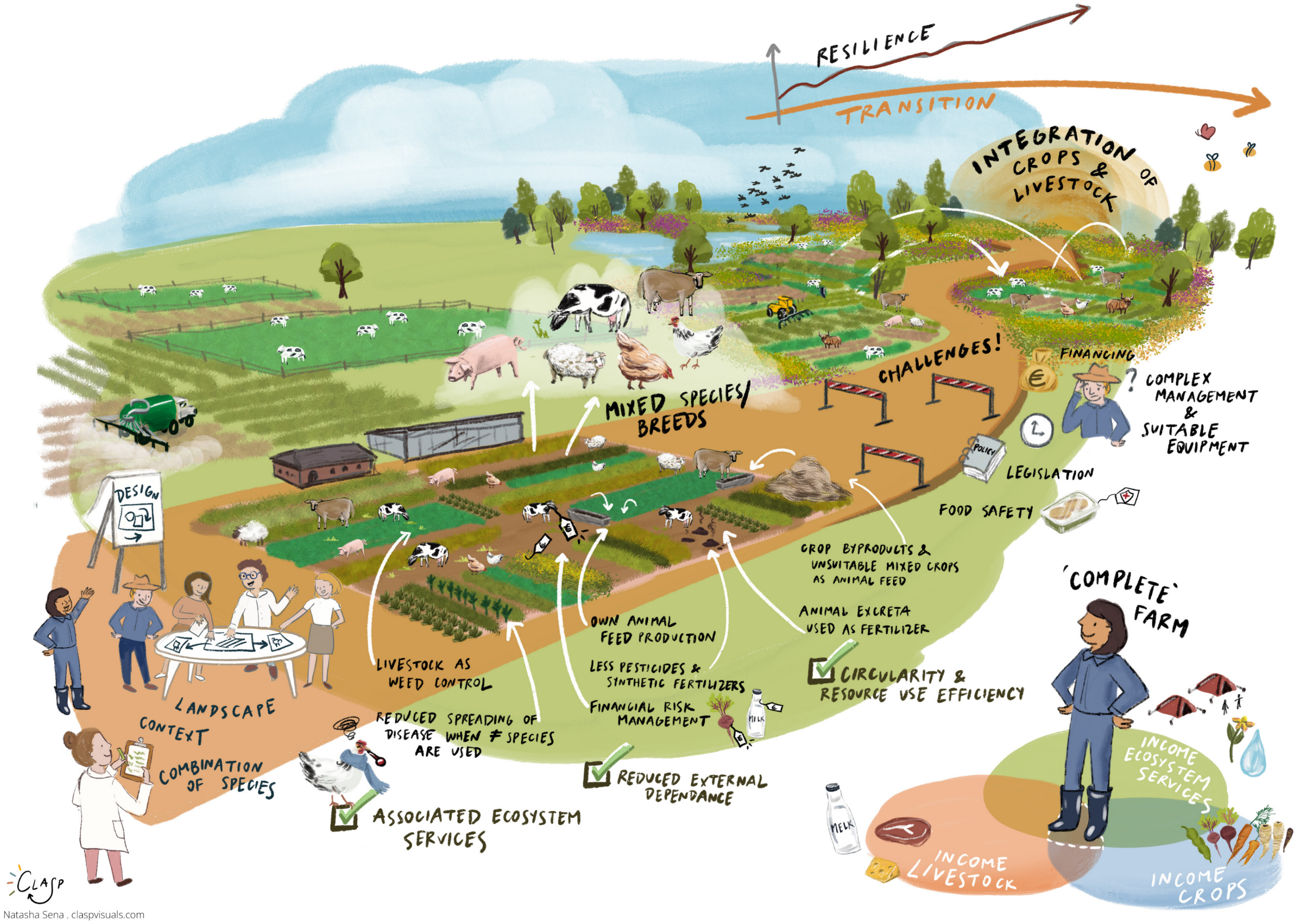

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WAGENINGEN UNIVERSITY & RESEARCH

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Integration of livestock in intercropping systems

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Samenvatting: Strokenteelt wordt gezien als een duurzamer alternatief voor monoculturen, en kan bijdragen aan verminderd gebruik van pesticiden en kustmest en aan behoud van biodiversiteit. Strokenteelt brengt echter verschillende uitdagingen met zich mee. Sommige van deze uitdagingen kunnen mogelijk worden overkomen door de integratie van vee in deze productiesystemen. Dit project onderzoekt de potentiële rol en voordelen van vee in relatie tot toegenomen gewasdiversiteit op bedrijfs- en perceelsniveau, door middel van 1) literatuuronderzoek, 2) interviews met boeren en 3) een focusgroepdiscussie waarin we een praatplaat hebben ontwikkeld over gewas-vee-integratie. Uit het literatuuronderzoek blijkt dat de integratie van landbouwgewassen en vee veel voordelen kan hebben, waaronder gereduceerde benodigde input van pesticiden en kunstmest, het gebruik en de omzetting van bijproducten van gewassen in dierlijke eiwitten, en financieel risicobeheer, maar er zijn ook nadelen, waaronder minder eenvoudig en efficiënt management van het bedrijf. De interviews ondersteunden de uitkomsten van het literatuuronderzoek en brachten aspecten naar voren die aandacht behoeven voor praktische implementatie. Hoewel de toegevoegde waarde van de integratie van vee sterk afhangt van de context en het bedrijfsmanagement, lijkt er potentie te zijn voor de implementatie van strokenteelt-vee-integratie, op veld-, boerderij- of regionale schaal, om zo een biodiversiteit-positieve landbouw te verwezenlijken.

Summary: Intercropping is considered to be a sustainable alternative to monocultures, and could contribute to reduced use of pesticides and artificial fertilizer and to biodiversity conservation. However, intercropping comes with several challenges. Some of these challenges can potentially be overcome through the inclusion of livestock in these production systems. This project investigates the potential role and benefits of livestock species in relation to intercropping and enhanced crop diversity at farm and field level, using 1) literature review, 2) farmer interviews and 3) a focus group discussion in which we developed an infographic on crop-livestock integration. The literature review indicated that crop-livestock integration can have many benefits, including less required input of pesticides and fertilizer, use and conversion of crop byproducts into animal protein, and financial risk management, but there are also downsides, including a reduced ease and efficiency of management. The interviews supported the outcomes of the literature study and highlighted aspects that require attention for practical implementation. Although the added value of integration of livestock strongly depends on the context and farm management, there appears to be great potential for the implementation of intercropping-livestock integration, on field, farm or regional scale, to achieve a biodiversity-positive agriculture.

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Foreword

This research was carried out as part of a Wildcard project within the Biodiversity-Positive Food Systems investment theme of Wageningen University and Research (WUR). This investment theme addresses the question of how we can transform food systems to make them biodiversity-positive, and aims to provide fundamental knowledge for innovative pathways that enhance biodiversity and ecosystem services on fields, farms, in landscapes and in value chains (WUR, 2023). The investment theme focusses on three main research themes (WUR, 2023):

1) Breeding for diversity to broaden the genetic base of the food system
2) Scaling up promising biodiversity-positive practices
3) Post-harvest implications for diversity and variation in raw materials.

In addition to these research themes, the investment theme supports several Wildcard projects, i.e., a set of smaller research and outreach projects. In the Wildcard project of which the outcomes are described in this report, we aimed to contribute to the first research theme, which focusses mainly on (inter)cropping strategies, by examining the potential role for animals in these food production systems. With this report we hope to inspire researchers, farmers and other stakeholders with examples of how intercropping-livestock integration can support biodiversity-positive food systems.

We would like to thank the farmers we have interviewed for their time and for sharing their thoughts and vision on the integration of animals in intercropping systems.

Summary

Diversification of farming systems is seen a potential means to achieve the transition towards more sustainable and biodiversity-positive food systems. One way to achieve diversification is intercropping, which is the growing of multiple crops on the same field at the same time. Intercropping may provide a more sustainable alternative to large monocultures on arable farms, reducing fertilizer and pesticide use while increasing absolute yields and biodiversity. However, intercropping comes with several challenges, such as difficulty with processing the resulting products when they are mixed and unsuitable field machinery. Some of these challenges can potentially be overcome through the inclusion of livestock in these production systems. Therefore, the main aim of this project was to investigate the potential role and benefits of livestock species in relation to intercropping and enhanced crop diversity at farm level. To this end, we explored interactions between crop and livestock species, for further development and implementation of biodiversity-positive food systems, focusing on 1) the potential of crop-livestock combinations in intercropping systems, 2) the relevance of particular crop combinations in intercropping within crop-livestock systems, and 3) relevant criteria for the use of genetic resources in integrated crop-livestock farming systems. To gather insight into these aspects, we used 1) literature review, 2) expert farmer interviews and 3) a focus group discussion in which we developed an infographic on crop-livestock integration. While we did not specifically focus on the Netherlands for this study as a whole, the farmer interviews were all with Dutch farmers. The literature review indicated that crop-livestock integration can have many benefits, including (but not limited to) less required input of pesticides and fertilizer, use and conversion of crop byproducts into animal protein, and financial risk management. However, there are also downsides, including (but not limited to) a reduced ease and efficiency of management, and the requirement of skills in a variety of activities. The interviews supported the outcomes of the literature study, for example in terms of improved resilience, feed-manure exchange, positive effects on biodiversity, and the challenges that these systems face, such as the dependency on good management. The interviews also highlighted aspects that require attention for practical implementation of intercropping, such as harvest timing considerations and adapted machinery. Overall, the interviews showed the added value of combining both scientific knowledge and practical experience in the study of intercropping-livestock integration. In the focus group discussion we developed an infographic on crop-livestock integration, highlighting the main conclusions from this study. Overall, we quite quickly discovered that intercropping-livestock integration has not yet reached a level at which breeding for specific characteristics in especially livestock is likely to be considered highly relevant, as there are considerable practical hurdles to overcome regarding mechanization, processing and legislation before these more 'detailed' aspects can start to play a significant role. However, even though the added value of integration of livestock strongly depends on the context and careful consideration of the system and adequate management are pivotal, there appears to be great potential for the implementation of intercropping-livestock integration, on field, farm or regional scale, to achieve a sustainable, biodiversity-positive agriculture.

1 Introduction

There is a need for a transition to achieve more sustainable and biodiversity-positive food systems, through improving circularity and resilience of farming systems and reducing their environmental impact. Diversification of farming systems is seen as an important means to achieve this transition (Kremen et al., 2012; Dumont et al., 2020). For example, enhanced species diversity at farm and field level directly affects the level of biodiversity in and around a farming system (**Box 1**) and can have a positive impact on the sustainability and resilience of a farming system. Intercropping, which is the growing of multiple crops on the same field at the same time (Willey, 1990), is therefore proposed as a sustainable alternative to large monocultures on arable farms. Growing more than one crop in a field has a range of (potential) productive and environmental benefits. For example, Li et al. (2020) performed a global meta-analysis of yield gain in intercropping for different species combinations, different temporal and spatial arrangements and different fertilizer inputs. They observed that, in comparison with monocultures, the greatest absolute yield gains arose for mixtures of maize with short-grain cereals or legumes that had considerable temporal niche differentiation from maize, when the crops were grown in multirow strips with a high input of nutrients. Another strategy, using low to moderate nutrient inputs, included the growing of (full) mixtures of short-stature crop species that had the same growing period. Li et al. (2020) observed that both intercropping strategies, in comparison to monocultures under the same management, saved 16% to 29% of the land and 19% to 36% of the fertilizer. This shows that intercropping may contribute to sustainable development of agriculture.

Optimization of intercropping is largely addressed in the Biodiversity-Positive Food Systems investment theme of Wageningen University and Research, but there are several challenges. For example, it may be

Box 1. Increases in biodiversity when adding prairie strips to monocultures (from Kremen & Merenlender, 2018).
Figure B1.1 shows the impacts of integrating prairie strips (i.e., strips of native prairie species) into a corn-soy rotation. This type of diversification can increase plant, pollinator, and bird species richness and abundance, while minimizing externalities and enhancing other ecosystem services.

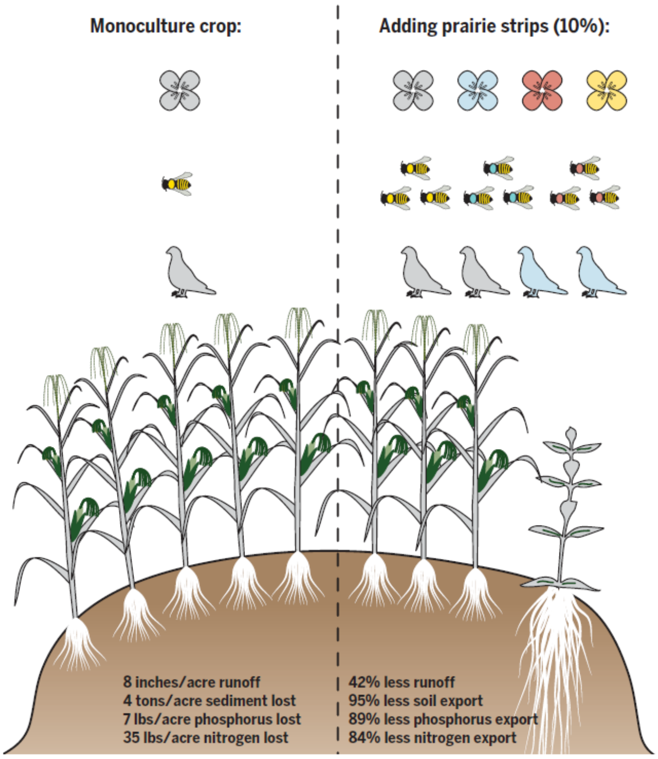

Figure B1.1 *The impacts of integrating prairie strips into a corn-soy rotation. From Kremen & Merenlender (2018), based on data from Schulte et al. (2017).*

difficult to market the resulting products when they are mixed, as the production chain is not yet adapted to mixed products (van der Sluis et al., 2022). Furthermore, also in terms of mechanization the market appears to not be completely ready for intercropping yet. For example, the heavy machines used in crop production would crush the adjacent crops when strip cropping is implemented. Therefore, a more sturdy vegetation could be introduced next to the crops, such as grass-clover mixes. These do not provide a direct purpose for human consumption, but they can function as living mulch and improve soil health (Carrillo-Reche et al., 2023).

Some of these challenges can potentially be overcome through the inclusion of livestock in the production systems in the transition from monocultures to fully integrated intercropping systems. For example, livestock can, while the market transition towards adaptation to mixed products takes place, be fed mixed products, as mixed products are generally less of a problem for livestock. In this way, livestock can provide a target or purpose for mixed products that are currently difficult to market for human consumption. Another way in which animals can contribute to intercropping is in the earlier-mentioned example of grass-clover being used next to crops. These mixes do not have a direct purpose for human consumption but can, however, be used as feed for livestock, converting this biomass into animal protein. The exchange of feed and manure between crops and livestock could be done at different scales (regional, local or farm). In this study, however, we will mostly focus on integration at a farm scale because of reduced costs and emissions from transportation, and to also explore other potential benefits of crop-livestock integration other than this exchange of resources. Schiere et al. (2002) described how livestock can create opportunities to improve sustainability in mixed crop-livestock farming systems and contribute to ecosystem services (**Figure 1**; Leroy et al., 2018). This figure highlights impact of the choice for specific livestock species and breeds (animal genetic resources (AnGR)) on the effect of a farming system on ecosystem services. Some breeds, for instance, are more locally adapted and are of more socio-cultural value than others (Leroy et al., 2018). Therefore, more insight into the potential benefits and downsides of integrating intercropping with certain livestock species and breeds in farming systems, and how a beneficial integration can be achieved in practice, would be valuable.

During a large part of history, integrated crop-livestock farming systems were dominant. This already started to slowly change in the 18th and 19th century, but, in Europe, the biggest shift to specialized production came

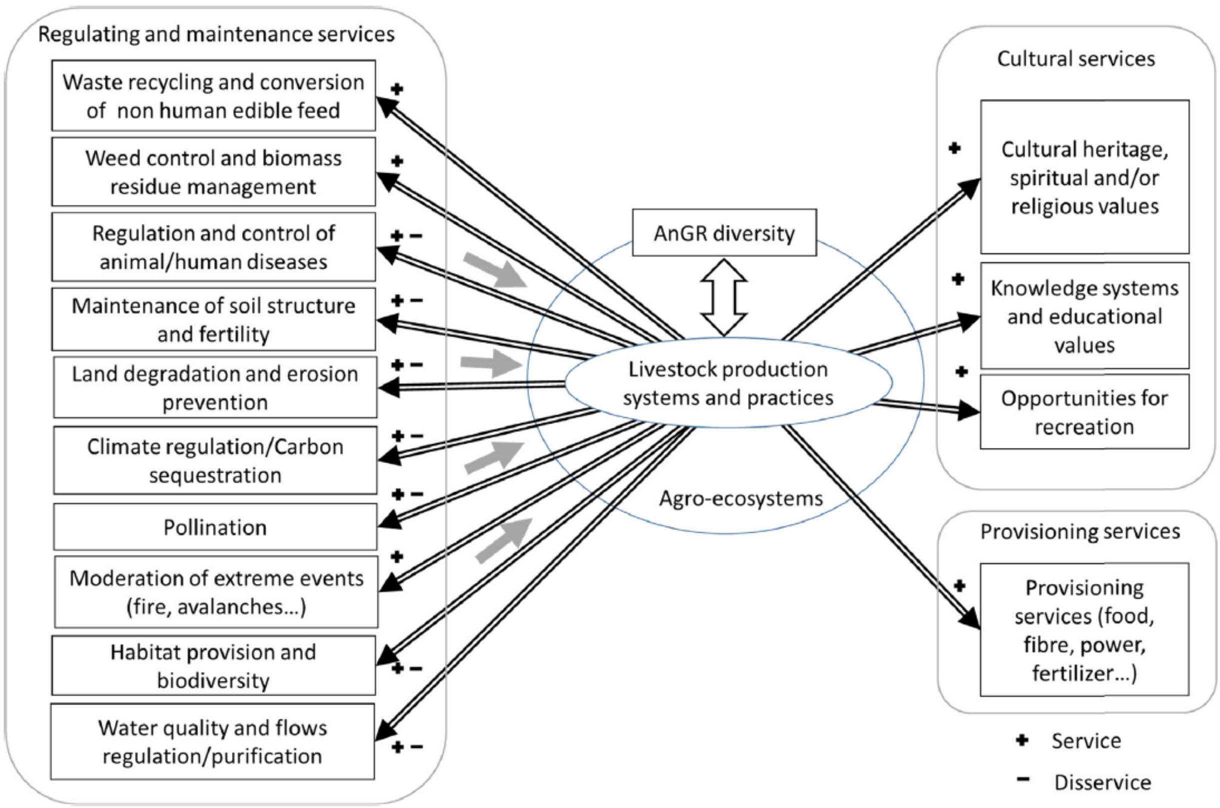

Figure 1 *Impact of livestock production systems and practices on ecosystem services (from Leroy et al., 2018).*

after the second world war when the Common Agricultural Policy was implemented (Schut et al., 2021). Nowadays, there are 2,785 mixed farms in the Netherlands (data from 2022), with mixed farms defined as 'Agri- and/or horticulture in combination with breeding and keeping of animals, with each of the activities not contributing more than 66% of the added value' (CBS, 2023a). This is a small number compared to a total of 12,921 arable farms, 6,998 horticulture farms, and 23,048 grazing animal farms (CBS, 2023b). There are many different degrees of crop-livestock integration, resulting in a continuum ranging from having crops and livestock on the same farm but completely separated from each other (in space and in terms of exchange of outputs) to fully integrated systems where outputs of one farming activity are used as inputs for the other. For example, Hilimire (2011) mentions different forms of crop-livestock integration on the farm scale:

1) *Spatially separated*: The animals are kept in a separate location on the farm, e.g., on a permanent pasture or in a barn. Permanent pasture is in a location that is never cropped and additional feed and forage crops are grown in other locations on the farm.
2) *Rotational*: The animals and crops are kept in the same field, but at different times, so a field is alternately used for crop production and forage.
3) *Fully combined*: The animals graze in between or underneath the crops.

Additionally, it is possible to combine different livestock species within a crop-livestock integrated system. In literature, different terms are used interchangeably to indicate systems anywhere on this continuum, often using terms like mixed farming or integrated farming. Therefore, also in this vision document, these terms are used interchangeably.

Mixed crop-livestock farming appears to provide a range of potential benefits, such as increased ecosystem biodiversity, flexibility of the system to deal with stressors, and improved nutrient use and overall may contribute to environmentally and economically sustainable agriculture (Lemaire et al., 2014; Ryschawy et al., 2012). Livestock can provide manure and draft power for crop production fields, whereas crop residues can be used as feed for the livestock, and when crop yields are low, for example because of droughts, livestock products can serve as a financial buffer (Herrero et al., 2010). This highlights the potential benefits of interactions between species in food production systems in a broader context than crop-crop interactions alone.

1.1 Aims of the project

The main aim of this project was to investigate *the potential role and benefits of livestock species in relation to intercropping and enhanced crop diversity at farm level*. To this end, we explored interactions between crop and livestock species, for further development and implementation of biodiversity-positive food systems, focusing on 1) the potential of crop-livestock combinations in intercropping systems, 2) the relevance of particular crop combinations in intercropping within crop-livestock systems, and 3) relevant criteria for the use of genetic resources in integrated crop-livestock farming systems.

1.2 Approach

To gather insight into promising partnerships between crop and livestock species, we used 1) literature review, 2) expert interviews and 3) a focus group discussion in which we developed an infographic on crop-livestock integration. For the literature review, we started with a search in Scopus and subsequently read a selection of the resulting review papers (based on the perceived relevance to our research questions) to obtain a general overview of the published knowledge. From there on, we mainly took a snowball approach, where we looked at references in these review papers. We also searched for additional (in-depth) papers on specific topics we wanted to obtain more information on.

To gain insight into the knowledge, personal experiences and motivations of pioneer farmers implementing a form of crop-livestock integration, i.e., obtaining so-called soft knowledge, we conducted expert interviews.

For these interviews, we used a semi-structured approach. The pre-developed questions for these interviews are given in **Appendix 1**.

In the focus group discussion, in which we developed an infographic on crop-livestock integration, we sat together with a group of experts on crop-livestock integration and a visual designer. Based on the discussion, the visual designer created an infographic that captured the essence of the potential role animals can play in the transition towards integrated farming and intercropping.

We end this vision document with a discussion and conclusion, in which we evaluate the benefits of - and opportunities for - crop-livestock interactions, that resulted from the literature and expert consultation, and discuss our recommendations for future research and implementation of livestock integration in intercropping systems.

2 Literature review

As mentioned earlier, including livestock in mixed systems provides opportunities to improve sustainability (Schiere et al., 2002). To obtain more insight in the potential of crop-livestock integration, a scientific literature study was performed. Due to limited literature on integration of livestock in intercropping systems specifically, we initially focus on crop-livestock integration without the intercropping aspect and subsequently, where possible, shine more light on the expected opportunities and results in intercropping systems.

2.1 The potential of integration of livestock in intercropping systems

In the scientific literature, a variety of roles for the crops and livestock in a production system are described, that provide insight into how crops and livestock may be complementary in a production system and improve nutrient cycles. Crops can provide feed for livestock (Yang et al., 2022) at an extremely low cost as most of the production costs are accounted for in crop production (Wright et al., 2012), and in this way residues, by-products and grazed biomass that are not suitable for human consumption can be converted into animal products for human consumption (Schut et al., 2021). Furthermore, crops and trees can aid in the sequestration of carbon, hereby reducing the net emissions from livestock (Lal, 2020), and can provide a source of shade and shelter for livestock (Pieri & Gething (1992) in Lal (2020)). On the other hand, livestock can provide manure to the crops (Yang et al., 2022), hereby reducing the need for external fertilizer input (Lal, 2020). Furthermore, the manure can be used as fuel or as building material (Wright et al., 2012). Livestock can also provide draft power for the cultivation of land (Herrero et al., 2010) and contribute to weed management and pest control (MacLaren et al., 2018; Ratnadass & Deguine, 2021). Furthermore, grazing by livestock may improve soil health (Kumar et al., 2019). The diverse roles of the crops and livestock in crop-livestock systems are visualized in **Figure 2**.

In the scientific literature, a range of potential benefits and downsides of (inter)crop-livestock integration are reported. To obtain a full picture of how (inter)crop-livestock integration can contribute to sustainable food production, we specifically focus on 1) ecosystem biodiversity (e.g., associated biodiversity), 2) flexibility of the system to deal with stressors (e.g., environmental resilience, economic resilience), 3) circularity and

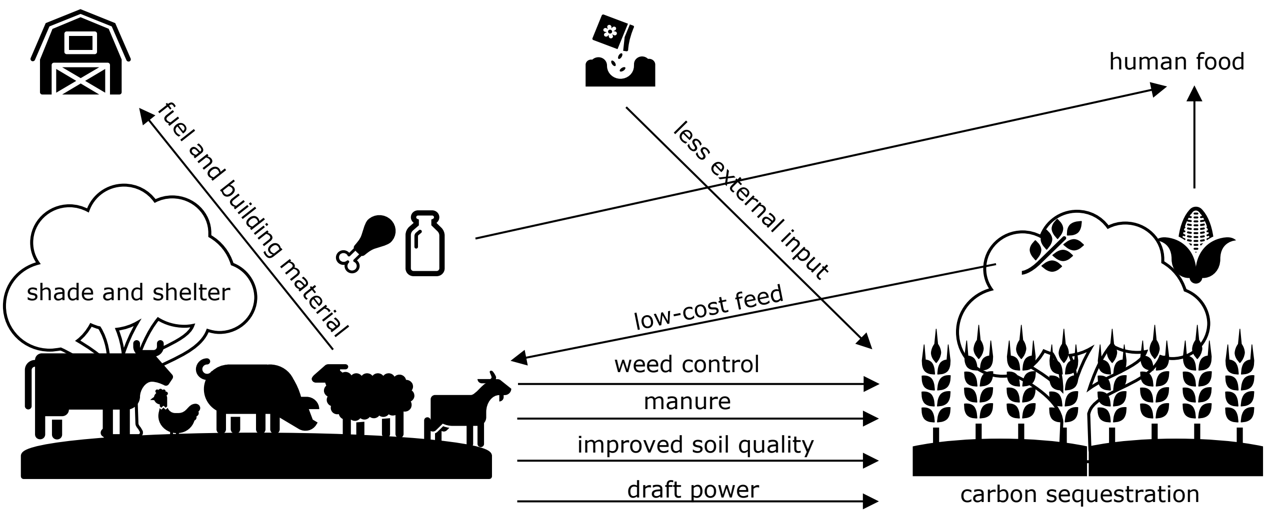

Figure 2 *Schematic overview of the roles of crops and livestock in integrated crop-livestock systems. See text for references.*

emissions, and 4) socio-economic and cultural aspects. The benefits and downsides of (inter)crop-livestock integration for each of these topics are discussed in more detail below.

2.1.1 Ecosystem biodiversity

The change in farming practices towards more intensive agriculture is considered a main cause of losses in farmland biodiversity, across many taxa. For example, **Box 2** shows how farming practices and farmland birds are (in)directly related (Benton et al., 2003). Compared to crop- or animal-only systems, integrated crop-livestock systems have a higher biodiversity (Funes-Monzote, 2008). This is both due to the direct integration of an additional species in an integrated system and the indirect attraction of more species, e.g., through the addition of pastures on crop farms that can result in higher abundances of native bees in the United States (Morandin et al., 2007; Hilimire, 2011). Furthermore, MacLaren et al. (2018) studied the effect of integrating livestock in diverse cropping systems through comparison of long-term weed seedbank trends. They observed, among other things, that in grazed rotation systems the weed diversity was higher compared to ungrazed rotation systems.

2.1.2 Flexibility of the system to deal with stressors

Integrated crop-livestock systems have the benefit of having multiple types of production or income streams, making these systems more flexible in dealing with stressors in one of the production types. These integrated crop-livestock systems may be more resilient, i.e., they maintain their system features in the presence of perturbations in ecosystems and social systems (Ten Napel et al., 2011). For example, it is often concluded, for several types of integrated farming, that more integrated farms are commonly more sustainable and more resilient to external shocks, such as extreme weather, because of spatial and temporal synergies between crops, pastures and animals (Schut et al., 2021). Moreover, animals supply a regular income source from the sale of animal products, such as milk or eggs, and in this way can serve as a buffer

Box 2. The relationship between farming practices and farmland birds (from Benton et al., 2003).
Figure B2.1 shows the relationship between farming practices and farmland birds.

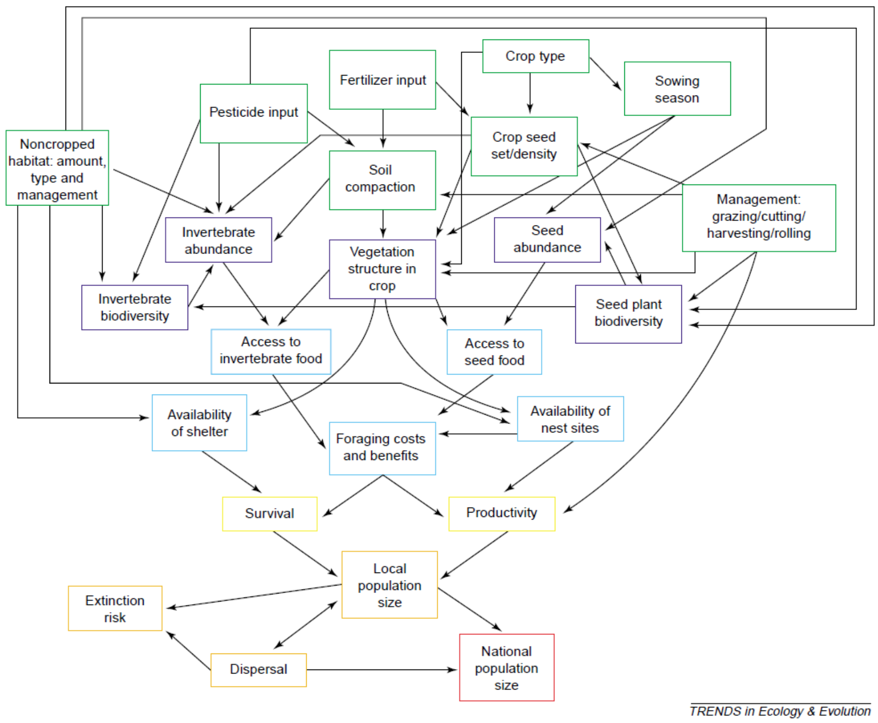

Figure B2.1 *The multivariate and interacting nature of farming practices and some of the routes by which farming practice impacts on farmland birds. Arrows indicate known routes by which farming practices (green boxes) indirectly (dark-blue boxes) or directly (light-blue boxes) affect farmland bird demography (yellow boxes), and therefore local population dynamics (orange boxes) and finally total population size (red box) (Benton et al., 2003).*

or insurance when crop yields are low (Herrero et al., 2010; Wright et al., 2012). Moreover, the animals themselves can be sold to obtain cash for (un)planned expenditures (Wright et al., 2012). Overall, crop-livestock integration can serve as a business risk management strategy, where the system can flexibly adapt to expected low crop yields, as well as to attractive prices for livestock products in comparison to the crop products (Bell et al., 2014).

Crop-livestock integration can also contribute to the management of weeds and pests, making the system more resilient to weeds and pests. This management of weeds and pests works both directly through livestock feeding on the weeds or pests and indirectly through the effects of pasture on the weed and pest populations (Hilimire, 2011). Through occupation of the bare ground, allelopathic interactions and competition, forage crops can limit weed populations, whereas some livestock species (e.g., cattle) can modify the habitat for pests sufficiently to limit their populations (Hilimire, 2011). In the earlier-discussed study by MacLaren et al. (2018) it was also observed that weed abundance was lower and less herbicides were applied in diverse cropping systems with integrated livestock. It appears that herbicides and the disturbance induced by grazing apply different selection pressures on weed and that these practices together form a more effective weed management than increasing the amount of herbicide or the diversity in mode-of-action of the herbicides (MacLaren et al., 2018). Therefore, it appears that the integration of livestock can contribute to making the system more resilient to weeds and pests. It must, however, be noted that other studies report, for example, no difference between mowing and grazing by sheep as cover crop termination method on weed and ground beetle control (MacKenzie et al., 2016) or even report negative effects of sheep grazing on weed management (Miller et al., 2015). It appears that the right management and careful consideration of which crop and livestock species to combine are required.

2.1.3 Circularity and emissions

Animals can form an important part of the on-farm cycle of nutrients and having livestock in crop systems can have positive effects on soil quality. Animals in integrated crop-livestock systems can recycle nutrients from the forage and feed to their excreta, which can subsequently be used to fertilize the soil (Hilimire, 2011). Through returning crop-livestock manure to the field, the physical properties and nutrients of the soil change (see **Table 1** (adapted from Hilimire, 2011); Yang et al., 2022). For example, increases in soil porosity, soil organic matter, soil-available phosphorus and soil-available potassium may result, improving overall soil quality (Yang et al., 2022). Furthermore, through the replacement of chemical fertilizers by manure, greenhouse gas emissions (N_2O and CO_2) can be reduced (Yang et al., 2022). It is, however, important that the application of manure to the field on farms is adequately managed to avoid over-

Table 1 *Soil quality studies comparing integrated systems with crop monocultures (adapted from Hilimire, 2011). + positive change; - negative change; 0 neutral results; grey boxes represent "no information available".*

Integrated system	**(total) nitrogen**	**(total) organic carbon**	**soil aggregate stability**	**soil microbial biomass**	**soil microbial biomass N**	**soil enzyme activity**	**water aggregate stability**	**soil penetration resistance**	**phosphorus**	**potassium**	**calcium**	**magnesium**	**CEC (cation exchange**	**organic matter**
Integrated beef cattle and cotton[1]	0	+	+	+	+	+								
Cattle grazing winter cover crop followed by corn[2]	+	+					+	-						
Sheep and broilers grazing for 5 months during spring-fall growing season[3]	+								+	+	+	+	+	+

[1]Acosta-Martinez et al. (2004); [2]Maughan et al. (2009); [3]Lowy (2009)

supplementation, and subsequent environmental contamination of nutrients such as phosphorus or nitrogen (Hilimire, 2011). Not only manure of the livestock, but also pastures for livestock (i.e., pasture plants such as grass or clover) themselves can positively impact soil quality, for example through their deep root systems and ability to fix nitrogen (Clark, 2004; Hilimire, 2011). De Camargo et al. (2022) studied soybean followed by a mixture of palisade grass, Niger, turnip rape, crotalaria and estilosantes, and cattle integrated for grazing. They compared this production system to other production systems (very low, low, medium and high diversity were compared in this study; see **Figure 3**) and observed that the increase in plant functional diversity, mainly under cattle grazing, positively affected soil quality properties (e.g., soil microbial biomass and activity). The microbial biomass carbon and microbial quotient were higher for the high diversity system than for the other systems (de Camargo et al., 2022).

Furthermore, crop-livestock integrated systems have potential to have a reduced environmental load ratio (**ELR**). The ELR is the ratio of possible non-renewable value to renewable energy value invested in a system (Yang et al., 2022). As reviewed by Yang et al. (2022), the ELR of crop-livestock is lower than for agricultural systems with independent growing of crops or livestock, mainly because of the reduction in non-renewable resource use, by 6-38.5% (Yang et al., 2022). Moreover, crop-livestock integration may provide an opportunity to reduce some of the net emissions from the livestock through carbon sequestration in grassland (Lal, 2020).

Crop-livestock integration can also help to use water more efficiently. Most of the water needed for livestock production is used for feed production and only a minor part is used as drinking water for the animals (Wright et al., 2012). Livestock water productivity, defined as '*the ratio of net beneficial livestock-related products and services to the water depleted in producing them*' (Peden et al., 2007), is higher in mixed crop-

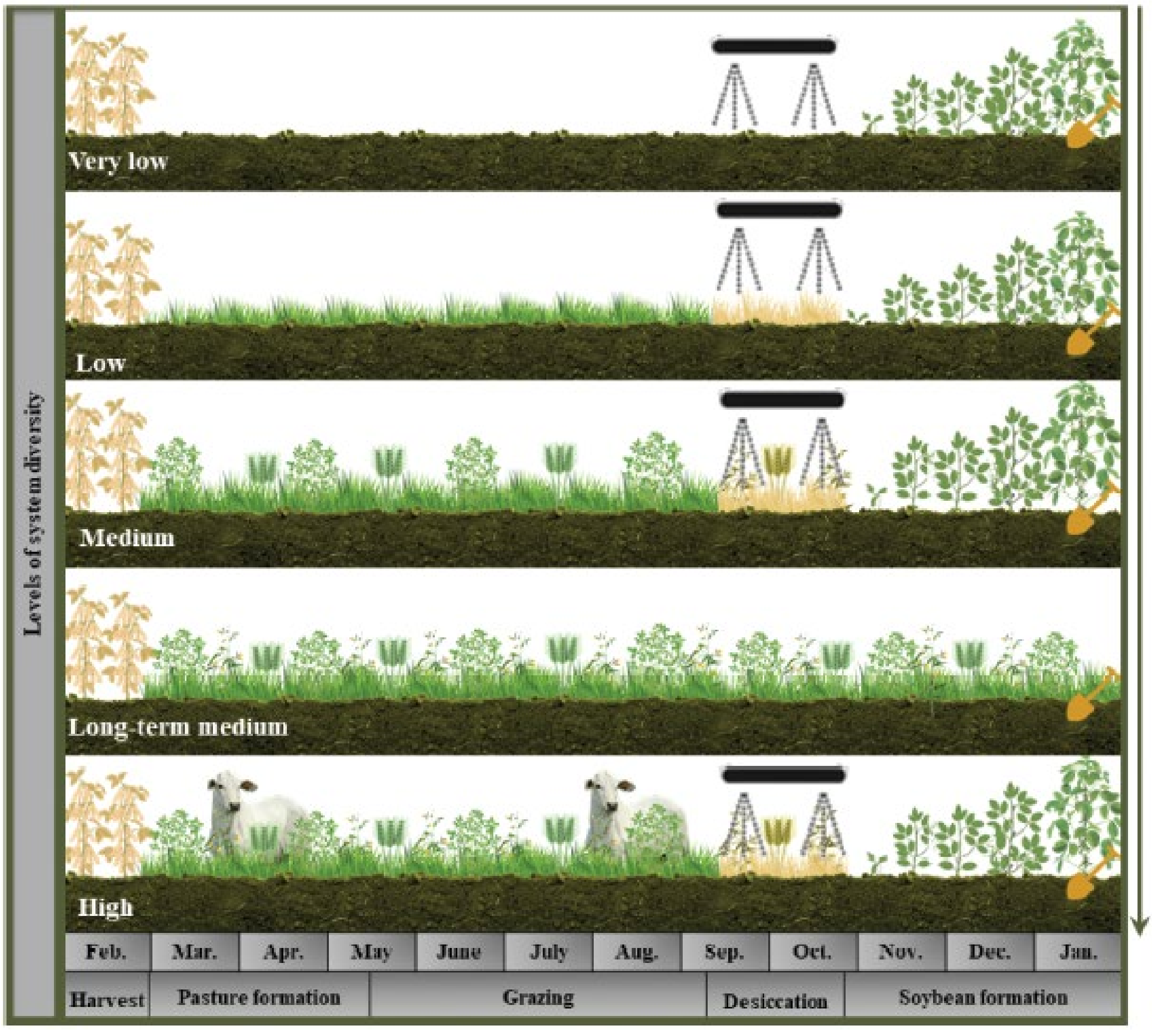

Figure 3 *Schematic and timeline map of soybean production systems with levels of functional diversity in a sandy soil in the experimental area at mato-grossense cotton institute, Rondonópolis county, Mato Grosso state, Brazil. From de Camargo et al. (2022).*

livestock systems compared to when crops are grown separately (Singh et al., 2004; Wright et al., 2012). This is because in mixed crop-livestock systems a high proportion of the animal feed comes from crop residues, and thus the water costs used for growing the crops can be divided over both the grain and the animal feed components (Wright et al., 2012). Indeed, when the proportion of crop residues in livestock's diets increases, so does the livestock water productivity (Peden et al., 2007).

2.1.4 Socio-economic aspects

Crop-livestock integration can result in improved economics (Yang et al., 2022) and can hereby contribute to increased income and subsequently to availability of, and access to, food (Herrero et al., 2010). One factor that plays a role in the improved economics of crop-livestock integration is the reduction in cost input, as for example chemical fertilizer can be replaced by organic fertilizers (manure) and crop residues can serve as feed (Yang et al., 2022). Subsequently, the net income and production-to-investment ratio are often higher than in agricultural systems with independent growing of crops or livestock (Yang et al., 2022). Moreover, a reduced dependency on external inputs can make systems more self-sufficient and less affected by market uncertainties (Bonaudo et al., 2014). Bell et al. (2014) discuss that the use of dual-purpose grain crops, that is, crops utilized for grazing by livestock during the vegetative state and then removal of stock to allow the crop to regrow and produce grain, can contribute to increased overall production and profit from both the grain crop and the whole farm (Bell et al., 2014). The use of dual-purpose crops, and thus crop-livestock integration, can increase the crop and livestock productivity by 25% to 75%, with only a limited increase in inputs. De Camargo et al. (2022) report, in addition to the earlier-discussed positive effects of crop-livestock integration on soil quality, that also soybean yield was positively affected. Moreover, in several crop-livestock integration strategies (see also introduction), the integration also allows for more animals to be kept per hectare and for improved resource use efficiency per unit to agricultural product produced (Regan et al., 2017). A modelling study was performed by Bos (2002 in Schut et al. (2021)), in which labor income (i.e., the financial returns from products sold and direct payments minus fixed and variable costs) was compared between specialized and mixed farms in the Netherlands, for crop and dairy production, where the manure legislation at the time was taken into account, with a maximum manure application rate and a maximum difference between calculated N and P input and output per ha. Labor income was maximized for the same total land area for all three systems (i.e., specialized cropping, specialized dairy, and mixed). Overall, the maximum labor income was 45% higher for mixed farming than for specialized farming under the manure legislation (that limited dairy production). A large part of the difference could be explained by higher yields per hectare of crops due to lower cropping frequencies of the more profitable crops under mixed farming, with an unaltered area cultivated. Regarding increased production, also the earlier-discussed positive effects of crop-livestock integration on soil quality appear to sometimes result in better yields, for example in a study where corn yield was compared for a system where cattle grazed a winter cover crop subsequently planted with corn versus a system with continuous corn cropping (Maughan et al., 2009). The higher production capacity has associated social benefits (Hilimire, 2011). Crop-livestock farms can have a higher food calorie production capacity per area of land (as discussed earlier), which may benefit local communities through achieving food security goals and aiding local food economy initiatives (Hilimire, 2011). Furthermore, the diversification of livelihood strategies and the risk reduction associated with mixed crop-livestock systems can benefit resource-poor farmers (Wright et al., 2012), and can help to improve food security and reduce malnourishment (Lal, 2020).

Another important aspect is that the diets that people consume are safe and healthy. Components of this are, for example, the biodiversity of the human diets and the presence of traces of pesticides. Agricultural biodiversity appears to be associated with more diverse household- and individual-level diets, through both subsistence- and income-generating pathways (Jones, 2017). Increased biodiversity in diets may result in better health outcomes, for example through contributing to achieving the recommended daily nutrient intake (Kennedy et al., 2005) and through the observed associated lower probabilities of obtaining chronic non-communicable diseases such as cancer and cardiovascular diseases (Johns and Eyzaguirre, 2006). For instance, Provenza et al. (2019) reviewed circumstantial evidence of linkages among plant diversity in herbivore diets and human health and concluded that there were indications that plant diversity (that is, phytochemical richness of landscapes) may affect the biochemical richness of dairy and meat, and may hereby affect human health. They discuss that phytochemicals in the diets of herbivores can contribute to protecting meat and dairy from protein oxidation and lipid peroxidation. Protein oxidation and lipid oxidation can cause low-grade systemic inflammation, which has been implicated in human heart disease and cancer. This highlights that a diverse range of crop products on which animals are fed could contribute to human health indirectly as well. The addition of livestock to fields can aid in the control of weeds or pests (Ratnadass & Deguine, 2021) and, consequently, the use of pesticides may potentially be reduced. This could benefit human health, as pesticides, including residues in food, can, depending on exposure levels, adversely affect human health (Alavanja et al., 2004). It must, however, be noted that the risk of viral zoonotic transmission may increase in some cases of introduction of livestock for the regulation of pests (Ratnadass & Deguine, 2021). Moreover, combined farming of different livestock species has been criticized as it might increase the risk of zoonoses, as was recently on the news in the Netherlands for the combined farming of poultry and pigs (Nieuwsuur, 10th of May 2023).

2.2 The relevance of particular combinations of crop and livestock species

Similar to the benefits and downsides, there appear to be more examples of specific crop-livestock combinations than of specific species combinations for intercropping-livestock systems. Nonetheless, here we aim to provide an overview of existing combinations, first for crop-livestock systems and then for intercropping-livestock systems, and to discuss the added value of specific combinations.

2.2.1 Crop-livestock combinations

It appears that the most common livestock species in crop-livestock integration studies are cattle (Hilimire, 2011). However, many different livestock species can be integrated, including cattle, bison, elk, llamas, horses, swine, sheep, goats, rabbits, turkeys, chickens, ducks and ostriches (Hilimire, 2011). **Box 3** shows a literature scan of reported crop-livestock combinations.

Box 3. Literature scan of reported crop-livestock combinations.

As a quick scan of crop-livestock combinations that have been published about, a Scopus search using the terms [crop AND livestock AND integrat*] was performed, in the publication titles, keywords and abstracts. This resulted in a total of 3,039 hits since 1990 (15th of February, 2023). Subsequently, the publication titles were searched for combinations of crop and livestock species, using the animal species as a starting point. Although the overwhelming majority did not mention specific species in the publication title, some combinations could be observed (**Table B3.1**). No mentions of elk, llamas, horses, rabbits or ostriches were observed.

Table B3.1 *Combinations of livestock and crops observed in the scientific publication titles. Note: some publications might be included multiple times due to mentioning of multiple livestock species terms.*

Livestock species searched	Crop combination reported
Cattle (n = 111)	Not specified (n = 71); Brachiaria and Panicum (n = 1); BRS Paiaguás and BRS Piatã (n = 1); Coconut (n = 1); Coffee (n = 1); Corn (n = 7); Cotton (n =1); Lolium multiflorum (n = 1); Maize (n = 1); Marandu palisadegrass (n = 1); (pearl) Millet grain (n = 2); Oat (n = 1); Oil palm (n = 5); Paiaguas palisadegrass and Tamani grasses (n = 1); Pineapple (n = 1); Rice (n = 5); Soy (n = 8); Wheat (n = 1)
Sheep (n = 45)	Not specified (n = 32); Bean (n = 1); Citrus (n = 2); Maize (n = 1); Rubber (n = 1); Ryegrass (n = 1); Vineyard/viticulture (n = 5); Wheat (n = 2)
Swine, pig (n = 16)	Not specified (n = 13); Corn (n = 1); Rice (n = 1); Sweet potato (n = 1)
Poultry (n = 16)	Not specified (n = 14); Corn (n = 1); Maize (n = 1)
Goat (n = 11)	Not specified (n = 9); Alexandergrass (n = 1); Oil palm (n = 1)
Chicken (n = 6)	Not specified (n = 5); Rice (n = 1)
Duck (n = 4)	Not specified (n = 2); Azolla (n = 1); Rice (n = 1)
Turkey (n = 1)	Camelina sativa (n = 1)

Which species may be integrated in a system depends on the desired goals of the integration. For weed or pest control, poultry are often included, whereas cattle can be included for forage-to-fertilizer conversion (Hilimire, 2011). In weed control, poultry can for example consume the weeds, as seeds or herbs, both to clean a field before crops are planted and during the growth of crops (Hilimire, 2011). An example of this comes from a study by Clark and Gage (1996), who investigated the effects of including free-range chickens and geese in an apple orchard with intercropped potatoes on insect pests and weeds. They observed that the chickens fed on multiple potential crop pests (e.g., Japanese beetles) but that this did not reduce the proportion of damaged fruit, and that weed abundance and crop productivity were not altered. However, the addition of geese appeared to be effective compared to a minimally weeded control, with 1) reduced weed abundance, 2) increased potato plant growth and yield, and 3) reduced fruit damage (Clark and Gage, 1996). Another example comes from Ako and Tamuru (2007), who studied the use of cayuga ducks to control apple snails in taro production, and observed that the ducks positively contributed to controlling the apple snails. It may, however, also be possible to manage pests through cattle grazing (O'Neill et al., 2003). Other examples of crop-livestock integrations include wheat maize rotation-swine systems and tea-swine systems, both of which have been indicated to be able to generally promote greenhouse gas mitigation, and to have ecological and economic benefits (Zheng et al., 2022).

2.2.2 Intercropping-livestock combinations

There are substantially fewer examples of intercropping-livestock integration (see the literature scan in **Box 4**), but some are highlighted here. Zhang et al. (2023) mention an example including swine, in a citrus alfalfa intercropping system, where the manure of the pigs was used as fertilizer and as fuel, and the alfalfa was used to feed the pigs (see **Figure 4**; Zhang et al., 2023).

Box 4. Literature scan of reported intercropping-livestock combinations.

As a quick scan of intercrop-livestock combinations that have been published about, a Scopus search using the terms [intercrop* AND livestock AND integrat*] was performed, in the publication titles, keywords and abstracts. This resulted in a total of 252 hits since 1990 (17th of February, 2023). Note that this is only approximately 8% of the number of publications found for the crop-livestock integration search in **Box 3**. The publication titles were searched for combinations of intercropping and livestock species, using the animal species as a starting point. Although the overwhelming majority did not mention specific livestock species in the publication title, a few combinations could be observed (**Table B4.1**). No mentions of bison, swine/pigs, goats, turkeys, chickens, ducks, poultry, elk, llamas, horses, rabbits or ostriches were observed.

Table B4.1. Combinations of livestock and crops observed in the scientific publication titles, in the intercropping-livestock search.

Livestock species searched	Crop combination reported (from additional examination of main text of publication)
Cattle (n = 4)	Soybean followed by a mixture of palisade grass intercropped with Niger, turnip rape, crotalaria, and estilosantes as cover crops (n = 1); Brachiaria and Panicum with soybean (n = 1); Oat and white clover (n = 1); examined previously intercropped soil (grain intercropped with forage in the past decade; n = 1)
Sheep (n = 1)	Citrus with legumes (n = 1)

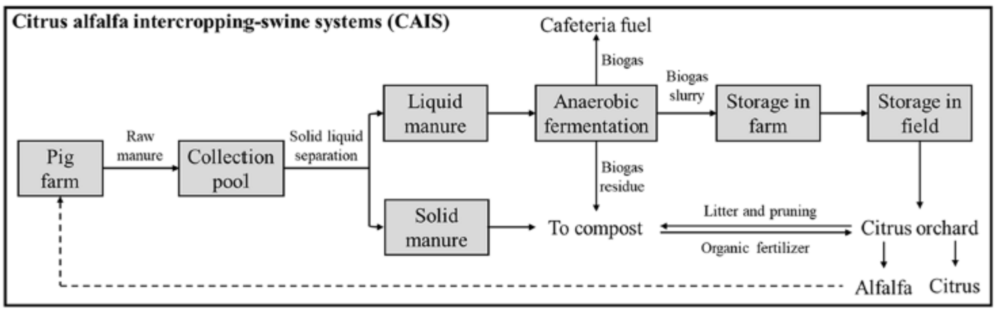

Figure 4 *The process flow of the citrus alfalfa intercropping-swine system (from Zhang et al., 2023).*

Dias et al. (2020) studied a forage grasses-soybean intercropping integrated crop-livestock (cattle) system in comparison to a soybean-maize succession system and concluded that the integrated crop-livestock system combined with a forage cropping system resulted in greater soil nutrient cycling and increased soybean yields. Crusciol et al. (2021) studied intercropping of upland rice with forage grasses in an integrated crop-livestock (cattle) system. They compared three intercropping systems: 1) monocropped upland rice, 2) upland rice intercropped with palisade grass, and 3) upland rice intercropped with guinea grass. They concluded that the intercropping systems showed benefits in terms of production, land use per unit area, nitrogen cycling and profitability. Another example that came up from the literature search came from Silva et al. (2022), who discuss a production system in which grass-legume intercropping is applied during the pasture phase of an integrated crop-livestock (cattle) system under no tillage (although it can be debated whether this falls within the definition of intercropping). They observed improved activity of soil microbial biomass in comparison to monoculture systems. Moreover, the grass-legume intercropping during the pasture phase increased soybean productivity and grass dry matter.

Another well-known example (not from the literature scan in **Box 4**) comes from Khumairoh et al. (2018). They compared a number of rice production systems, including conventional (characterized by the use of artificial fertilizers, pesticides and herbicides), organic (characterized by organic fertilizers and bio-pesticide applications), and complex (integration of azolla, fish and ducks into organic rice systems, coupled with growing border plants on 50-100 cm wide ridges that surrounded the plots; border plants consisted of green manures and vegetables, that have potential to supply food and feed, as well as refugia to attract natural enemies and hence no pesticides were applied), compared across temporal and spatial scales. They concluded that the complex system appeared most resilient to extreme weather events in terms of rice yields, through the integration of flora and fauna that contributed to weed and pest suppression (as extreme weather events may coincide with pest outbreaks) as well as increased nutrient cycling. Overall, the complex system appeared to be more robust than the conventional and organic systems, and the authors concluded that the design of the complex system is scalable and replicable.

2.3 Relevant criteria for breeding goals for crops and livestock

Which varieties (crops) or breeds (livestock) best fit in an integrated system depends on the goal of the integration and the corresponding roles of the crops or livestock. Subsequently, the optimal choice might not always be the commercial breeds, but local breeds instead. For example, when raised on pasture, commercial breeds might be more susceptible to disease and environmental stress compared to animals bred for pasture-based rearing (Hilimire, 2011). Therefore, access to suitable varieties or breeds is of great importance for successful crop-livestock integration (Hilimire, 2011). Furthermore, emphasis might lie on different traits of the animals. For example, Bonaudo et al. (2014) discuss an integrated dairy-crop production system, and discuss how in such a system a farmer might not seek the full expression of animals' genetic potential, but instead aim for a herd of moderate-yielding cows, in which the lower milk production per cow is compensated for by reduced metabolic stress, fewer health and reproductive problems, and a higher lifetime production (Bonaudo et al., 2014).

There is potential to breed for specific traits that are beneficial for (inter)crop-livestock integration, when there is close collaboration between animal scientists and crop variety research authorities (Wright et al., 2012). For example, Wright et al. (2012) discuss that not only existing variation in fodder quality of crop residues can be used for improved animal production, through substitution of low-nutritive-value varieties by more nutritious (higher digestibility and nitrogen content) varieties, but that also selection for improved fodder quality in crop breeding should be possible. Indeed, this is already being implemented (see e.g. Xu et al. (2023) who improved forage quality in alfalfa through selection for increased stem fiber digestibility). Similarly, Herrero et al. (2010) note that breeding programs for dual-purpose crops increasingly include residue quality, without compromising yield-related objectives. This can have substantial impacts on crop-dairy system productivity and efficiency: for example, in India, improved sorghum and millet dual-purpose varieties have contributed to an increase in buffalo and cow milk production of up to 50%, while maintaining the same crop grain output (Herrero et al., 2010).

However, it may not always be straightforward to breed for trait improvements. Leroy et al. (2018) discuss the link between animal genetic resources for food and agriculture (i.e., those animal species that are used, or may be used, for the production of food and agriculture, and the populations within each of them) and ecosystem services. They discuss that, at the individual as well as breed level, there might be negative genetic correlations between different traits of interest, such as production traits and functional traits. To find the right genotype for a specific system, the most relevant traits must first be identified and ranked. However, several challenges may be faced: there might be limited experience in the implementation of sustainable breeding programs in low-input production systems, it may be difficult to develop certain selection criteria, and it can be challenging to include non-economic traits in breeding goals (Leroy et al., 2018).

2.4 Concluding remarks

Overall, crop-livestock integration can have many benefits, as nicely summarized by Kronberg and Ryschawy (2019):

"*The specific advantages of integrated crops-livestock production systems include (but are not limited to) the following:*

1) *the option of feeding the crops produced on the farm to livestock produced on the farm without the added cost of transport and/or profit to a supplier of the feed,*
2) *less or no import of expensive inputs such as pesticides, synthetic fertilizer, and livestock feed, which can also bring excess nutrients* [note that this is situation-dependent] *within the feed to the farm (e.g., nitrogenous and phosphorus compounds) that can become a costly environmental and economic problem (and poor nutrient management by not properly recycling a valuable nutrient back to its source),*
3) *use of excreta (feces and urine) from the livestock as a valuable source of nutrients, organic matter, microbes, and perhaps other constituents that improve soil fertility [..] rather than as a waste problem, as in many confined animal feeding operations,*
4) *use and conversion of crop residues/byproducts by livestock,*
5) *encouragement for producing perennial forages for livestock in rotation with annual crops with associated benefits for insect pollinators, birds, and other wildlife,*
6) *dual-purpose use (grazing) of cereals and brassicas for forage while vegetative, then later harvesting seeds from these plants,*
7) *use of livestock for weed control in annual crop fields to reduce or eliminate herbicide spraying,*
8) *profitability in one or more aspects of a diverse crop-livestock farm when other aspects are less or not profitable (financial risk management),*
9) *readily available use of annual crops by livestock if yields or prices are too low for conventional harvesting, and*
10) *potentially less dependence on government payments to survive financially.*" (Kronberg and Ryschawy, 2019).

However, it must be noted that there are also downsides to crop-livestock integration, including, for example, a reduced ease and efficiency of management (Schut et al., 2021), the requirement of skills in a wide range of activities (Schut et al., 2021), and high concentrations of animals posing a risk for outbreaks of emerging infectious diseases (Herrero et al., 2010). Careful consideration of the system and adequate management are pivotal. Furthermore, it is important to keep in mind that the added value of integration of livestock strongly depends on the context. Livestock can be essential for achieving a more sustainable system in one context, while being detrimental for sustainability in another (or even the same) system in another context where the resource flows might be different (Schiere et al., 2002). In general, there is much less published knowledge on the integration of livestock specifically in intercropping systems. However, it appears likely that many of the benefits and downsides of livestock integration listed above would also apply to integration of livestock in intercropping systems. The scientific literature provides multiple examples of different crop(-crop)-livestock integrations, that use different species to achieve different goals. Moreover, it has been reported that different farming systems in different locations might not only require the integration of different species but may also require specific breeds with certain characteristics. There appears to be potential to breed for characteristics that are beneficial in (inter)crop-livestock integration, but practical implementation seems to currently be challenging.

3 Expert interviews

To obtain so-called soft knowledge and experiences from practice, three pioneering intercropping-livestock farmers were interviewed. All three farmers are part of the Wageningen University & Research CropMix project. The list of guiding questions we used can be found in **Appendix 1**. In this section, we first provide a short description of each of the farms, before discussing the main interview outcomes and the alignment with literature.

3.1 Short farm descriptions

3.1.1 Laying hens and crop production

This farm in the north of the Netherlands combines egg and crop production. About 3,000 chickens are kept in a biodynamic setting, with two percent of the birds being roosters, five birds per square meter and 100% organic feed, of which (in this case) 70% is produced on their own land. These chickens are kept in a barn with a large outside area with trees, to support the birds' comfort. The integration of animals with crops lies in the exchange of feed and manure. For the crop production, this farm works mainly with strip cropping, apart from (currently) one square field of carrots (see **Figure 5**). Each of the strips is 6 m wide and about 1,100 m long. About six of these strips (15-20 ha) are needed to produce the feed for the birds. The remainder of the land is used for growing crops for human consumption. They grow maize and wheat as single crop in several of these strips. In the other strips, they grow mixes, consisting of the combinations wheat-wildflower, barley-pea or oat-lupine. On leased land ("Land van Ons") they grow buckwheat, wheat, spelt and huttentut (Camelina sativa), also in strips.

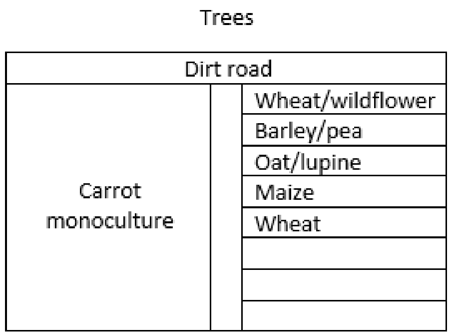

Figure 5 *Schematic view of the (strip)cropping layout of the laying hens and crop*

3.1.2 Agroforestry

This farm is in development towards agroforestry. The first trees were planted in 2020, when the coronavirus pandemic started. With the trees, the farmer aims to create a connection between two forests located on both ends of the farm. The farmer, with help of experts, decided to use a wide variety of species including sweet chestnut, peach, sweet cherry, elder, plum, sea buckthorn, legumes, olive willow, honeyberries and other berries. The plantation of trees is curved, to minimize shadow on the (annual) crops that will be grown between the rows of trees. Other parts of the farm, that are intended to also become agroforestry, are now still used for arable farming or as grazing area for suckler cattle of the Canadian breed Speckle Park. The grass clover growing between the trees is used as feed for the cattle. Cattle manure, in return, is used as fertilizer for the agroforestry. Ideally, chickens would be kept between the trees in a mobile home, but legislation and fencing were mentioned to be constraining factors.

Figure 6 *Picture taken at the agroforestry farm.*

3.1.3 Mixed crop-livestock

The last farmer we interviewed is the manager of the oldest biodynamic farm of the Netherlands. The farm consists of apple and pear orchards, agricultural land for crops and animals, a bakery and a farm shop. For a couple of years already, intercropping is applied to almost all 90 hectares of the farm. The spatio-temporal design of this intercropping system was developed in collaboration with researchers from Wageningen University. They used the indicators gross margin, habitat score and spatial crop compatibility to design the intercropping system for this farm (Juventia et al., 2022). The intercropping design consists of 3 m wide strips in which they grow grains, chicory, wheat, cauliflower, sugar beet, alfalfa and grass clover. At the time of our interview, however, weather conditions did not allow for seeding, so most of it was bare soil, except for the grass clover strips. These grass clover strips, of 6 m width, are used for the grazing of 16 dairy cattle during the summer season. The milk they produce is used for ice cream production. In addition to these cows, there are some livestock species kept on this farm, each of them having different (potential) roles. In the apple and pear orchard there is a mobile home for 249 laying hens. There are also a number of pigs on the farm, which are fed with the left-overs from the shop, lunchroom and bakery. The idea is to put them in the potato fields after harvesting to eat the leftover potatoes from the soil. There are some sheep roaming around the campsite and the property, and they keep bees.

Figure 7 *Picture taken at the mixed crop-livestock farm.*

3.2 Main interview outcomes

3.2.1 Motivation

All three farmers we interviewed are part of the Wageningen University & Research CropMix project. This shows the farmers' innovativeness and their curiosity for alternative ways of farming. For years already, all farmers farm organically or biodynamically, and combine crop and livestock production. They deliberately decided to implement a non-conventional way of farming for personal reasons, but the motivation to take better care of nature, the environment and their own animals played a big role. They see a need for society to transition towards more sustainable, animal friendly and biodiverse agriculture. With their way of farming they aim to contribute to solutions to the challenges that the (Dutch) agricultural sector is facing right now, such as excessive nitrogen emissions and loss of biodiversity. Although these three farmers have made the transition themselves, they understand the barriers that conventional farmers face to change their farming systems too.

The farmers have different reasons for combining crops and livestock on their farms. One farmer has worked with a crop-chicken combination for many years already, while the other two farmers are varying the type and number of animals they keep over the years. Also the way and extent of integration of crops and livestock vary between the farms. In all cases, crops are grown as animal feed and the manure of the animals is used as fertilizer for the crops. However, physical integration of animals into intercropping fields is only present at one of the farms at this point in time. This farmer indicated that one of the reasons for keeping animals on the fields was for the so-called "animal energy". This "animal energy" was not necessarily related to the biodynamic principles and preparations, but it was rather something intuitive about the connection between humans, animals, and the land. Having this "complete farm" is his main motivation for incorporating animals into the strips of crops. In addition, he hopes that the grazing of the cows on the grass clover strips will improve soil health. Recently, a group of students have worked on a potential re-design of the system, aiming to improve and diversify the integration between the livestock, crops and land, to evenly spread this animal energy over the farm (Goudsblom et al., 2023). Their redesign includes cows and sheep grazing consecutively on 12 m wide grass-clover strips, pigs cleaning the potato strips after harvest and using the grass-clover strips, and allowing the chickens to visit the fields after all crops are harvested and using them in the orchard to work the leaves into the soil.

3.2.2 Barriers and opportunities

The interviewed farmers currently face – and have faced – many barriers themselves, to implement and develop their way of farming. Often it requires substantial financial investments to make the transition, and bank loans are not always available for non-conventional production plans. Especially high land prices make it difficult for farmers. Similarly, legislation is mostly designed for conventional systems, making it sometimes difficult for these pioneer farmers to operate in their preferred ways. At the same time, however, these farmers find opportunities in making use of subsidies, alternative financiers (e.g., Land van Ons) and new market opportunities. In that way, all three farmers found a business model to make their farm economically viable.

3.2.3 Practical implementation

Besides the system barriers described above, also more practical barriers and challenges for running an integrated crop-livestock system were mentioned by the farmers. Machinery is often not adapted to strip cropping systems, but rather to large monocultures. Development of more suitable (robotic) machinery for intercropping takes time and requires financial investments and motivation of suppliers to develop this (i.e., there needs to be a sufficiently large market for this machinery). Similarly, fencing for animals in intercropping or agroforestry systems is a constraint for keeping animals in the same field as the crops or (growing) trees, due to fencing being costly and time consuming to place and move. Mobile homes for chickens, as intended to be used by farmers 2 and 3, is a first step in that direction, but this still needs optimization. In addition, (growing) trees can be very vulnerable to damage by the cows. It was also seen that grass clover strips of 6 m wide impact the behaviour of cattle in a negative way, because it is harder for them to pass each other and they disturb each other while ruminating for example. These practical limitations sometimes form a challenge for achieving the 'ideal' form or level of integration.

3.2.4 Choice of breeds and varieties

Breeding crops for intercropping, although studied in this investment theme, is still at an early stage and not really something that practice is really focused on currently. From the interviews with these three farmers, it appears that the lack of adequate machinery for intercropping is a problem that needs to be solved first, before moving on to the more detailed level of specific breeds or varieties for intercropping-livestock systems. Currently, the selection of crops is very much at the species level and focused more on general preconditions such as similar harvest time and water requirements. Selection of animals is mostly done at breed level, where farmers indicate that they want robust animals for their production systems.

3.3 Alignment of practice with literature

The interviews highlighted some aspects that were also reported in the literature study (see **Section 1: Literature review**). Regarding intercropping, on all farms legumes played an important role in the system for nitrogen fixation. The required amount of fertilizer was noted to be much lower in the intercropping system, because intercropping with a legume can help pass nitrogen to wheat for example. Moreover, one of the farmers indicated that mixtures of two crops contribute to a reduced weed abundance and an improved resilience of crops. Two farmers indicated a reduced disease pressure, because diseases 'stop' at the edge of a strip. Furthermore, positive impacts on associated biodiversity were observed on the farms, such as the presence of ladybirds, partridges, pheasants, roe deer and hares. The reasons for one of the farmers to implement integration of trees into the intercropping are also in line with literature. The trees were mentioned to support the resistance to dry periods and climate change because they develop deeper root systems than annual crops. Furthermore, the trees provide shade, increase water retention, sequester carbon from the air and some tree species fix nitrogen. The farmer mentioned that growing trees in this way contributes to solving many of the challenges that the world faces right now. However, there are also (practical) challenges when it comes to intercropping, that are addressed less clearly or only to a limited extent in literature. It was, for example, mentioned that the mixed cropping requires harvests to be ready around the same time and poses challenges for crop management, if the two crops for example require different amounts of irrigation in dry summers.

Regarding crop-livestock integration, one of the farmers highlighted the advantage of crop and livestock integration in the sense that the production of their own chicken feed made the farm more certain of the raw feed materials and quality, and less susceptible to external shocks such as the current war in Ukraine. Physical integration of intercropping and animals, as described in literature, was only applied on Farm 3. At this farm, the animals were kept in specific locations and often had multiple roles or functions. The chickens were kept in the orchards, which resemble their natural habitat. The pigs were used for converting leftovers into animal products and for clearing the potato strips after harvesting. The cows were used to graze the grass-clover strips. Still, many practical challenges arise and it is sometimes hard to demonstrate the direct benefits. The farmer indicated that adequate management (e.g., do not keep animals in the field after heavy rainfall or in winter) is key to obtain benefits from the animals, and they keep experimenting with this for improvement. Strip or intercropping and animal farming requires a lot of knowledge and expertise, as well as good machinery. However, knowledge and suitable machinery are currently limited. Also the financing and market are challenging, as banks tend to push towards upscaling and, for example, currently eggs are expensive so people avoid buying the (even more expensive) biodynamic eggs. One interview highlighted that the supermarkets are considered to currently have too much power in determining product prices, and may not adequately value (in monetary terms) the additional ecosystem services that mixed farming provides.

Overall, the interviews indicated some practical aspects and challenges that complement the knowledge from literature, highlighting the added value of combining both scientific knowledge and practical experience in the study of intercropping-livestock integration. There was a clear overlap with scientific literature in terms of, for example, improved resilience, feed-manure exchange, positive effects on biodiversity, but also the challenges that these systems face, such as the dependency on good management. The interviews also highlighted aspects that require attention for practical implementation, such as harvest timing considerations, required knowledge and expertise, and adapted machinery.

4 Focus group discussion: infographic

In the focus group discussion that was organized, we sat together with a group of experts on crop-livestock integration and a visual designer. The group of experts consisted of the researchers involved in this project, that had both 1) personal experience and expertise regarding intercropping, animals and/or integrated systems and 2) read the literature review and interview section of the current report to obtain a good overview of the outcomes of the project at that point. In the focus group discussion, we talked about our perceived key messages of the project and the knowledge that we wanted to share with a wider audience. Based on this conversation, the visual designer created an infographic that captured the essence of the potential role animals can play in the transition towards integrated farming and intercropping and the challenges that may be faced in the process. The result is shown in **Figure 8** and can serve as a helpful communication tool for outreach.

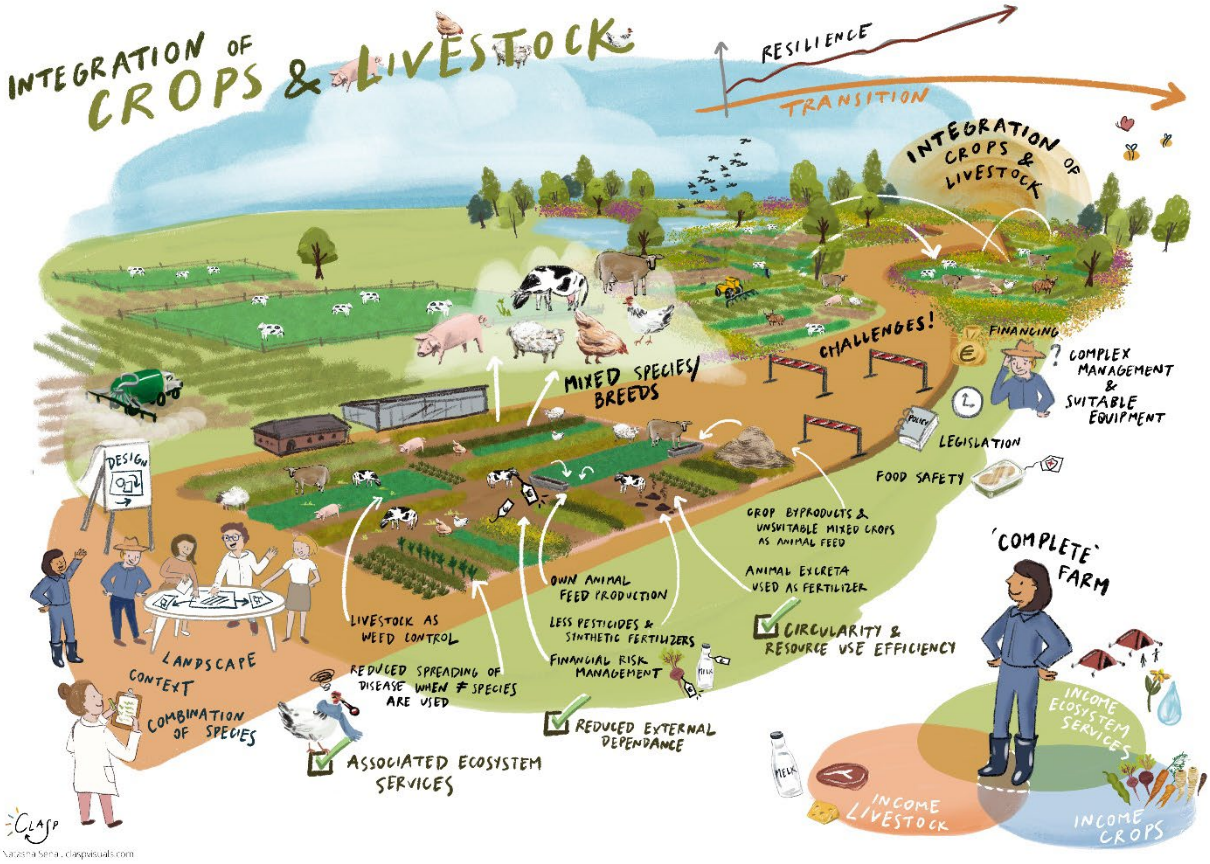

Figure 8 *The infographic that resulted from the focus group discussion and highlights the key messages of our project.*

5 Discussion and conclusion

In this project, we set out to investigate the potential role and benefits of livestock species in relation to intercropping and enhanced crop diversity at farm level. We explored interactions between crop and livestock species, for further development and implementation of biodiversity-positive food systems, focusing on 1) the potential of crop-livestock combinations in general in intercropping systems, 2) the relevance of particular crop combinations in intercropping within crop-livestock systems, and 3) relevant criteria for the use of genetic resources in integrated crop-livestock farming systems. For this, we used 1) literature review, 2) expert interviews and 3) a focus group discussion in which we developed an infographic on crop-livestock integration. Here, we present our view on the benefits of – and opportunities for – crop-livestock interactions, and discuss our recommendations for future research and implementation of livestock integration in intercropping systems.

5.1 How can intercropping-livestock integration benefit sustainable farming?

The literature study and interviews have highlighted that there can be many potential benefits to crop-livestock integration, that can contribute to a more sustainable way of farming. Although knowledge and investigation of intercropping-livestock integration is much more limited than for crop-livestock integration in general, it appears likely that many of the benefits of crop-livestock integration hold true for intercropping-livestock integration as well. The potential benefits of crop-livestock integration can be split into three main categories: 1) improved biological resilience in multiple aspects, 2) improved economic resilience (and reduced external dependence), and 3) circularity and increased resource use efficiency (**Figure 9**).

However, there are also downsides to (inter)cropping-livestock integration, such as the required skills in both animal and crop farming and the reduced ease and efficiency of management of integrated farms. In the next section, we will discuss some drivers that are currently limiting the implementation of integrated (inter)cropping-livestock systems.

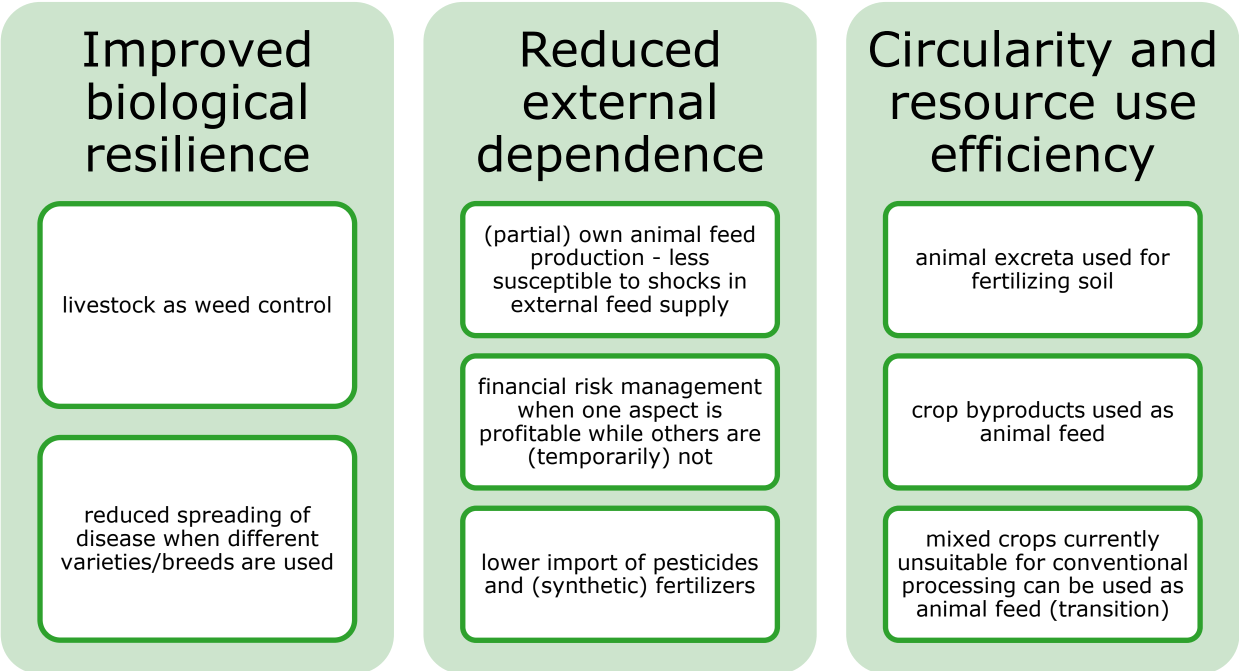

Figure 9 *Main potential benefits of (inter)crop-livestock integration for sustainable farming.*

5.2 What is limiting the implementation of integrated intercropping-livestock systems?

Both the scientific literature and the farm interviews highlighted some barriers for the wide-scale implementation of integrated (inter)cropping-livestock systems. For example, Bonaudo et al. (2014) discuss three main drivers that can potentially negatively affect the development of sustainable integrated crop-livestock systems (thus explaining the decline in integrated crop-livestock systems over time), including 1) the general economic and political environment, 2) farm structure and 3) regional location. Regarding the economic and political environment, they discuss that economies of scope have been limited in comparison to economies of scale, that output-based subsidies have contributed to specialization, and that the dominance of a reductionist approach in research and development led to policies focused on single-criterion performances (Bonaudo et al., 2014). Regarding farm structure, they discuss that the general tendency for farm enlargement has limited the survival or redevelopment of integrated crop-livestock systems and that adaptive management is a learning-by-doing process that involves an increased dedication to system observation. The complexity of integration can limit the adoption of integrated crop-livestock systems, as agricultural education is currently focused on single-crop or -livestock production (Bonaudo et al., 2014). This appears not only true for crop-livestock integration, but also for the change from a monocropping to a multiple-cropping system. An example highlighting the complexity – or the numerous (side) effects – of crop-crop integration is shown in **Figure 10** (from Burgess et al., 2022), in which changes in key microclimate, farm and social variables are shown that may take place in the conversion from a single to a multiple cropping system. Regarding regional location, Bonaudo et al. (2014) discuss that the regional location may determine the market and the soil-climatic conditions, that may or may not favor the survival of integrated crop-livestock systems.

The interviews with the farmers indicated similar barriers, noting that substantial financial investments are required to make the transition, and that bank loans are not always available for non-conventional production plans. Also legislation and machinery are mostly designed to fit conventional systems, making it sometimes challenging to implement crop-livestock integration.

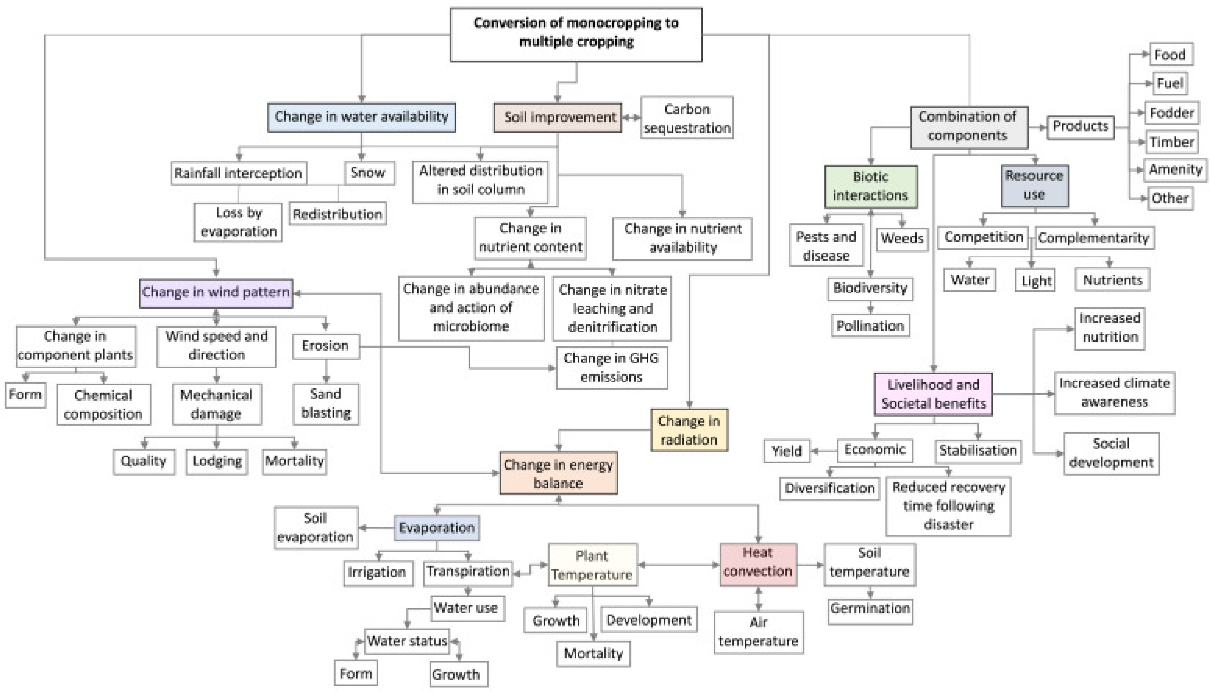

Figure 10 *Changes in key microclimate, farm and social variables that may take place in the conversion from a single to a multiple cropping system. From Burgess et al. (2022).*

5.3 A view towards the future

In this project, we set out to examine the role of livestock and the potential of crop-livestock combinations in intercropping systems, the relevance of particular crop combinations in intercropping within crop-livestock systems, and relevant criteria for the use of genetic resources in integrated crop-livestock farming systems. Because of opportunities for livestock to improve biological resilience and resource use efficiency, and reduce the need for external inputs to farms, we see a potential role for the integration of livestock in intercropping systems, in future ‘complete’ production systems but also in the transition from monocropping to intercropping. As became clear from the interviews, the products from intercropping are sometimes difficult to market, as the processing industry is currently adapted to pure products and not mixes of products. While the adaptation of the processing industry is taking place, animals can provide a clear target for the intercropping products that the human consumption market is not yet ready for. In this way, these intercropping products can still be of value for food production, as the livestock can convert these mixed products into animal protein.

Although farmers indicated to prefer robust species, we quite quickly discovered that intercropping-livestock integration has not yet reached a level at which breeding for specific characteristics in especially livestock is likely to be considered highly relevant. There are considerable practical hurdles to overcome regarding mechanization, processing and legislation before these more ‘detailed’ aspects can start to play a significant role. However, breeding or genetic selection is a more long-term process and one needs to start selecting crops or animals now to have access to the benefits in the future. Therefore, we advise to, in the short term, start looking systematically at breeding for crop-livestock integration to facilitate future integrated systems. Aspects to consider in this regard could include the potential roles of the animals within the integrated production system, the adaptation of animals to the environment they are kept in and the animal’s ability to function well on the feed they will receive which might consist of more mixed products. It is likely that this offers opportunities for more (albeit perhaps altered) use of landraces.

Overall, even though the added value of integration of livestock strongly depends on the context and careful consideration of the system and adequate management are pivotal, there appears to be great potential for the implementation of intercropping-livestock integration, on field, farm or regional scale, to achieve a sustainable agriculture. Integration of livestock into (inter)cropping systems could improve the biological resilience, resource use and circularity and the independency of the farm. Its application in practice will need an integrated vision of the future of the role of livestock in farming systems.

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Appendix 1: Interview questions (in Dutch)

The questions below (in Dutch) were used in the semi-structured interviews:

1. Hoe ziet de strokenteelt er op uw bedrijf uit?
    a. Welke soorten?
    b. Hoe lang past u dit al toe? Hoe is het ontwikkeld over tijd?
    c. Op welk percentage van uw land past u strokenteelt toe?
2. Welke dieren worden er gehouden/geproduceerd?
3. Hoe (sterk) zijn die verschillende gewassen en vee geïntegreerd?
    a. Hoe lang heeft u deze samenstelling van gewassen en vee al?
    b. Hoe is dat ontwikkeld over de tijd?
    c. Hoe passen deze soorten (combinatie van soorten) in dit land(schap)/omgeving?
4. Waarom juist deze diersoorten en gewassen? Welke rol(len) hebben ze in het systeem?
5. Hoe ziet de bedrijfsvoering rondom de akkerbouw/strokenteelt en het vee er door het jaar heen uit?
6. Waarom heeft u gekozen voor deze/een integratie van gewassen/strokenteelt en vee? Wat zijn de belangrijkste voordelen naar uw idee?
    a. Nutriëntkringlopen
    b. Biodiversiteit
    c. Weerbaarheid van het systeem
    d. Flexibiliteit en verdienmodel
7. Wat zijn de grootste (praktische) uitdagingen bij het combineren van akkerbouw/strokenteelt en veehouderij (zowel productie als verwerking)?
    a. Hoe die overkomt u die uitdagingen?
    b. Waar haalt u de benodigde kennis vandaan? Of van wie?
8. Zijn er uitdagingen in de maatschappij/wetgeving?
9. Zou u dit bedrijfssysteem aan iemand anders aanraden? Waarom wel/niet?
    a. Locatie-afhankelijkheid, opschaalbaarheid?
10. Specifiek over de plant- en diersoorten: welke rassen heeft u voor gekozen? Waarom?
    a. Wat zijn de sterke dier/plantkenmerken van deze rassen?
    b. Waar zitten de uitdagingen/verbeterpunten van deze rassen?
    c. (bij eigen opfok/selectie) Wat zijn uw selectie kenmerken en fok- en veredelingsdoelen?
11. Wat zijn uw toekomstplannen met het bedrijf?

To explore the potential of nature to improve the quality of life

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Wageningen Livestock Research creates science based solutions for a sustainable and profitable livestock sector. Together with our clients, we integrate scientific knowledge and practical experience to develop livestock concepts for future generations.

Wageningen Livestock Research is part of Wageningen University & Research. Together we work on the mission: 'To explore the potential of nature to improve the quality of life'. A staff of 6,500 and 10,000 students from over 100 countries are working worldwide in the domain of healthy food and living environment for governments and the business community-at-large. The strength of Wageningen University & Research lies in its ability to join the forces of specialised research institutes and the university. It also lies in the combined efforts of the various fields of natural and social sciences. This union of expertise leads to scientific breakthroughs that can quickly be put into practice and be incorporated into education. This is the Wageningen Approach.