological systems is assumed to be lower than that of sustainably or traditionally intensified systems. This is denied by AE advocates who stress the high long-term performance (Murgueitio *et al.*, 2011) and higher resilience of tropical agroecological systems (Altieri *et al.*, 2017). In addition, an increase in the complexity of crop rotations with temporary fodders, catch and cover-crops and traditional mixtures of crops and legumes (such as 'milpa' in Mexico or 'méteils' in France), mostly to the detriment of cereals, will likely enhance production and ecosystem services in both tropical and temperate environments (Altieri *et al.*, 2017; Barbieri *et al.*, 2017). There is indeed no *a priori* for system intensification in the agroecological framework, as previously illustrated by the example of French CIVAM farms, for which profitability was high for farmers (Dumont *et al.*, 2013; Duru and Therond, 2015). One characteristic of most agroecological systems is that more time is required to supervise and observe the system. Consequently, labour productivity and productivity per unit area can be lower than in classically or sustainably intensified systems. This can be buffered by creating added value on the farm from higher-value products due to their better sensory quality or image, associated certification, and sometimes on-farm processing. Intrinsically, functional diversity plays a key role in the design of agroecological

Table 1 A comparative summary of how sustainable intensification (SI) and agroecology (AE) have been applied to temperate and tropical ruminant systems

	Sustainable intensification	Agroecology
Production per unit area or per animal	Aims at increasing agricultural yields. Productivity is assumed to increase through intensification of existing farmland	No <i>a priori</i> for intensification. Production can slightly decrease per unitary component but at farm level, diversification of production increases overall farm yields, ES and profitability to farmers
Use of inputs	A key point is to increase nutrient use efficiency to minimise negative impacts on the environment (no <i>a priori</i> for levels of inputs required for production)	A key point is to propose systems that are less dependent on chemical inputs and use more on-farm produced inputs through recycling
Link to local environment	Makes best use of environment potential, e.g., through adapted cultivars/breeds. Inputs buffer environmental fluctuations	Weakly artificialised systems tied to their biophysical environment and that use diversity to strengthen their adaptive capacity and resilience
Biodiversity and ecosystem services (ES)	SI entails increasing food production from existing farmland, as part of a <i>land sparing</i> strategy. Up to a given stocking density, regulating ES can be provided, but there is little or no incentive for producing positive outcomes by using biodiversity and ES	Agroecology can be seen as part of a <i>land sharing</i> approach with functional links with ES. It considers biodiversity as both a resource (that provides ES to farmers) and an output. Scaling-up AE would benefit from payment for environmental services
Animal selection goals	Selection on feed efficiency (to ensure efficient transformation of feed into animal protein) or on residual feed intake. Efficient animals emit less greenhouse gases per unit of product	Selection on a number of productive and adaptive traits (i.e., breeding for robustness). Animal genetic resources and local breeds offer opportunities to adapt animals to their local environment
Role of technology	Technology is used to optimise the timing and quantity of inputs applied. Anaerobic digestion recovers utilities from wastes. SI and precision livestock farming are highly complementary	Technology facilitates the collection of individual-based information and can be used to monitor every component of the system to increase its overall efficiency. Technology needs to remain accessible to smallholder farmers
Knowledge transfer	Mainly a top-down approach, though participation of farmers was initially considered crucial for the development and extension of productive technologies	Mainly bottom-up, as agroecology places strong value on local knowledge. Farmer-to-farmer networks also play a key role in information transfer
Labour	Aims to increase labour productivity as part of efficiency improvement	More time to supervise and observe the system. Labour productivity can thus be lower than in industrial or SI systems
Market	Non-differentiated products sold on the global market	Selling in niche markets allows benefiting from the added value created on the farm
	= > A weak form of ecological modernisation largely based on nutrient use efficiency and technology	= > A strong form of ecological modernisation largely based on system re-conception and ecosystem services

ruminant systems so that they both benefit from and provide ecosystem services. Scaling-up agroecological livestock farming would thus benefit from payment for environmental services.

Functional diversity is assumed to increase system resilience, redundancy being the underlying property that supports mechanisms of stabilisation since the collapse of any species can be offset by another species with similar characteristics. The 'portfolio effect' states that communities with higher species richness are more likely to include the species that is best adapted to any given condition in fluctuating environments so that the number of species *per se* has a positive effect on system resilience (Dumont *et al.*, 2017). Within herds, diversity of individual trade-offs between functions that was quantified in dairy goats (Puillet *et al.*, 2010) and dairy cows (Ollion *et al.*, 2016) does not increase herd milk production but is assumed to stabilise it under fluctuating environmental conditions. Abiotic and biotic interactions, including biogeochemical cycles and trophic interactions, lend ruminant systems further resilience properties (Dumont *et al.*, 2017). The extent to which ecological processes benefit long-term system performances needs to be analysed for a fair evaluation of agroecological ruminant

systems. So far, there has been a huge gap in terms of investments in research between traditionally or sustainably intensified systems and agroecological systems since the former have received the majority of governmental funding and almost the total investment in research by the private sector (Tittonell, 2014). A fair answer to the question of how much can AE can contribute to feeding the world thus requires the opening of a vast research agenda for the animal science community (Dumont *et al.*, 2014). In the AE paradigm, researchers no longer produce generic solutions or tools but consider farmer skills and knowledge (Altieri *et al.*, 2017). This calls for a transdisciplinary approach of the research-development-innovation chain to bridge the gap between science and practice.

How can sustainable intensification and agroecology converge for a better future?

A comparative summary of the two frameworks is given in Table 1. It shows that SI and AE represent different forms of ecological modernisation of agriculture. Sustainable intensification is mainly related to a 'shallow sustainability' approach

(Hill, 1998), also called a 'weak form of ecological modernisation' (Horlings and Marsden, 2011; Duru and Therond, 2015), that is largely based on an increase in nutrient use efficiency (Garnett, 2014). Agroecology goes beyond the use of alternative inputs and promotes system redesign. It can thus be seen as a 'deep-sustainability' approach (Hill, 1998), also called a 'strong form of ecological modernisation', in which ruminant farming systems benefit from functional diversity and provide ecosystem services (Horlings and Marsden, 2011; Duru and Therond, 2015). In this perspective, ruminant farming is more than just the production of meat and milk, so that a simple functional property (for instance, GHG emissions expressed in kg CO₂-eq/kg product) is an inadequate measure of system performance (Dumont *et al.*, 2014; Makkar, 2018). In line with this dichotomy, different farmers' worldviews were shown to co-exist in Californian organic cropping systems (Guthman, 2000) and French Protected Designation of Origin cheese production areas (Cayre *et al.*, 2018). On the one side, some farmers focus mainly on input substitution and use technology to achieve a high level of food production, while on the other small-scale farmers follow agroecological 'ideals' in more diversified systems.

Convergence between sustainable intensification and agroecology requires moving towards a wider food system scale

Agroecology and SI historically did not pay the same attention to the social dimensions of sustainability (Wezel *et al.*, 2009; Loos *et al.*, 2014). Agroecology and SI could now converge as some researchers investigating SI have proposed the adoption of a food-system transformation perspective (Garnett *et al.*, 2013). Central to this is the conviction that excessive meat consumption is a leading cause of the environmental crisis. For instance, Popp *et al.* (2010) examined non-CO₂ GHG emissions from agriculture under different assumptions of food demand and concluded that reduced meat consumption would be far more effective than any technical mitigation measure. This goes in line with outputs from a recent meta-analysis (Aleksandrowicz *et al.*, 2016). Consistently, most ongoing scenarios simulate a decline in animal protein consumption and limit livestock production to pasture and co-products from human food (e.g., van Zanten *et al.*, 2016). However, some proponents of SI, including actors and lobbies from food and farming industry, and researchers, still highlight the short-term negative effects such options could have on livestock business and economic growth in the agricultural sector (Röös *et al.*, 2017).

While both frameworks aim to optimise land-use at the global level, there are still different views on where food should be produced. Indeed, while enough food is produced globally there remains strong food security challenges. This mismatch emerges through the complex patterns of global trade in food products (Smith, 2013; Gordon *et al.*, 2017). Integrated global markets have often been advocated by SI proponents (Röös *et al.*, 2017). For instance, demographic shifts and economic development in emerging countries have stimulated EU exports, notably for the dairy and pork sectors.

By contrast, AE calls for new forms of regionally embedded agri-food systems, which implies rethinking market mechanisms. It has given priority to local autonomy and community control of land since the very beginning (Altieri, 2002; Rosset *et al.*, 2011; Cardoso and Mendes, 2014). In addition, AE calls to strengthen links between producers and consumers. In Europe and North America, local production emerged to restore consumer confidence in food systems. In Europe, local production creates added value for high-quality products with a strong territorial identity. In developing countries, the local production aims to secure food sovereignty based on low-input production systems. As no space is available for agricultural land expansion, for instance, in South Asia and East Asia (Smith, 2013), local production will imply a search for methods to increase yield, an increase in cropping intensity (e.g., double or triple cropping within a year), and/or increased and more resilient production in complex silvopastoral systems. This can be achieved through the use of adapted crossbreeds or local breeds rather than the use of high-yielding livestock breeds that may be ill-adapted to climate change. Intensification efforts should also consider the social context and are made easier when innovations have been co-designed by farmers and NGO's involved in rural development from the start of the process (e.g. Kosgey *et al.*, 2006 for small ruminant breeding programmes in the tropics).

Beyond closing yield gaps, meeting the projected demands of population growth calls for improving food distribution and access, as well as market infrastructure, which will require changing policies and global mechanisms that rule the food system (Foley *et al.*, 2011). As reviewed by De Schutter and Vanloqueren (2011), market and political obstacles could be overcome through six policy principles: (i) focusing efforts on the needs of smallholders; (ii) redistributing public goods as part of food security policies; (iii) gaining a richer understanding of innovation that includes traditional knowledge; (iv) involving meaningful participation of smallholders in local programmes and nationwide policies; (v) using public procurement to speed the transition towards sustainable agriculture; and (vi) redefining performance criteria used to monitor agricultural projects beyond classical measures such as productivity per unit of land or water. This confirms that SI and AE cannot be considered from their biotechnical definition only and should further move towards a wider food system scale, encompassing productive, environmental and social dimensions.

Use of new technologies is widespread in sustainable intensification and offers opportunities for scaling-up agroecology

The application of new technologies has a different share within the SI and AE frameworks. Within SI, new technologies provide a foundation for the transition towards more efficient and intensified systems, for instance, through the optimal timing and amount of feed offered to the animals, nutrient recycling, early detection of livestock diseases, and alternative reproduction techniques (Food and Agriculture

Organisation, 2011; Dumont *et al.*, 2013; Garnett *et al.*, 2013; Campbell *et al.*, 2014). Makkar (2018) advocated the need to develop a business model around these technologies and to bring private companies on board. Through the SI framework, biotechnology and the use of genomic information have also found a new avenue to promote themselves as a solution to world hunger (Tittonell, 2014). The most recent example is the Bill and Melinda Gates Foundation funding a non-profit research alliance to select cows that are both more productive and resistant to heat stress, for instance by providing genomic tools for screening young animals that have the desired traits for a particular environment. Early detection of livestock diseases through precise animal monitoring would benefit animal welfare. More broadly, making appropriate use of digital sciences is likely to help in the gathering of individual-based data and the monitoring of every component of the system to increase its overall efficiency (Ingrand, 2018). Livestock farmers are indeed becoming increasingly reliant on new digital technologies and communication tools that increase knowledge dissemination and connections among actors. For instance, pastoralist communities in East Africa and Mongolia use smartphones as an early warning system for predicting forage availability in arid rangelands, which increases system long-term efficiency. The key issue for making digital science part of the agroecological transition is that it remains at a low cost and is thus accessible to smallholder farmers.

Strict certifications could offer opportunities to boost sustainable intensification and agroecology

Consumers and civil society pressures have led to increased adoption of sustainable practices by food companies (Thorlakson *et al.*, 2018), which is likely to have some animal welfare and environmental benefits. Although varying across regions and socio-demographic characteristics of consumers, the willingness of consumers to pay for farm animal welfare is higher for beef and dairy cows than for pigs, poultry and aquaculture (Clark *et al.*, 2017). This reveals the potential of labelling ruminant farming systems through strict welfare certifications so that citizens can develop their own system of consumption ethics (Dumont *et al.*, 2014). Regarding environmental benefits, compliance with the Brazilian Forest Code was achieved thanks to increased transparency in the Brazilian cattle supply chain (Guéneau, 2018; zu Ermgassen *et al.*, 2018). This increased compliance did not affect the productivity of beef and dairy farms. Success depended on the independent audit of slaughterhouses, to ensure they only purchased livestock from farms/municipalities in compliance with the Forest Code (zu Ermgassen *et al.*, 2018). In Latin America, AE, however, does not operate through any standard or certification system (Tittonell, 2014). Botreau *et al.* (2014) showed that it is possible to build a multicriteria evaluation tool that qualifies the compliance of mountain dairy systems with agroecological principles. By crossing agroecological principles with categories of state variables on which the fulfilment of these principles should have a positive effect, it becomes possible to identify a complete range of

practice-based criteria accounting for ecological processes and interactions within a system. The criteria should be understood and acceptable by farmers and technical advisors and are specific to the mountain context (Botreau *et al.*, 2014), as agroecological practices must be adapted to local conditions (Altieri, 2002). This methodology allows the comparison of mountain dairy farms and can thus lead to a strict and verifiable certification of agroecological systems.

Conclusion

Both SI and AE promote ways to reconcile natural resource management and food production in the long term. In spite of a common goal, SI and AE are underpinned by different values and worldviews about food consumption patterns, the role of technology and our relationship with nature. Historically, SI sees the increase in animal protein demand as inevitable and therefore focuses on increasing production efficiency as part of a land sparing strategy. Agroecology appears more open to dietary shifts towards less animal protein consumption to rebalance the whole food system and gives a key role to nature-based processes in the design of livestock farming systems. Sustainable intensification and AE could, however, converge for a better future. Food-system transformation perspectives and attention on social justice have been recently integrated into the SI framework. As no space is available for agricultural land expansion in many areas, local production from agroecological systems also requires an increase in the productivity of ruminant systems. Intensification of agroecological systems should, however, be achieved differently than what occurred in industrial systems, by considering context specificities and farmer knowledge. Applying SI to industrial systems could be seen as a green-washing strategy because it leads only to a weak form of ecological modernisation. Conversely, identifying first the key ecological processes to be optimised, is more likely to lead in the direction of a strong form of ecological modernisation assumed here to be more desirable.

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Declaration of interest

The authors declare no competing interests regarding this publication.

Ethics statement

Section is irrelevant for this literature review.

Software and data repository resources

No new software or database were generated as part of the outcomes of this literature review.

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