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Review Article

Impacts of agricultural production decisions on the safe and just operating space: A systematic literature review

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Abstract

Agricultural production decisions impact how agriculture navigates within the safe and just operating space (SJOS). The ability to model and assess these impacts is crucial for policy analysis. This study systematically explores the literature for links between agricultural production decisions and SJOS. As agricultural production decision categories, we examine on-farm technology usage, farm structural change, and field structural change. We identify the impact mechanisms of various aspects of these categories and discuss the scope of evidence available. Technology usage impacts the SJOS often through farmers' choice of technology and its effect on yield. Farm structural change impacts the SJOS through economies of scale and scope, while field structural change impacts directly and through management efficiency. There is considerable knowledge of these relationships but also research gaps. The study provides fundamental insights for characterizing the decision properties of agricultural production and is useful for guiding policy modelling for improved SJOS outcomes.

Keywords: Safe operating space, Just operating space, Planetary boundaries, Technology usage, Farm structural change, Field structural change

JEL codes: Q15, Q16, Q18

1. Introduction

Recent transformations of the European Union (EU) agriculture strongly involve policy processes that address environmental concerns while improving social conditions. The core policy strategy of the EU for tackling climate change and environmental degradation is the Green Deal. To contribute to its overall climate neutrality goal, the strategy aims, among others, at improving the sustainability of the EU food system, thereby reducing the impact of food and agricultural production on the earth system. However, recent reviews of the Green Deal initiatives have underscored non-conformity of agricultural and food chain practices with the set objectives of the Green Deal (Guyomard et al. 2020; Boix-Fayos and de Vente 2023). The strategy also faces limitations in attaining its social objectives; for example, consumption patterns still do not exhibit improvement in targeted health areas of weight and disease management (Guyomard et al. 2020). This suggests that the attainment of the EU objectives as outlined in the Green Deal strategy necessitates enhancements to the strategy and associated policy actions.

The safe and just operating space (SJOS) concept (Raworth 2012) is a framework useful in identifying the shortcomings of policies such as the current Green Deal and help to steer the attainment of the policy goals. It combines the well-established concept of planetary boundaries for earth system processes (Rockström et al. 2009) and indicators for assessing social well-being. Thereby, it provides thematic focus areas and suggests indicators to model and assess environmental and social policy impacts. The framework captures major parameters of the earth system that are impacted by agriculture (Foley et al. 2005; Rockström et al. 2009; Conijn et al. 2018; Goglio et al. 2018; Zappe et al. 2020; Rockström et al. 2023). Müller et al. (2024) provide a refinement of the SJOS concept to constitute a minimum set of thematic areas of environmental and social outcomes relevant to EU agriculture. Using this as a compass, we aim to provide a systematic review of theoretical and empirical knowledge on how agricultural production decisions impact SJOS outcomes. Specifically, we identify and discuss how different aspects of production decisions link to the EU SJOS thematic areas. To do this, we discuss aspects of production decisions under three broad umbrella categories: (1) on-farm technology usage (OFTU) capturing tillage, fertilization, crop rotation and protection, organic farming, precision farming, and biotechnology, (2) farm structural change (FaSC) capturing change in farm size and farm specialization, and (3) field structural change (FiSC) capturing change in the size, number, and shape of agricultural fields. Furthermore, we summarize the scope of theoretical and empirical evidence available for modelling of biophysical and economic properties of agricultural production systems, and we identify knowledge gaps for future research considerations in areas where we have theoretical knowledge but do not find enough empirical evidence. The study provides the basis to extend and refine existing policy simulation models to assess how EU agricultural policies impact safe and just outcomes.

We follow a systematic literature review procedure, which we describe in Section 2. Sections 3, 4, and 5 present the literature evidence on the relationship between agricultural production decision categories and the SJOS thematic areas. In these sections, we group and discuss together thematic areas that have similar impact relationships. Section 6 summarizes the main relationships and mechanisms identified in Sections 3, 4, and 5 as well as knowledge gaps. The section also presents how key outcomes can be used in ex-ante agricultural policy models, the requirements and challenges for capturing the identified relationships, and recommendations for future empirical research. Section 7 concludes the study.

2. Methodology

The literature review follows a systematic procedure to find records relating the three umbrella categories (OFTU, FaSC, and FiSC) to the minimum set of twelve thematic areas

Table 1. Volume of unique studies cited as evidence for the relationships between agricultural production decision categories and the minimum set of SJOS thematic areas relevant for the EU agricultural system.

Thematic areas		OFTU	FaSC	FiSC	Sum
Environmental thematic area (safe operating space)	Biodiversity	23	11	21	55
	Nutrient flows	9	5	9	23
	Aerosol loading	1	2	4	7
	Climate change	22	6	3	31
	Chemical pollution (novel entities)	10	1	1	12
	Land use	3	3	0	6
	Water use	0	1	0	1
Social thematic area (just operating space)	Nutrition security	14	19	4	37
	Farm resilience	7	12	13	32
	Health	16	1	0	17
	Social equity	0	13	0	13
	Economy	3	0	0	3
Sum		**108**	**74**	**55**	**237**
Total unique studies		95	72	51	218[a]

Note: Total unique studies refer to the sum adjusted for studies cited in multiple thematic areas.
[a]Three studies out of the total 218 were cited in FaSC and FiSC, reducing the actual number of unique studies cited as evidence within the three decision categories to 215.

of environmental and social dimensions that are relevant for the EU agricultural system. Web of Science (WoS) is used as the primary search database and additional documents are snowballed as supporting argumentation in required cases. Topic keywords for each umbrella category are based on the aspects we aim to cover within each category, and the keywords for thematic areas are based on the understanding of the SJOS thematic areas and control variables as specified in pioneer SJOS papers (Rockström et al. 2009; Raworth 2012;Steffen et al. 2015; O'Neill et al. 2018). Appendix A shows, for each category, the concatenated keywords that form the search queries. From the search outcomes, only published, peer-reviewed, accessible, English articles are considered. Among these, screening and selection of relevant records are conducted in two stages. Firstly, titles and abstracts are screened to assess their relevance. Secondly, the review selects and considers eligible studies based on identified findings of interest in the full text. While the regional focus of the paper is the EU, we do not systematically exclude findings from other parts of the world as they may provide useful insight into possible impact mechanisms for EU-relevant SJOS thematic areas. Although some of the reviewed and cited studies apply to multiple thematic areas within a decision category, respective totals of 95, 72, and 51 unique studies (Table 1) were consulted and referenced in the next three sections.

3. On-farm technology usage

Based on the definition of technology from Ruzzante, Labarta, and Bilton (2021), we understand OFTU as the application of 'equipment, genetic material, farming techniques, and agricultural inputs that have been developed to improve the effectiveness of agriculture'. Several aspects of OFTU are central to agricultural production and impact many thematic areas of the SJOS. However, considering the extensive breadth of OFTU in agriculture, we focus on a select number of technologies in this study: tillage, fertilizing, crop rotation, crop protection, organic farming, precision farming, machinery, and biotechnology. The select technologies are from the categories provided by Ruzzante, Labarta, and Bilton (2021), namely natural resource management, improved varieties, chemical inputs, and mechanization and infrastructure. In addition, we cover OFTU related to smart farming.

3.1. Biodiversity

OFTU has a strong impact on *biodiversity*. Many studies show that conventional tillage, inorganic fertilizing, chemical plant protection, and heavy harvesting with machinery are negatively associated with species richness. This is found to be due to consequent changes in the environment, soil chemical properties, and soil physical conditions, which sometimes result in habitat destruction (Diame et al. 2015; Frazão et al. 2017; García-Tomillo et al. 2017; Toffoli and Rughetti 2017; Dekemati et al. 2019). In contrast, no-till treatment, crop diversification, organic farming, precision agriculture, and biotechnology use are considered to exhibit mitigating effects on biodiversity loss (Schwab, Schickhoff, and Fischer 2015; Goded et al. 2018; Kholilah et al. 2019; Eyinade, Mushunje, and Yusuf 2021; Beaumelle et al. 2023). No-till treatment is found to increase species richness (Dekemati et al. 2019; Martin et al. 2020) and organic fertilization maintains the soil functional stability and diversity (Diame et al. 2015; Luo et al. 2023). Similar to inorganic fertilizers, pesticide use for plant protection harms biodiversity through its negative impact on important groups of soil biota, including earthworms, arbuscular mycorrhizal fungi, and nitrogen (N)-fixing bacteria (Romero et al. 2023). Chemical plant protection also negatively affects insect diversity and insect-eating animals (Toffoli and Rughetti 2017). Contrarily, minimizing pest pressure through spatial and temporal diversification improves biodiversity (Beillouin et al. 2021).

Organic farming is found to be a farming system that preserves and sometimes increases the abundance of organisms and species richness (Seufert and Ramankutty 2017). This is because of effects attributable to a more varied presence of plant and animal species and functional diversity effects such as greater protection of pollinating insects (Seufert and Ramankutty 2017; Calabro and Vieri 2024). These advantages are higher in arable systems than in grassland systems (Diame et al. 2015; Goded et al. 2018) and within individual fields than at the farm-scale level (Eyinade, Mushunje, and Yusuf 2021). Literature also shows a positive impact of precision agriculture on biodiversity. Smart technologies can help reduce chemical input use as they help reduce soil compaction, enable early detection, and allow for early and selective action against weeds and diseases (Gackstetter et al. 2023). The use of biotechnology in agriculture also has the potential to conserve natural ecosystems and genetic resources by reducing the requirements for crop protection chemicals, artificial fertilizers, tillage, and irrigation (Souza and Santos 2017; Santos Do Vale et al. 2020). However, biofortification and other methods of genetic engineering applied in modern agriculture could pose risks to biodiversity (e.g. due to the potential introgression of transgenic traits into wild plants and soil degradation) (Hansson and Joelsson 2013; Székács et al. 2020).

From the above, we identify no-till, crop diversification, organic farming, and precision agriculture as clearly beneficial for biodiversity, inorganic fertilization as detrimental and biotechnologies currently have mixed evidence in the literature. Although many studies have investigated the relationship between these OFTU and biodiversity outcomes, methodological differences (e.g. different biodiversity indices), along with varying responses of organisms to changes in farming practices, crops, and site-specific factors, make quantitative synthesis of these results challenging. For example, the zero use of pesticides was found to have a positive impact on birds, mammals, bacteria, and earthworms, but not on fungi (Cozim-Melges et al. 2024). Studies have also found that neighbourhood (or scale) effects influence the impact of OFTU on biodiversity, with some species benefiting more when biodiversity-friendly OFTU applies regionally rather than on individual biodiversity-friendly farms (Ostandie et al. 2021). For modelling activities, it is thus crucial for models to account for the complexity and specificity of the relationship between OFTU and *biodiversity*.

3.2. Nutrient flows

Fertilizer usage influences *nutrient flows* considerably. Synthetic N fertilizers, which are the common primary input used to enrich soil nutrients, can contribute to higher nitrate concentrations and nitrate leaching if applied at inappropriate times and in excessive amounts (Noor and Tejada Moral 2017). Several studies have found that even partial substitution of synthetic N fertilizer with livestock manure decreases reactive N losses due to improved synchronization between crop N demand and supply (Liu et al. 2021). On the other hand, research shows that the N use efficiency is lower when more organic N is used (Yu et al. 2022; Löw and Osterburg 2024), leading also to higher losses to the environment.

The efficiency of fertilizer can be improved through precision farming, which allows for even site-specific fertilizer applications, resulting in lower N fertilizer inputs overall and preventing nutrient imbalance (Hussein et al. 2021; Al-Gaadi et al. 2023). This differs from traditional techniques, which causes under-fertilization of some parts of the field and over-fertilization of others. Tillage, crop diversification, and rotation also influence soil quality and, consequently, nutrient flow (Kiani et al. 2017; Nazaries et al. 2021). Mixed cropping systems (including crop diversification and rotation), minimum-till, or no-till practices allow better uptake of nutrients from different depths of the soil profile and restoration of nutrient balance by the N fixation process (Noor and Tejada Moral 2017).

In general, evidence from various studies that have compared organic and conventional farming concerning different aspects of nutrient flows shows that the impact on nutrient flows of organic farming depends on a broad range of production, soil, and weather conditions in different contexts (Biernat et al. 2020; Calabro and Vieri 2024). Thus, modelling *nutrient flows* requires an approach that accounts for the diverse impacts of fertilizer types, precision application techniques, and various land management technologies. Modelers face the challenge of accurately representing N and phosphorus balances across different scenarios, depending on site-specific conditions. Another significant hurdle in this modelling effort is the reliance on detailed field-scale data, which is often scarce or difficult to obtain.

3.3. Climate change, chemical pollution, and aerosol loading

Agricultural practices have been positioned as significant drivers of climate change. On the one hand, use of fertilizers, conventional tillage, pesticides application, and machinery in farms contribute to high greenhouse gas (GHG) emission due to N_2O, CO_2, and CH_4 emission, and reduction of carbon sequestration potential. On the other, crop diversification, minimum tillage and no-tillage cultivations, crop rotation, use of enhanced efficiency fertilizers, precision/smart farming technologies, and organic farming contribute to reducing GHG emissions and mitigating *climate change* (Guardia et al. 2016; VandenBygaart 2016; Necpalova et al. 2018; Plaza-Bonilla et al. 2018; Menichetti, Kätterer, and Bolinder 2020; Gao and Cabrera Serrenho 2023).

The highest source of GHG emissions in conventional crop production is soil N_2O emissions, which can be reduced using nitrification inhibitors (Ortiz et al. 2008; Hargreaves et al. 2021) or slow-release fertilizers (Tuomisto et al. 2012). However, reducing N application in cases of over-fertilization appears to be the most effective strategy (Menegat, Ledo, and Tirado 2022). Minimum tillage and no-tillage treatments decrease the use of energy-consuming machinery in soil preparation and thus reduce CO_2 emissions from machinery fossil fuel use (Kamyab et al. 2024). The practices also contribute to lower GHG emissions by reducing soil CH_4 emission (Huang et al. 2018) and increasing carbon sequestration in soil (Mangalassery et al. 2014). Considering N_2O emissions, the results are mixed. While Mehra et al. (2018) found that no-till treatment reduces N_2O emissions associated with soil disturbance, Huang et al. (2018) reported that no-till practice increases soil N_2O emissions due to increased soil moisture and decreased soil aeration. Moreover, this reduction is crop- and site-specific (Sørensen et al. 2014). Precision farming technologies, which allow the use of more accurate and efficient fertilizer application methods, also minimize the release of related emissions (Chataut et al. 2023).

Studies show that organic farming has considerably lower GHG emissions than comparable conventional systems per agricultural production area. However, depending on yield difference, this benefit can be lost when system production is measured per ton (Venkat 2012; Bos et al. 2014; Meemken and Qaim 2018). More so, Gattinger et al. (2012) highlighted evidence for higher levels of carbon sequestration in organic systems compared to conventional ones. However, maintaining the current production levels while expanding organic farming to replace conventional farming could only be achieved through a higher availability of lands and increased use of manure with an inevitable increase in methane emissions (Muller et al. 2017; Calabro and Vieri 2024).

Applying synthetic pesticides and fertilizers for crop production and protection is a prominent practice through which a wide range of substances are emitted, resulting in *chemical pollution*. However, organic farming, precision/smart farming, and biotechnologies are found to help in reducing chemical pollution (Stoian et al. 2022; Pérez-Méndez et al. 2023). Organic farming helps to decrease chemical pollution because of the restriction of chemical inputs (Puech et al. 2014). However, the lower persistence of organic insecticides in the environment compared to synthetic ones can lead to more frequent use of these insecticides, which could reverse the benefits of organic systems for chemical pollution (Edwards-Jones and Howells 2001). Temporal crop diversification as on-farm land management practice is found to be negatively associated with insecticide use and associated chemical pollution. Same applies to the use of resistant varieties (Guinet et al. 2023). Employing precision farming technologies for pest prediction, early detection, and control is found to be associated with reduction in pesticide use (Anastasiou et al. 2023). Additionally, smart agricultural technologies enable the application of fertilizers based on real-time assessments of soil fertility and plant health, thereby mitigating the risk of chemical pollution (Thorat, Patle, and Kashyap 2023).

In general, biotechnologies are considered as promising farm technologies for management of heavy metal tolerance (Elango et al. 2022) and crop resistance to pathogens (Schaak et al. 2021). Use of biotechnologies allows a reduction in the use of chemicals like insecticides and fungicides in crop production. However, biotechnological interventions for agricultural pollution mitigation are constrained by their specificity to particular pollutants and environmental conditions. Furthermore, introducing genetically engineered organisms into agroecosystems presents potential ecological risks, including the gene transfer to non-target species and ecosystem perturbations (Tsatsakis et al. 2017).

For *aerosol loading*, we did not find results for many of our focus areas of OFTU in our literature search. However, one study that examines farm machinery (tractor) and aerosol loading (specifically, matter emission) shows that tractors equipped with the most recent emissions savings technologies can reduce matter emission (Bacenetti et al. 2018).

The review identified use of enhanced efficiency fertilizers, conservation tillage practice, crop diversification, organic farming, precision farming, and biotechnologies to contribute to reducing greenhouse gas emissions and chemical pollution from agricultural production while the excessive application of synthetic fertilizers and pesticides, along with conventional tillage, contributes to increasing emissions. In ex-ante modelling, these technologies can be incorporated via land management, such as organic farming and tillage practices, or through reduced chemical input usage, as seen in crop diversification, biotechnologies, and precision farming. The site-specific nature of many of the identified relationships complicates the modelling process, and the complexity of interactions highlights the importance of multifaceted modelling approaches to assess the environmental impacts of different on-farm technologies accurately.

3.4. Nutrition security and land use

The main mechanism of how OFTU could impact *nutrition security* is indirectly via its effects on yields and, hence, on total available supply of calories produced. This could impact food prices, food affordability, and thus nutrition security. Technologies might also change relative production costs for different food categories and impact relative costs for different food products with different health benefits. No-till treatment and organic farming tend to have observably lower yields, which gives reasons for concern when considering the growing demand for food (Pittelkow et al. 2015; Kirchmann 2019). Combining biotechnology (Wu et al. 2014; Bearth, Kaptan, and Kessler 2022) and the adoption of precision farming technologies (Reis et al. 2020; Figiel 2022; Mizik 2023) with tillage and organic farming represent potential solutions to increase yields. With the development of new plant breeding technologies (NPBTs), the possibilities of allowed use of biotechnology in organic agriculture could reduce the food security risks caused by scaling up organic farming (Purnhagen et al. 2021). Precision farming technologies allow farmers to increase crop yields through better land management and increased input efficiency. Also, biotechnologies can contribute to increasing yields (e.g. by modifying the plant genes that control the carbohydrate accumulation processes for improving carbohydrate allocation from source and sink organs to harvesting organs). They can also prevent yield reduction by improving genetic tolerance against abiotic stress (Burgess et al. 2023).

The impact of OFTU on *land use* is also very connected to yield. Lower yields of some agricultural technologies can lead to *land use* change. Organic farming is found to impact land use and land cover change through the requirement for more land to compensate for the lower yields (Meemken and Qaim 2018; Kirchmann 2019) to produce the same output as in the conventional production system. However, we find no relevant studies to relate other focus aspects of OFTU, such as fertilizing, tillage, precision farming, or biotechnologies within the scope of review.

Similar to earlier addressed thematic areas, the impact of OFTU on nutrition security is also crop- and site-specific. For example, Cui et al. (2024) showed that no-till increases crop yields in relatively arid areas but reduces yields in more humid areas. Pittelkow et al. (2015) report comparable yields for oilseeds, cotton, and pulses under no-till compared to conventional tillage, but lower yields for cereals under no-till treatment. Summarizing the results of three meta-analyses on crop yields, Meemken and Qaim (2018) identify lower organic farming yields but with considerable differences across different crops. Also, genetic engineering, which is found to increase the global supply of crops such as maize and soybean (Scheitrum, Schaefer, and Nes 2020), shows yields (for maize) that are influenced by the environment in which the plants are grown (Leibman et al. 2014). Changes in crop yields can manifest in changes in *land use*. However, we find no evidence for this thematic area and OFTU other than organic farming in our search. When modelling the impacts of OFTU on *nutrition security*, it is imperative to correctly capture yield changes and incorporate crop-specific and site-specific yield effects, as these variables significantly shape total calorie production, food prices, and affordability. Models must, therefore, carefully consider the nuanced impacts on yields across different crops and regions, and also address the complex interactions between yield changes and land use requirements. A considerable challenge lies in modelling complex food systems to provide a comprehensive analysis that goes beyond solely addressing supply-side aspects like yield changes (Muller et al. 2017).

3.5. Farm resilience and economy

When examining OFTU impacts on *farm resilience*, assessing the yield effects of technology appears again as one of the most relevant indirect aspects. Other aspects are investment needs and how (novel) technologies will affect production costs. Price premium on certified organic products and reduced organic input costs can improve the income of smallholder farmers (Panneerselvam, Hermansen, and Halberg 2010; Malek, Tieskens, and Verburg 2019; Ramankutty et al. 2019). Thus, farming under organic conditions might also allow farmers to realize higher prices if consumers are willing to pay a premium and if adequate marketing and labelling regulations are in place. However, the effect of price premiums on poverty reduction is not clear.

Non-European studies found that the adoption of soil fertility conserving technologies (including improved seeds, minimum tillage, crop rotation, and a combination of organic and inorganic fertilizers) (Hörner and Wollni 2021) and adoption of biotechnologies (Ali and Abdulai 2010) have a positive relationship with yields and consequently contribute to higher household income and poverty reduction. Furthermore, precision farming helps increase crop yields and animal performance, as well as optimize the use of inputs, thereby reducing costs and contributing to farm incomes (Anastasiou et al. 2023). However, adopting advanced agricultural technologies frequently entails considerable initial investments, which can be prohibitive for resource-constrained (smallholder) farmers. This economic barrier may result in heterogeneous adoption patterns, potentially widening income disparities between adopters and non-adopters (Barnes et al. 2019).

The literature review on energy access, an aspect of thematic area *economy*, reveals that the main aspects of OFTU that can influence energy access are biotechnologies. Recent advances in genetic engineering allow farmers to use less energy on farms (Hansson and Joelsson 2013), increase agricultural land productivity, and consequently increase the amount of land available for biofuels (Zilberman et al. 2013) as well as reduce the costs of producing biofuels (Debnath et al. 2019).

These results inform that modelling the impacts of OFTU on *farm resilience* should comprehensively evaluate how various OFTUs impact income distribution and farm viability. This involves assessing yield effects, investment requirements, and production cost changes across various technologies, including potential price premiums for systems like organic farming. Within the *economy* thematic area, it is imperative to consider the role of biotechnologies with regard to energy access and land productivity.

3.6. Health

On-farm technologies impact *health* in various ways. Applying chemical fertilizers and pesticides is associated with the direct exposure of farmers and agricultural workers to these chemicals (Dhankhar and Kumar 2023). Also, excessive use of pesticides and fertilizers can lead to contamination of air, water, soil, and food, which adversely impacts food security and food safety (Gagliardi and Pettigrove 2013; Elango et al. 2022; Mack et al. 2023).

Organic farming, precision farming, and biotechnologies appear as technologies that minimize these negative impacts. Research reports that organic farming has lower pesticide residues than conventional production (Gamage et al. 2023) and, that other unhealthy components, such as nitrates and cadmium, are lower (Meemken and Qaim 2018). However, regarding nutritionally desirable components (such as proteins, amino acids, antioxidants, and vitamins), the results of organic versus conventional studies are nutritional component- and plant-specific. For instance, while organic crops generally exhibit higher concentrations of antioxidants and (poly)phenols but lower levels of proteins, amino acids, and vitamin E (Barański et al. 2014), the effects on vitamin C and carotenoids vary, with conventionally grown fruits (raspberries) containing more vitamin C (Ponder and Hallmann 2020), whereas organic vegetables (sauerkraut and cucumbers) show higher vitamin C content (Breza-Boruta, Ligocka, and Bauza-Kaszewska 2022). Precision farming technologies considerably reduce pesticide dependency and, consequently, pesticide residues. For example, autonomous systems can perform plant protection tasks such as pesticide application more accurately, efficiently, and healthily for humans (Anastasiou et al. 2023).

Although biotechnology is also discussed as a potential threat to the environment and human health, several authors argue that agricultural biotechnology can positively affect human health by decreasing exposure to pesticides, improving the nutritional value of food, and producing pharmaceuticals more efficiently (Kouser and Qaim 2011;

Hansson and Joelsson 2013; Yang and Chen 2016; Veettil, Krishna, and Qaim 2017). With respect to the NPBTs, there are several promising applications with improved food and feed quality, such as lettuce with increased vitamin C content, wheat with lower gluten content, or oilseed rape with improved fatty acid composition (Purnhagen and Wesseler 2021).

OFTU impacts *health* directly and indirectly, requiring consideration of the health effects associated with food production and consumption. This impact can be quantified using indicators such as life expectancy, as employed by studies that analyse dietary patterns (e.g. Fadnes et al. 2023). Ex-ante models for health require a comprehensive approach to encompass both the benefits (e.g. reduced exposure to chemicals) and risks (e.g. antimicrobial resistance) associated with different technologies. Given the multidisciplinary nature of these relationships, it is challenging to acquire and synthesize data from fields such as agricultural science, toxicology, nutrition, and epidemiology, which is necessary to parameterize models for assessing health impacts. The complexity underscores the considerable challenge in modelling this relationship within the thematic areas of SJOS.

Concluding this chapter, the review identified four thematic areas of the safe operating space that are significantly driven by on-farm technologies: climate change, biodiversity, chemical pollution, and nutrient flows; and four thematic areas of the just operating space: nutrition security, health, farm resilience, and economy. The outcomes of OFTU are intricately intertwined and embedded within physical, social, environmental, and economic systems. For instance, chemical pollution caused by heavy metals affects not only food quantity and farm income through diminished crop productivity but also biodiversity and human health. The interconnectedness of dimensions within the SJOS necessitates an interdisciplinary approach to analysing the outcomes. Simultaneously, enhancing the analysis (and quantification) of outcomes would benefit from incorporating greater depth and specificity, such as crop and site specificity.

4. Farm structural change

Farm structure is here understood as the composition and organization of an agricultural production unit. It includes elements such as the size of the land area and livestock herds, the labour force's characteristics, the means of production, and legal and organizational aspects of land tenure, farm management, and market access. Together with OFTU it is a crucial component of an agricultural system, along with agro-ecological and economic factors (Rossi 2020). It should be noted that while farm structure includes the size of the land area, the composition or structure of the land(scape) is not included here as this is covered in Section 5. The scope of FaSC is defined by differences and changes in farm specializations and farm sizes. Farm specialization is determined by the dominant farm activity, which contributes the most to the farm's total standard output while farm size refers to the amount of land used for agriculture or in economic terms.

4.1 Biodiversity

The reviewed literature offers evidence that farm sizes and specializations impact *biodiversity*. Smaller farm sizes are associated with enhanced biodiversity (Belfrage, Björklund, and Salomonsson 2015; Karlsson, Tidåker, and Röös 2022; Noack et al. 2022) as small-scale farms are associated with more varied landscapes, including semi-natural grasslands, which increase biodiversity (Karlsson, Tidåker, and Röös 2022). Similar to the discussion in Section 5, the impact of farm size on biodiversity is mainly attributed to land cover simplification resulting from the farm size increase (Noack et al. 2022). The interplay of farm sizes and agricultural activities in different farm specializations can generate varying biodiversity outcomes (Smith et al. 2020; Dabkiene, Balezentis, and Streimikiene 2021; Karlsson, Tidåker, and Röös 2022). Descriptive evidence shows that, for example in Lithuania, medium-sized family farms as well as farms specializing in integrated field crops and grazing livestock exhibit the most environmentally beneficial characteristics while small and large farms as well as farms specializing solely in various crops, livestock, and orchards are less beneficial (Dabkiene, Balezentis, and Streimikiene 2021). Karlsson, Tidåker, and Röös (2022) also found that farms specializing in monogastric livestock and rather larger farms are associated with less varied landscapes and suboptimal crop sequences, which decreases biodiversity. An examination reveals that integrating livestock and crop production fosters resilient native bird communities, particularly within landscapes dominated by intensive food production (Smith et al. 2020). Integrated crops and livestock systems generate diversifying habitat types on the farm (Benton, Vickery, and Wilson 2003), supply extra food sources through grain-based livestock feed and insects found in faeces (Evans et al. 2006; Carlson et al. 2015; Hald et al. 2016), and by offering extra structures for nesting (Hiron et al. 2013; Salek et al. 2018).

Overall, farms specializing in field crops, grazing livestock, or ruminants are found to be more beneficial for biodiversity compared to those specializing in horticulture or monogastric livestock. However, these reviewed works primarily show correlations between farm size and biodiversity measures without showing causal effects or controlling for crucial unobserved confounders. Therefore, it remains open whether there are direct effects of farm size on biodiversity. For modelling activities, it appears crucial for models to be capable of considering different farm specializations to capture impacts on *biodiversity*. Even though some studies explained how different farm specializations are related to *biodiversity* outcomes, quantitative numbers that can be used in modelling activities are lacking.

4.2 Nutrient flows, aerosol loading, and health

Nutrient flows relate to FaSC through fertilizer use in farm specializations and through management intensity. In the context of specializations with intensive fertilizer use, farm size can impact nutrient flows as change in farm size potentially changes fertilizer use efficiencies through economies of scale. However, the connections between farm size, fertilizer use, and *nutrient flows* are multifaceted, resulting in different outcomes depending on various factors, such as efficiency, production, environmental impact, and nutrient management practices. Some studies show that larger farms are associated with less N and phosphorus flows (Liu et al. 2020; Ren et al. 2022; Zhu et al. 2022) due to higher efficiency levels of fertilizer use. However, Li et al. (2020) cautioned that although this positive association exists, accelerated soil erosion and associated nutrient losses with increasing farm size may offset this benefit. Contrasting, Hu, Zhang, and Zhou (2019) show that farm size has negative effects on fertilizer efficiency use.

Aerosol loading from FaSC might be related to specific farm specializations with high N use or livestock husbandry because the more N is used or livestock heads are involved, the higher the ammonia emission which contributes to aerosol formation. Also, agricultural production can impact *health* through the use of pesticides, insecticides, or other chemical inputs on farms, mainly when farmers or local farm residents come into contact with chemicals or emissions. Although we found insufficient evidence on aerosol loading and health, a Kenyan study on aerosol loading shows that smaller farm sizes and higher livestock densities are related to higher particulate emissions per unit area (Ortiz-Gonzalo et al., 2017). More so, aerosol loading, like particular matter, comes mainly from ammonia emissions in agriculture through mineral fertilizer use and livestock production (Bauer, Tsigaridis, and Miller 2016). These emissions are a major health problem and the exposure to these risks varies across different production specializations.

To include *nutrient flows* in ex-ante modelling activities, it seems promising to capture the efficiency of fertilizer application. This might be possible through modelling management behaviour in single farm models or adoption rates of new emission-avoiding technologies for aggregated models. Meanwhile, it is generally crucial to have information about the usage of pesticides or mineral fertilizers in different production activities when considering health impacts. Even though there is plenty of evidence of health issues and agricultural production, we find only minimal evidence that farms specialized in fruits and permanent crops in France exhibit the highest levels of insecticide use per hectare and a consistent association to Parkinson disease (Moisan et al. 2011).

4.3 Climate change and chemical pollution

Two mechanisms seem most relevant for the impact of FaSC on *climate change*. First, farm specializations differ with respect to greenhouse gas emissions (e.g. livestock vs. crop production). Second, an increase in farm size might allow the realization of economies of scale, which can increase efficiency and decrease emissions on a per-unit output basis.

Findings in the literature show that the impact of farm sizes on climate change must be analysed within specializations. Due to lower energy use and slightly higher yields, larger rice-producing farms have lower carbon footprints per production unit than smaller ones (Kashyap and Agarwal 2021) while smaller farms in integrated crop–livestock systems show higher emissions per unit of production through higher livestock densities (Ortiz-Gonzalo et al. 2017). Differently, moderate-sized farms specialized in beef production show lower GHG emissions, higher animal productivity, and reduced input usage than larger farms on a per-output basis (Veysset et al. 2014). Regardless of farm size, specialized crop farms and combinations of crop and cattle activities contribute significantly to N_2O releases, while specialized dairy and pig farms show fewer emissions (Boeckx, Van Moortel, and Van Cleemput 2001). Similarly, higher greenhouse gas emissions on a per-hectare basis are associated with farms engaged in granivores, cattle production, or mixed farm systems, while specialized crop farming results in lower emissions (Samson et al. 2012). These cases highlight the possible emission implications of farms with mixed specializations. A Norwegian case study suggests that regional concentration of agriculture might lead to a decline in emissions, whereas policies favouring small-scale farm structures could potentially increase emissions (Mittenzwei 2020). In essence, smaller farms are suggested to have higher negative impacts on climate per unit of output than larger farms, and even though animal production activities are prone to high emissions, crop production farms or mixed farms similarly produce substantial emissions.

Little research on farm structure and chemical pollution is found. Evidence from China shows that larger farms lower pesticide application intensity through use of agricultural machinery and different management capabilities (Gao et al. 2021). The study corroborates similar patterns found for climate change that larger farms are often more efficient in input use, and this can reduce chemical pollution.

Considering *climate change* and *chemical pollution* in ex-ante modelling, it would be important to differentiate between farm specializations. Modelling efficiency gains, which might be more feasible for larger or more viable farms, also appears to be relevant. If the models are granular enough to represent the production activities across specialization, GHG emission factors per production activity can be attached and *climate change*-related outcomes can be modelled. Modelling the impacts of farm specialization on emissions relevant for *climate change* might be more feasible than in the case of farm size changes, where the direction of the effects is not always clear.

4.4 Land use and water use

Farm size and farm specialization can impact land use. Similar to the previous two themes, the most crucial mechanism is potential economies of scale or scope. However, only few evidence can be connected to *land use* and *water use*. Larger farms may be better capable of adopting crop rotations due to better access to machinery that enables to diversify crops and associated land use (Karlsson, Tidåker, and Röös 2022). Moreover, farms specialized in ruminant livestock also show higher crop rotations due to their higher share of ley in the crop sequences (Karlsson, Tidåker, and Röös 2022). The number of bovine heads, used as an indicator of farm size and specialization, suggests that larger and more specialized farms were less likely to abandon land (Díaz et al. 2011). In Finland, larger and more specialized farms show differences in crop cover patterns with a marked reduction in shares of cereal species monocultures and an increase in diverse crop rotations (Peltonen-Sainio, Jauhiainen, and Sorvali 2017). FaSC might also play a role in freshwater use as some specializations require more water than others. For example, animal production is typically found to have a larger water footprint than production of crops of similar nutritional value (Mekonnen and Hoekstra 2012).

Given the scarcity of literature, it is challenging to make clear recommendations for modelling farm size and specialization concerning *land* and *water use*. Additionally, modelling *water use* may require regional-scale data, which can be difficult to obtain.

4.5 Nutrition security

Nutrition security depends on the farm sector's ability to provide sufficient food, which is influenced by farm size, specialization, and production efficiency. Several studies assess the relationship between farm size and productivity. An important information regarding this relationship is that it depends on the state of economic development in an area (Rada and Fuglie 2019). Therefore, in developed countries, like the United States, Key (2019) finds a positive relationship between farm size and productivity whereas several studies show differing relationships. In developing countries, this relationship is inversed (Khataza et al. 2019) or detected only for smaller farm sizes (Yamauchi 2016; Muyanga and Jayne 2019). Additionally, one study for Brazilian farms finds a U-shaped relationship between farm size and total factor productivity, which was even more pronounced for more recent data (Helfand and Taylor 2021). Other studies mainly conclude increasing productive efficiency for larger farms (Ajayi and Olutumise 2018; Ardakani, Bartolini, and Brunori 2020; LaFevor and Magliocca 2020), but this hinges critically on the context of chemical fertilizer and irrigation management (LaFevor and Magliocca 2020). A meta-regression of 75 studies in developing countries reveals that small-scale farms (at the lower end of the country's distribution of agricultural land size) are more productive and play a critical role in achieving food security (Azadi et al. 2023). These outcomes suggest in line with Sumner (2014) that the relationship between farm size and productivity is complex and varies across different contexts. For example, in more developed economies, there is an increased likelihood and necessity for larger farms to substitute capital for labour (such as machinery and new technologies) due to factors such as less fragmented markets, improved access to credit, institutional arrangements, access to technology, and a higher proportion of the workforce employed in non-farm sectors. This shift towards capital-intensive methods can enhance productivity and demonstrate economies of scale (Peterson and Kislev 1986; Daberkow and McBride 2003; MacDonald and McBride 2009; Schimmelpfennig and Ebel 2016). As developing countries progress, mechanisms may emerge that promote economies of scale in information gathering or accessing services related to risk management, marketing, or finance. These developments could potentially mitigate the inverse relationship between farm size and productivity that is often observed in developing countries (Deininger and Byerlee 2012; Collier and Dercon 2014). It should be noted, that if the smaller farms are only a small fraction of all farms, their productivity advantage might be not of large relevance in providing food at the macro scale. Controversially, at the global scale, small and medium farms produce more than half of nearly all commodities and nutrients and even more in developing countries (Herrero et al. 2017). Small farms also produce more diverse nutrients (Herrero et al. 2017).

Modelling aspects of *nutritional security* involves assessing the agricultural sector's ability to produce sufficient food within a country, which is influenced by farm specialization and size. To capture these effects, models need to reflect the farming structure as well as the productivity level depending on size and specialization. Furthermore, it is crucial to incorporate trade dynamics, which necessitates modelling competitive and institutional arrangements both domestically and internationally. Understanding economies of size, scope, or scale in ex-ante assessments is essential for effectively modelling *nutritional security*.

4.6 Farm resilience

A *resilient farm* can adapt to changing conditions, absorb disturbances, and continue to provide essential goods and services, such as food and livelihoods, even in the face of adversity. Therefore, different farm specializations or farm sizes might be differently resilient. As far as resilience also stems from higher financial endowments, larger farms earning more income may be more resilient than smaller farms. Across specializations, some farm's production patterns may be more flexible to adapt to disturbances, most likely being it rather mixed farms than farms that are specialized in rather a few productive orientations and with high investments in immobile assets.

Many studies show a positive relationship between farm size and income or profitability. Farm size can have a positive relationship with labour productivity and in turn influence income (Fan and Chan-Kang 2005), alongside factors such as higher education, training, experience, and agricultural practices (Dolenc 2011; Wang et al. 2017; Seghezzo et al. 2020; Donkor et al. 2022; Morantes et al. 2022). Further evidence shows that expansion of farm size contributes to improved incomes for both workers and owners, whereby on-farm wage labour is positively influenced by farm size and diversification levels, while off-farm activities are more likely for farm managers with specific demographic and educational profiles (Lips, Schmid, and Jan 2013). Relevant to the EU agricultural system, evidence shows that farms that are more dependent on the common agricultural policy (CAP) subsidy (e.g. specialist cattle, specialist cereals, oilseeds and protein crops, and small farms) face higher income risks from policy changes (Ciaian, Louhichi, and Perni 2020). But there is also descriptive evidence that shows mixed profitability results across different farm sizes (Slavickiene and Savickiene 2014). Studies also highlight variations in viability across farm specializations (Vrolijk et al. 2010; Ryan et al. 2016; Hlavsa et al. 2020). One study shows that horticulture, permanent, and granivore farms are above EU average viability, whereas grazing livestock and field crop farms are below. The variation of these results is huge between countries and is connected to the economic size of these farms (Vrolijk et al. 2010).

For ex-ante modelling of *farm resilience*, accurately representing how income and viability are generated is crucial. This means that differentiating between different farm sizes or specializations alone is not sufficient to model *resilience*. It requires also detailed input and output prices, subsidies, and other regulatory factors, which may also need to be regionally disaggregated. Further, farm-level personal information like education is also relevant but hard to get on the larger (EU) scale.

4.7 Social equity

FaSC might be interconnected to *social equity* as different farm specializations or farm sizes determine income opportunities and income distribution for farmers and farm labour. Social equity within the agricultural sector might also depend on farmers' organizational power, their political representation, or their economic influence. However, important aspects of social equity in the agricultural sector are mainly income opportunities and income distribution. The same processes of how income (related to *farm resilience*) is related to FaSC appear to be relevant for social equity. As larger farms are generally capable of generating higher incomes than smaller farms, studies show that small farms, due to land constraints or the age of farmers, increase the risk of farmers falling into and staying within lower income groups (Phimister, Roberts, and Gilbert 2004; Headey, Dereje, and Taffesse 2014). Additional findings underscore the limitation of small farm sizes in driving agricultural intensification to elevate households from the bottom quartiles of the international poverty line (Urfels et al. 2023). However, some studies show the importance of smaller farms in distributing income in rural or regional contexts. In Austria, smaller dairy farms (measured as milk quota) are said to exhibit a greater proportion of diversification and contribute notably to regional economies, because smaller farms have larger expenses on regional services on a per area or production unit basis (Kirner and Kratochvil 2006). Further, in the post-communistic era of Romania, small-scale farms contributed strongly to food security, job opportunities, and income not only in rural areas (Tudor 2015). Also, farmlands concentrated among smaller farms are positively associated with rural household incomes (Chamberlin and Jayne 2020), which might be facilitated through higher local expenditure propensities by small farm holders (Johnston and Kilby 1975; Mellor 1976). But there might also be benefits for all households from larger farms through spillover effects from additional private or infrastructure investments (von Braun and Meinzen-Dick 2009; Collier and Dercon 2014; Deininger and Xia 2016) or through knowledge transfers and increased access to agricultural technologies (Rakotoarisoa 2011; Kleemann et al. 2013).

Given the mixed results regarding the association between farm size and *social equity*, ex-ante modelling activities cannot rely solely on farm size. Since *social equity* is strongly connected to the production of income, and income is an integral part of most of the models, producing some resilience or distributional indicators is feasible, provided the model has a sufficiently high regional resolution. This might be not feasible in an EU-wide context.

As another relevant aspect of social equity, gender equality can be related to FaSC through the perspective of gender quality in management of farms (especially large or corporate farms[1]). Here, one may try to understand equality parameters such as gender roles and gender balance in different management levels as well as workload and time poverty of women on the farm. Evidence from Kansas shows that decrease in the average farm size has contributed to increase in the number and percentage of women farmers particularly as 'principal farm operators' within the agricultural sector, paving the way for more inclusive participation and allowing women to engage effectively in agricultural activities (Ball 2014). Modelling gender equality issues as part of *social equity* likely requires detailed information at the farm level. However, the absence of mechanisms explaining how farm size (or even specializations) affects women's management roles or employment on farms makes such modelling efforts almost impossible.

5. Field structural change

Agricultural landscapes considerably shape the outcomes of the SJOS. This is due among others to the high proportion of agricultural land among earth's land use types and the association of agricultural production to integral ecosystem functions as well as the continuous changes in the composition and configuration of agricultural landscapes. In this section, we investigate the relationship between the SJOS thematic areas and structural changes in the agricultural landscapes. Specifically, we look at changes in the structure of the agricultural fields. For this, we define FiSC as the simultaneous change in the size, number, and shape of agricultural fields within defined landscape boundaries. Related concepts, which are described in the literature, are land fragmentation, which entails a decrease in field size and an increase in the number of fields (see e.g. van Dijk 2003; Tan et al. 2006; Thenail and Baudry 2004; Hartvigsen 2014) and land consolidation, which entails a decrease in the number of fields and an increase in field size (see e.g. Zang, Yang, and Liu 2021; Xu, Chen, and Zhu 2022). Both processes as well as other examples of shifts in number and size of fields tend to occur along with change in field shape.

5.1 Biodiversity

FiSC can influence genetic and functional species diversity through changes in occurrence, richness, and functionality of different species on agricultural fields and landscapes. Changes in field size, shape, and number can have direct impacts on species inhabiting fields and on the broader landscape species interaction. Changes in field shape determine the structure of field edges and affect the connectivity of fields to other landscape elements. Thus, it may impact migration and dispersal activities of species.

With several years of ecology and related domain's research on this topic, it is established in the literature that changes in structure of agricultural landscapes are crucial for changes in biodiversity (Ruuska and Helenius 1996; Bianchi, Booij, and Tscharntke 2006; Gayer et al. 2019; Török et al. 2021). Among the evidence on structure of agricultural landscapes, we find field size to be the most represented aspect of FiSC that directly impacts *biodiversity*, and this impact is associated with agricultural intensification (Batáry et al. 2017; Gayer et al. 2019; Török et al. 2021). Batáry et al. (2017) for example narrate some key history of how agricultural intensification constituted by the homogenization of agricultural landscape drives biodiversity loss. According to the study, the historical large-scale homogenization of small farms into larger ones in the associated regions resulted in removal of field margins, hedgerows, and other semi-natural landscape elements that serve as species habitat and help with biodiversity. Several studies show that increasing field size leads to decrease in species diversity and richness (Gonzalez-Estebanez et al. 2011; Stefanova and Salek 2014; Fried, Villers, and Porcher 2018) while decreasing field size is beneficial for improving species richness and multitrophic diversity (Collins and Fahrig 2017; Sirami et al. 2019; Geppert et al. 2020). This is especially the case when small fields imply the presence of large semi-natural habitats between the fields (Salek et al. 2018). However, some case studies show that certain species are not impacted by FiSC in a pattern similar to the aforementioned. For example, in Germany, some skylark species are not affected by increase in field size (Gayer et al. 2019), and larger field sizes are even found to positively correlate with the richness of web-building spiders and carnivore beetles (Galle et al. 2020). While some studies show no evidence of the impact of change in field shape on biodiversity (Cousins and Aggemyr 2008; Dorigo, Boscutti, and Sigura 2021), other studies describe patch shape as influential to species richness and density (Wagner and Edwards 2001; Heegaard et al. 2007; Tagwireyi and Sullivan 2015; Steel et al. 2017; Silveira dos Santos et al. 2022; Aksan 2023).

While the evidence of impact of field shape on biodiversity is limited, there is strong evidence for the impact of field size. Thus, capturing changes in field size and related biodiversity changes within a landscape is crucial for modelling FiSC impacts on biodiversity in ex-ante agricultural policy models. Several studies (Salek et al. 2018; Sirami et al. 2019; Geppert et al. 2020) provide statistical estimate of changes in biodiversity as mean field size changes. Although often species-specific, these studies provide numerical insights on the impact of field size change on biodiversity, and this could be useful for ex-ante modelling. There are also few occurrences of studies on shape that provide quantification of change in biodiversity as shape changes. For example, Aksan (2023) provides regression coefficients of change in bird species diversity depending on the change of field shape, measured by an average weighted mean shape index, including cultivated wheat fields.

5.2 Nutrient flows, aerosol loading, climate change, and chemical pollution

These thematic areas are likely to not be directly impacted by FiSC but rather through management mechanisms that relate to FiSC. This is because change in field structure is linked to management decisions and practices that impact variables such as N and phosphorus flows, particulate matter formation, and GHG emissions as well as chemical production and associated pollution.

Many studies use farm size or field size as a measure of the environmental outcomes of fertilizer use based on the strong influence of fertilizer application on environmental aspects like *nutrient flows* (Steffen et al. 2015; Yuan et al. 2022). However, there is often no clear distinction made between farm and field size; thus, it is not always precisely clear whether the impact identified in studies that mention farm size also implies field size impacts. Often also referring to field size, several studies show an inverse association between farm size and use of chemical inputs such as fertilizer (Niroula and Thapa 2007; Wu et al. 2018; Gao et al. 2021; Li et al. 2022). The higher use of inputs on smaller fields can be linked to the economies of scale effect whereby input use efficiency increases for larger farms. But this association between input use efficiency and farm size is not simply linear. Several studies show a U-shaped relationship between technical efficiency (capturing input use efficiency) and farm size whereby efficiency drops as size rises beyond a certain point (Muyanga and Jayne 2019; Ferreira and Féres 2020; Li et al. 2022). Li et al. (2022) suggest that the high input use efficiency could be as a result of higher management incentives to save production cost by smaller farms compared to medium farms and the use of machinery by large farms. Generally, knowledge, management skills, and access to complementary technologies for improving technical efficiency are usually higher for larger farm/field farmers (Wu et al. 2018) and this could increase input use efficiency and decrease the leaching of N and phosphorus into the ecosystem. Gyldengren et al. (2020) provide evidence regarding shape, showing that the accuracy and precision of N fertilizer application decreases in small and irregularly shaped fields but increases in large and regularly shaped fields. This shows that not only field size is important for input application and the consequent rate of nutrient flow but also field shape.

Aerosol loading and FiSC are linked by the different uses of machinery and fossil fuel combustion on varying agricultural field sizes and shapes. Field shape is considered a determinant of the impact of machine operations on the environment such that tractor working time, fuel consumption, and aerosol emissions are found to decrease on more square-shaped fields (often homogenous fields with increased sizes) compared to irregularly shaped fields (less homogenous or plane-filling and small fields) (Lovarelli, Bacenetti, and Fiala 2017). This variation is attributed to the high amount of headland turns made by tractors on irregular shapes and the consequent increase in operation time (Janulevičius and Čiplienė 2018). This is further supported by studies that show that land consolidation and the subsequent increase in field sizes are economically beneficial because they reduce field shape irregularity, travel distances, time, and fuel consumption (Bahar and Kirmikil 2021; Valtiala et al. 2023).

For *climate change*, there is evidence that connects a negative relationship between non-renewable energy use and field size to GHG emissions (Mohammadi et al. 2014). Mohammadi et al. (2014) found that total energy use decreases by up to 7 per cent with an increase in field size because farmers could complete field operations in less time on fields with larger width where tractor horsepower could also be increased. This decrease in energy use decreases GHG emissions from energy generation. The study also shows that larger fields may be associated with an overall reduction in GHG emission if, as found in the study, large field farmers use less non-renewable energy inputs per hectare. Other studies also analyse the interaction between field structure and climate change on the earth system (McCord et al. 2015; McRae et al. 2012), highlighting the importance of field connectivity and structural change in mitigating and managing the impact of climate change on ecological processes.

For *chemical pollution*, we find that increasing field size is associated with increasing use of insecticide, and this relationship can depend on the type of crop cultivated on the field (Larsen and Noack 2021). However, the extent to which this evidence can be generalized is unknown and the causal mechanism of how field size affects chemical pollution through chemical (e.g. insecticide) use is not clear here. It would be interesting to know what range of deviation in size increase generally results in an increase in insecticide use and if there is a tipping point at which the relationship changes, as posited by the U-shaped relationship discussed under Section 3.2.

Though results are mixed, our perspective is that change in input use efficiency that is associated with field size change is one main mechanism through which FiSC indirectly impacts the thematic areas nutrient flows, aerosol loading, climate change, and chemical pollution. To capture this in ex-ante models, models would need to be able to consider the variation in different input use coefficients according to differences in field structure. Existing literature provides some indication about the direction of the effect but does not provide an exhaustive evaluation and quantitative assessment that would allow to model these effects on a larger (EU) scale. Additionally, the relation between field size and input use efficiency is likely to be strongly impacted by the type of technology use, with precision farming technology likely to reduce some of the negative relations between field size or shape and input use efficiency. Hence, it would also be required for ex-ante modelling to quantify and capture these relations for new and upcoming technologies and to make assumptions about future technology adoption and usage.

5.3 Nutrition security, farm resilience, and social equity

As discussed previously, FiSC impacts production efficiency and hence also the thematic areas *nutrition security*, *farm resilience*, and *social equity*. FiSC determines how efficiently fields can be managed and hence impacts possibilities to produce food and to ensure nutrition security, to generate farm income, and to achieve farm resilience. Mechanisms of how FiSC impacts *social equity* are less apparent. However, when including spatial income distribution as an aspect of social equity, a potential association with field structure (but not necessarily the change in field structure) might exist because possible field structures in a location might be influenced by prevailing natural conditions (e.g. mountainous regions might not allow large regular fields). Hence, spatial heterogeneity in geography might lead to heterogenous income possibilities depending on which field structures are possible. However, we find no evidence to test this association.

Fragmentation of land can be a threat to food production because of the possibility of land abandonment that may result from inefficient field management, reduced utility of fields, and low upscaling potential (Shi et al. 2016; Kolecka et al. 2017; Li et al. 2018). This shows how *nutrition security* can be affected by changing field structure from a more homogenous form to fragmented and smaller fields. In areas where farmers have flexible decision on land allocation and there are no strict regulations about what crops can be cultivated where, field structure may drive the allocation of land to different crops by farmers as farmers will economically be motivated to allocate larger fields to profitable crop (Peltonen-Sainio et al. 2018).

Also, *farm resilience* is conditional on farm economic returns, which depend on farm and field size (Arslan, Degirmenci, and Kartal 2020; Tanaka et al. 2023). Farmers mainly increase field size or consolidate fields as a strategy to reduce costs (Kirmikil and Arici 2013; Duan et al. 2021) because land fragmentation negatively impacts farmers' income due to smaller field parcels having lesser production efficiencies than large parcels (Niroula and Thapa 2007). When fields are consolidated, labour productivity can increase and change the labour needs (e.g. by reducing labour per hectare and investment in technologies) (Eigner and Nuppenau 2019). Additionally, field size and shape are important structural elements that contribute to determining application and profitability of agricultural machinery (Shockley et al. 2012; Zandonadi et al. 2013). Results from earlier cited works for nutrient flow, aerosol loading, and climate change show that regular large fields reduce machinery working time (Janulevičius and Čiplienė 2018; Bahar and Kirmikil 2021; Valtiala et al. 2023) and a rational expectation from this would be for such fields to reduce machinery cost. In line with this, Nilsson and Rosenqvist (2021) and Spekken, Molin, and Romanelli (2015) found that cost of production is higher on small and irregularly shaped fields due to higher machine operation costs, higher setup costs, or higher headland yield losses. However, in a case of automatic section control—a precision technology for reducing overlapped areas commonly present in irregular shaped fields, Shockley et al. (2012) show that smaller, irregular shaped fields increased economic gains more than large regular fields. This illustrates that although working on smaller, irregular fields with local, large farm machineries like tractors is more challenging and costly, farm income could possibly be optimized by the use of precision technology on smaller, irregular fields.

We conclude from this that, as with the previous thematic group, FiSC impacts *nutrition security* and *farm resilience* based on its importance for production efficiency. Regarding farm resilience, the existing literature mainly provides insights on standard economic indicators that are part of the resilience concept. These are already part of ex-ante modelling approaches but, capturing the explicit relation to FiSC requires the parametrization of model activities in relation to field size and shape. We did not find empirical evidence for the linkage between FiSC and social equity although the field structure might impact the regional distribution of income. More knowledge is needed on such effects before their implementation in models can be considered.

5.4 Land use, water use, health, and economy

FiSC can lead to increase, decrease, or elimination of margin elements and change in *land use* between fields. However, we find no evidence for this thematic area as well as *health*, *water use*, and *economy* in our search.

Overall, to conclude the section, findings relating to nutrient flow, aerosol loading, and climate change posit that larger field sizes are more beneficial in obtaining the desired outcomes for these thematic areas. This contradicts the need for smaller, less homogenous fields, which findings on biodiversity show are needed to reduce biodiversity loss. This contradiction in requirement for the thematic areas could raise difficulty in simultaneously pursuing goals for biodiversity and the other thematic areas. Therefore, ex-ante modelling to improve the safe space outcome as an aggregated goal requires capturing the different dimensions and potential trade-offs to provide a comprehensive evaluation. Furthermore, an aggregated indicator for the thematic areas requires a sophisticated approach for capturing the diverse requirements and encompasses, besides being challenging to implement, there is the danger of disguising negative impacts.

6. Discussion

This study relates the SJOS to agricultural production decisions. Understanding these relationships is important if we aim to use the concept of the SJOS for model-based policy evaluation. In this section, we summarize and prioritize the main relations of production decisions and the SJOS identified in the literature review. Furthermore, we discuss the implications for modelling activities, which want to capture the link between agricultural production and the SJOS

6.1 On-farm technology usage

OFTU can affect SJOS outcomes either via production intensity or via its effect on land productivity and hence yield (Fig. 1a). OFTU mainly impacts the thematic areas *biodiversity*, *nutrient flows*, *chemical pollution*, *climate change*, and *aerosol loading* by influencing agricultural management intensities. Notably, technologies can lead to intensification of production but can also enable less intensive production systems (e.g. via organic farming). Also, technologies and production intensity can in principle impact human *health*; however, their exact impact in European countries is not provided by the reviewed studies. By impacting yields and land productivity, OFTU determines land demand for agricultural

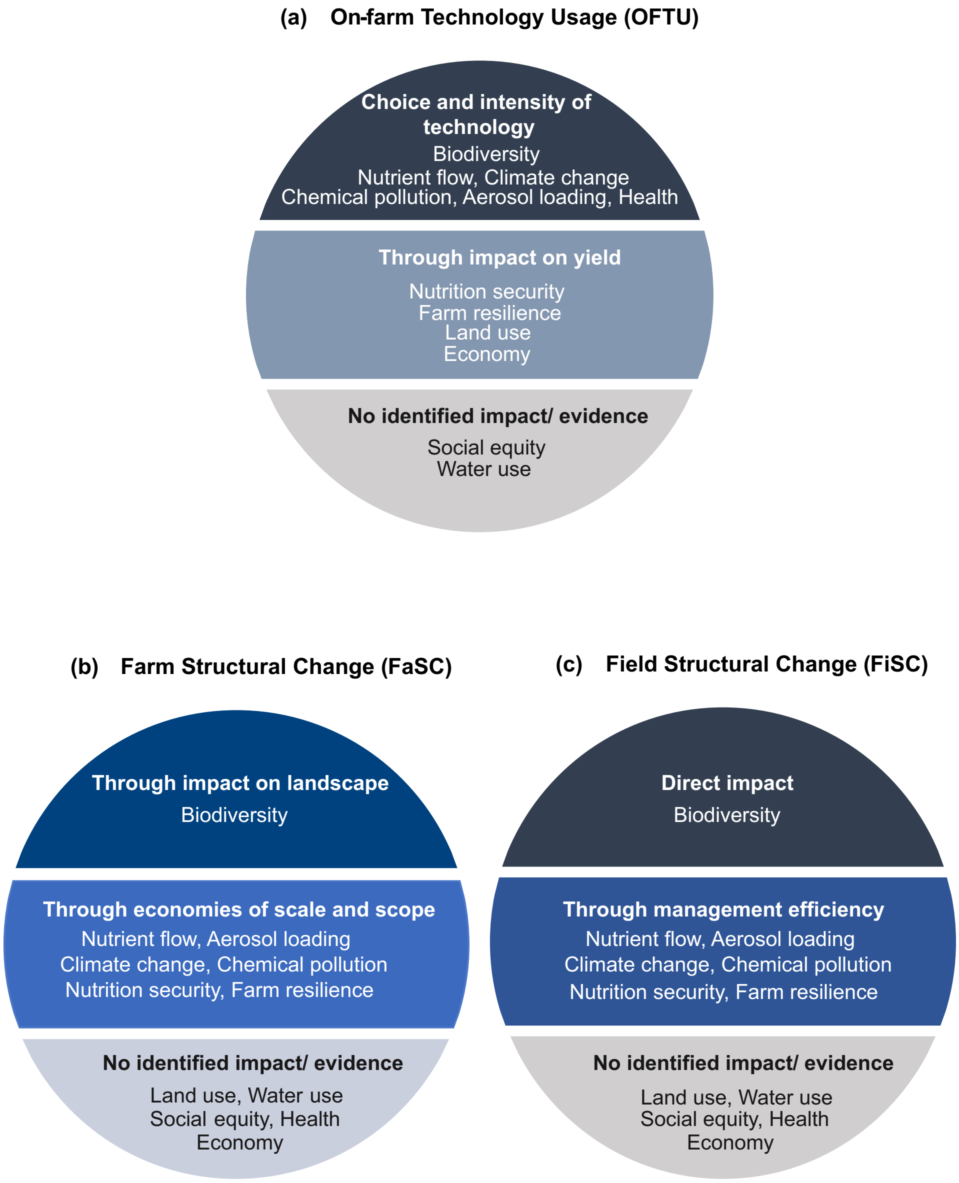

Figure 1. Categorization of SJOS thematic areas according to the literature review findings on (a) OFTU, (b) FaSC, and (c) FiSC.

production. This in turn impacts *nutrition security* and *farm resilience*. We find no evidence of impact on *water use* and *social equity*.

Agricultural policy modelling that seeks to capture OFTU impact on the SJOS therefore primarily needs to (1) assess how technology impacts farming intensity and how it affects yields, (land) productivity, and farm income opportunities (in respect to associated just outcomes). Further, (2) we need to be able to assess how these different levels of intensity or production systems affect SJOS outcomes. For (1), the key challenge is to identify the most relevant technologies and to provide an empirical parameterization of their production effects and costs, preferably distinguishing required investments, fixed, and variable costs at a sufficient level of detail. For many technologies, data do not exist to parametrize production functions in large-scale models as these technologies are currently not sufficiently spread in general or in the EU. Furthermore, to reflect the possibilities of technology upscaling (moving from the situation of current negligible use to a massive uptake), the drivers of technology adoption should be investigated and ideally also endogenized in the models. Concerning biotechnologies, adoption depends significantly on the R&D transfer supported or driven by regulatory approval. Assumptions of regulatory approval are thus important drivers of biotechnology adoption that should be included in the models. Contrary to organic farming where cost structures can be obtained for parametrization of the production functions, at least in some of the EU member state countries, parameterization of genetically modified organisms/new genomic techniques would need to be done based on data from outside of the EU.

For (2), models need to be able to quantify how farming intensities and different production systems relate to safe outcomes: *biodiversity*, *nutrient flows*, *chemical pollution*, *climate change*, *aerosol loading*, and relevant just outcomes (e.g. *health*). Existing policy models are already quite detailed in this respect, but with a huge variation of the potential SJOS-related outcomes that can be modelled, depending on the scope of the model. In general, the simulation models can either directly calculate indicators for SJOS outcomes as endogenous variables or estimate indicators post-model after the actual modelling. An example of the former is GHG emissions in the farm-level model FarmDyn (Britz et al. 2021), which are included as endogenous variables and can be directly included in the optimization process (e.g. for an emission cap). In the same model, biodiversity indicators, for instance, are calculated based on a range of variables like land allocation after the model was executed. If the SJOS impacts are directly linked to standard input–output coefficients, information on the impact of new technologies on these coefficients is sufficient. However, technologies that cause changes in the bio-physical properties of farming activities require additional data as for example in the case of feed additives for lowering methane emissions.

Ultimately, it is required to prioritize technologies according to their potential on productivity and farming systems and to provide empirical information for parametrization of those technologies in terms of yield effects, costs, and impacts on safe and just outcomes.

6.2 Farm structural change

FaSC influences *biodiversity* mainly through landscape changes (we discuss this in detail under Section 6.3). Larger farms allow to realize economies of scale, which impacts land use productivity and input use efficiency. These farm size impacts are crucial for safe outcomes such as *nutrient flows*, *chemical pollution*, *climate change*, and *aerosol loading* and just dimensions such as *farm resilience* and *nutrient security* (Fig. 1b). To capture this, models need to be capable of reflecting how farm sizes relate to land use productivity and input use efficiency, while empirical studies need to provide empirical information to parametrize those aspects. Aggregated models should also incorporate adoption rates and uptake of new technologies that increase productivity and efficiency. It might also make models with a highly aggregated farming sector unsuitable and, thus, might require farm-level modelling approaches, which come with other challenges such as substantial input data requirements or limited regional coverage. Farm specialization, or diversification, impacts SJOS outcome as it determines possibilities for economies of scope and because specializations differ concerning their impact on SJOS outcomes. Therefore, similarly as with farm size, models need to be able to reflect economies of scope and how different farm specializations impact SJOS outcomes, particularly with respect to safe dimensions and *farm resilience*. However, how farm specializations relate to the SJOS outcomes is very heterogenous within and between thematic areas as well as across countries or regions.

The way in which FaSC aspects can be represented in simulation models is also very heterogeneous and depends on scope and structure of the respective model. Farm models are in general able to capture economies of scale and scope as well as farm decisions such as exiting, enlarging, or different farm specialization. However, important drivers for such decisions are exogenous to farm models and their representation requires large-scale models with commodity and labour markets. The requirement of farm-level modelling approaches for FaSC aspects and larger-scale models that capture drivers of FaSC infers the need for model coupling to fully capture FaSC.

Only a small number of the reviewed studies particularly quantified the relationship between FaSC and thematic areas of the SJOS in European countries. Therefore, there is a need for further research on this relationship, especially across the just thematic areas. Additionally, empirical studies need to provide the bases to parameterize identified effects and it will be valuable for future studies to show more causal mechanisms rather than correlational evidence for thematic areas of *land use* and *water use* and to reveal the distinctive differences in *farm resilience* between different farm specializations.

6.3 Field structural change

Two main mechanisms are relevant for FiSC. First, FiSC directly impacts biodiversity by affecting migration and dispersal possibilities of species on the landscape and by affecting the configuration of semi-natural habitats within landscapes. Secondly, FiSC can vary the efficiency of management, hence land productivity and input use efficiency. This indirectly impacts safe dimensions such as *nutrient flows*, *aerosol loading*, and *climate change* as well as *chemical pollution* (Fig. 1c), and also just dimensions such as *nutrition security* and *farm resilience*. However, we find no literature evidence of FiSC impacting thematic areas of *land use*, *water use*, *social equity*, *health*, and *economy*.

Modelling of FiSC relation to biodiversity requires that models are capable to capture how different field sizes, shapes, and their changes are impacted by policies and economic drivers. Additionally, they need to capture how FiSC relates to biodiversity outcomes. This requires a clear definition of appropriate measures for FiSC, and parameterizing their relation to biodiversity outcomes. Models also need to reflect how FiSC translates into land productivity, yield, and production costs. Similar to the OFTU and FaSC, this allows to assess the indirect impacts of FiSC on SJOS outcomes.

The large volume of evidence relating to biodiversity mostly provides direction of association. Some further provide statistical estimates of the predictive power of the various applied empirical models used to analyse the association. However, there is a scarcity of studies that provide actual causal estimates. Also, heterogeneity of evidence between species and geography makes it difficult to generalize findings for modelling. Many studies regarding nutrient flows come from study areas in Asia, which might not easily be transferred to EU agriculture. Nutrition security and farm resilience have studies which qualitatively relate to FiSC, but the strength of the effect and the causal mechanisms are not clearly identified. There is little evidence for the expected relation to climate change and chemical pollution. Thus, there is a need for further empirical research that delves into the causal relationships with FiSC. The empirical research needs to identify appropriate measures to quantify the relevant aspects of FiSC and how they relate to biodiversity outcomes and the efficiency of management that impacts other outcomes.

7. Conclusion

In this study, we conduct a systematic literature review on the linkage between the SJOS and agricultural production decisions, providing guidance and prioritization for future modelling as well as further research activities. Our findings reveal substantial knowledge available on the relationship between the OFTU, FaSC as well as FiSC and the thematic areas of the EU SJOS. Three key outcomes applicable across the three decision categories reviewed include firstly that many of the evidence on the identified relationships are context-specific in terms of production aspects (e.g. crop types or animal specialization), geography, and fauna or flora species as relevant for biodiversity. This specificity challenges the extrapolation and applicability of results for large-scale (e.g. EU-wide) modelling. Secondly, within the scope of our review, there are aspects of the covered production decision categories for which we find not enough comparative evidence that rigorously establishes the relationship to the SJOS outcomes. Particularly, in the case for novel aspects of OFTU, it is difficult to assess their future impacts. While reviewed studies establish the benefits of precision farming, it is challenging to assess how technology will be adopted in the future and how novel, currently unavailable technologies will change the impacts of OFTU on SJOS outcomes. Thirdly, in all three production decision categories, the impact of technology as a mediator of impact on SJOS is strongly established. In OFTU, we see that the addition of a second technology can buffer the effect of one technology on the SJOS (e.g. combining biotechnology with organic farming). In FaSC and FiSC, the effect of change in structure is dependent on the practice or technology used for management. For example, changing farm and field size changes the rate of nutrient flow, GHG emission, chemical pollution, nutrition security, and farm resilience. However, the extent of this change hinges critically on the on-farm technological changes that accompany the FaSC and FiSC. Overall, there are still gaps for future empirical analysis to fill such in the understanding of OFTU impacts on water use and social equity, FaSC impacts on land use, water use, health, and economy and FiSC impacts on water use, land use, social equity, and economy. Integrating the linkages identified in this study between SJOS and agricultural production decisions into agricultural policy models and closing the existing research gaps will inform on how to further improve EU policies as, for instance, included in the European Green Deal.

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Data availability

No new data were generated or analysed in support of this research. Rather, existing literature was reviewed.

End Notes

1 The legal status of farms is not part of the terminology of farm structure in this study.

Appendix A Systematic search queries and results for Sections 3, 4, and 5

Sections 3, 4, and 5 of the paper present the findings on relationships between the target agricultural production decision categories and SJOS thematic areas. The literature search process for these sections involves (1) developing appropriate representative keywords for decision categories and SJOS thematic areas, (2) generally reviewing the literature of the categories, and (3) combining the category and thematic area keywords using different Boolean operators to find relevant records that connect the production decision categories and the SJOS thematic areas. Table A1 shows the developed keywords and how they are used. We position decision category keyword(s) as Y such that, for every search for relationship between agricultural decision categories and SJOS thematic areas, the representative decision category keywords come first in the search query and then followed by the thematic area keywords. To control the volume of results, WoS categories—agriculture multidisciplinary and agriculture economics and policy—were connected with OR and combined with every combination of keywords in the search queries.

Due to the large volume of records obtained for Section 3 while using the keyword structure similar to the structure used in Sections 4 and 5, we restructured the search query for Section 3 to obtain the minimum set of relevant literature for the section. Tables A2, A3, and A4 present for each section the search queries, the number of records found on WoS, and the final number of studies considered relevant and reviewed. However, this does not equal the number of works finally cited.

In general, search considerations such as the afore stated imply that we do not consider the works reviewed in the study to be all relevant works on the subject matter. Giving the limitations of our search strategy, the literature coverage of the study is further extended by using a snowball technique where we include works not found within the literature search system but considered relevant.

Table A1. Keywords and general structure of search queries used for literature search on Web of Science.

		Literature search keywords and structural formation of search queries
	Basic structure	'Decision category keyword(s)' and agricultur* and dimension keyword(s) (Topic) and Agriculture, Multidisciplinary OR Agricultural Economics & Policy (Web of Science categories)
Decision categories	**On-farm technology usage**	Land management, machinery, biotechnology, precision farming, organic farming, smart farming Y: 'land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)
	Farm structural change	Y: 'farm struct*' or 'farm speciali*' or 'farm size*'
	Field structural change	Field shape, parcel shape, field size, parcel size, field structure, parcel structure Y: ('field shape' or 'parcel shape') or ('field size' or 'parcel size') or ('field structur*' or 'parcel structur*')
SOS dimensions	Biodiversity	Biodiversity, 'genetic diversity', 'functional diversity', 'biosphere integrity', (extinction NEAR/2 rate), (species NEAR/2 variability) Y and agricultur* and (biodiversity or 'genetic diversity' or 'functional diversity' or 'biosphere integrity' or (extinction NEAR/2 rate) or (species NEAR/2 variability)) (Topic) and Agriculture, Multidisciplinary OR Agricultural Economics & Policy (Web of Science categories)

Table A1. Continued

		Literature search keywords and structural formation of search queries
	Climate change	'climate change', 'greenhouse gas*', 'global warming' Y and agricultur* and ('climate change' or 'greenhouse gas*' or 'global warming') (Topic) and Agriculture, Multidisciplinary OR Agricultural Economics & Policy (Web of Science categories)
	Nutrient flows	((usage or use or appl*) NEAR/2 (nitrogen or phosph* or fertilizer)) Y and agricultur* and ((usage or use or appl*) NEAR/2 (nitrogen or phosph* or fertilizer)) (Topic) and Agriculture, Multidisciplinary OR Agricultural Economics & Policy (Web of Science categories)
	Land use	'forest cover' or (land NEAR/2 conversion) or deforestation or 'land use change' Y and agricultur*and ('forest cover' or (land NEAR/2 conver*) or deforestation or 'land use change') (Topic) and Agriculture, Multidisciplinary OR Agricultural Economics & Policy (Web of Science Categories)
	Water use	((groundwater or freshwater or 'blue water' or 'surface water*') NEAR (withdraw* or extract* or use)) Y and agricultur* and ((groundwater or freshwater or 'blue water' or 'surface water*') NEAR (withdraw* or extract* or use)) (Topic) and Agriculture, Multidisciplinary OR Agricultural Economics & Policy (Web of Science categories)
	Chemical pollution (novel entities)	'chemical pollut*', 'novel entities', chlorofluorocarbon, pesticide, 'heavy metal', microplastics Y and agricultur* and ('chemical pollut*' or 'novel entities' or chlorofluorocarbon or pesticide or microplastic* or 'heavy metal') (Topic) and Agriculture, Multidisciplinary or Agricultural Economics & Policy (Web of Science categories)
	Aerosol loading	air, air pollution, 'air pollut*', 'particulate matter', emission of sulphur, nitrate and carbon Y and agricultur* and (aerosol or (air NEAR/4 pollut*) or (fuel NEAR/2 combustion) or (partic* NEAR/2 (pollution or matter)) or ((sulf* or nitrate or carbon) NEAR/4 emission)) (Topic) and Agriculture, Multidisciplinary or Agricultural Economics & Policy (Web of Science categories)
	Nutrition security	food, undernourishment, hunger Y and agricultur* and (food or undernourish* or hung*) (Topic) and Agriculture, Multidisciplinary or Agricultural Economics & Policy (Web of Science categories)
	Health	health Y and agricultur* and health (Topic) and Agriculture, Multidisciplinary or Agricultural Economics & Policy (Web of Science Categories)

Table A1. Continued

	Literature search keywords and structural formation of search queries
Social equity	Gender, education, social equity Y and agricultur* and (gender or (gender NEAR/2 equality) or educat* or literacy or 'social equity') (Topic) and Agriculture, Multidisciplinary or Agricultural Economics & Policy (Web of Science categories)
Economy	Energy, 'sectoral VAD', 'sectoral employment', 'sectoral wages' Y and energy (Topic) and Agriculture, Multidisciplinary or Agricultural Economics & Policy (Web of Science categories)
Income: **additional search area used to generate income-related findings that have been used under social equity and farm resilience areas within the sections**	income or (income NEAR work) Y and agricultur* and (income or (income NEAR work)) (Topic) and Agriculture, Multidisciplinary or Agricultural Economics & Policy (Web of Science Categories)
Farm resilience	resilien* Y and resilien* (Topic) and Agriculture, Multidisciplinary or Agricultural Economics & Policy (Web of Science categories)

Table A2. On-farm technology usage search queries and results.

	Full search query	Date of last search	Records found	Relevant studies
Biodiversity	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and (biodiversity or 'genetic diversity' or 'functional diversity' or 'biosphere integrity' or (extinction NEAR/2 rate) or (species NEAR/2 variability)))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	347	20
Climate change	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and ('climate change' or 'greenhouse gas*' or 'global warming'))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	309	36
Nutrient flows	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and ((usage or use or appl*) NEAR/2 (nitrogen or phosph* or fertilizer)))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	181	5
Land use	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and ('forest cover' or (land NEAR/2 conver*) or deforestation or 'land use change'))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	88	3
Water use	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and ((groundwater or freshwater or 'blue water' or 'surface water*') NEAR (withdraw* or extract* or use)))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	8	0
Chemical pollution (novel entities)	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and ('chemical pollut*' or 'novel entities' or chlorofluorocarbon or pesticide or microplastic* or 'heavy metal'))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	243	14
Aerosol loading	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and (aerosol or (air NEAR/4 pollut*) or (fuel NEAR/2 combustion) or (partic* NEAR/2 (pollution or matter)) or ((sulf* or nitrate or carbon) NEAR/4 emission)))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	47	0
Nutrition security	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and (food or undernourish* or hung*))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	895	11

Table A2. Continued

	Full search query	Date of last search	Records found	Relevant studies
Health	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and health)) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	293	17
Social equity	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and gender or (gender NEAR/2 equality) or educat* or literacy or 'social equity')) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	193	0
Economy	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and energy or (sector* NEAR/2 (VAD or employment or wage*)))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	284	15
Income & work: **findings from here are used under social equity and farm resilience**	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(agricultur* and (income or (income NEAR work)))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	220	10
Farm resilience	(TS=('land management' or machinery or biotechnolog* or ((precision or smart or organic) NEAR/1 farming)) AND TS=(resilien*)) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	22 November 2023	83	0
Total			**3,191**	**131**

Table A3. Farm structural change search queries and results.

	Full search query	Date of last search	Records found	Relevant studies
Biodiversity	TS=('farm struct*' and agricultur* and (biodiversity or 'genetic diversity' or 'functional diversity' or 'biosphere integrity' or (extinction NEAR/2 rate) or (species NEAR/2 variability))) OR TS=('farm speciali*' and agricultur* and (biodiversity or 'genetic diversity' or 'functional diversity' or 'biosphere integrity' or (extinction NEAR/2 rate) or (species NEAR/2 variability))) OR TS=('farm size*' and agricultur* and (biodiversity or 'genetic diversity' or 'functional diversity' or 'biosphere integrity' or (extinction NEAR/2 rate) or (species NEAR/2 variability))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	26 July 2023	48	5
Climate	TS=('farm struct*' and agricultur* and ('climate change' or 'greenhouse gas*' or 'global warming')) OR TS=('farm speciali*' and agricultur* and ('climate change' or 'greenhouse gas*' or 'global warming')) OR TS=('farm size*' and agricultur* and ('climate change' or 'greenhouse gas*' or 'global warming')) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	26 July 2023	70	7
Nutrient flows	TS=('farm struct*' and agricultur* and ((usage or use or appl*) NEAR/2 (nitrogen or phosph* or fertilizer))) OR TS=('farm speciali*' and agricultur* and ((usage or use or appl*) NEAR/2 (nitrogen or phosph* or fertilizer))) OR TS=('farm size*' and agricultur* and ((usage or use or appl*) NEAR/2 (nitrogen or phosph* or fertilizer))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	26 July 2023	45	5
Land use	TS=('farm struct*' and agricultur* and ('forest cover' or (land NEAR/2 conver*) or deforestation or 'land use change')) OR TS=('farm speciali*' and agricultur* and ('forest cover' or (land NEAR/2 conver*) or deforestation or 'land use change')) OR TS=('farm size*' and agricultur* and ('forest cover' or (land NEAR/2 conver*) or deforestation or 'land use change')) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	26 July 2023	26	2
Water use	TS=('farm struct*' and agricultur* and ((groundwater or freshwater or 'blue water' or 'surface water*') NEAR (withdraw* or extract* or use))) OR TS=('farm speciali*' and agricultur* and ((groundwater or freshwater or 'blue water' or 'surface water*') NEAR (withdraw* or extract* or use))) OR TS=('farm size*' and agricultur* and ((groundwater or freshwater or 'blue water' or 'surface water*') NEAR (withdraw* or extract* or use))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	26 July 2023	6	1
Chemical pollution (novel entities)	TS=('farm struct*' and agricultur* and ('chemical pollut*' or 'novel entities' or chlorofluorocarbon or pesticide or microplastic* or 'heavy metal')) OR TS=('farm speciali*' and agricultur* and ('chemical pollut*' or 'novel entities' or chlorofluorocarbon or pesticide or microplastic* or 'heavy metal')) OR TS=('farm size*' and agricultur* and ('chemical pollut*' or 'novel entities' or chlorofluorocarbon or pesticide or microplastic* or 'heavy metal')) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	26 July 2023	36	1

Table A3. Continued

	Full search query	Date of last search	Records found	Relevant studies
Aerosol loading	TS=('farm struct*' and agricultur* and (aerosol or (air NEAR/4 pollut*) or (fuel NEAR/2 combustion) or (partic* NEAR/2 (pollution or matter)) or ((sulf* or nitrate or carbon) NEAR/4 emission))) OR TS=('farm speciali*' and agricultur* and (aerosol or (air NEAR/4 pollut*) or (fuel NEAR/2 combustion) or (partic* NEAR/2 (pollution or matter)) or ((sulf* or nitrate or carbon) NEAR/4 emission))) OR TS=('farm size*' and agricultur* and (aerosol or (air NEAR/4 pollut*) or (fuel NEAR/2 combustion) or (partic* NEAR/2 (pollution or matter)) or ((sulf* or nitrate or carbon) NEAR/4 emission))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	27 July 2023	3	1
Nutrition security	TS=('farm struct*' and agricultur* and (food or undernourish* or hung*)) OR TS=('farm speciali*' and agricultur* and (food or undernourish* or hung*)) OR TS=('farm size*' and agricultur* and (food or undernourish* or hung*)) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	27 July 2023	172	7
Health	TS=('farm struct*' and agricultur* and health) OR TS=('farm speciali*' and agricultur* and health) OR TS=('farm size*' and agricultur* and health) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	27 July 2023	35	1
Social equity	TS=('farm struct*' and agricultur* and (gender or (gender NEAR/2 equality) or educat* or literacy or 'social equity')) OR TS=('farm speciali' and agricultur* and (gender or (gender NEAR/2 equality) or educat* or literacy or 'social equity')) OR TS=('farm size*' and agricultur* and (gender or (gender NEAR/2 equality) or educat* or literacy or 'social equity')) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	8 August 2023	1	1
Economy	TS=('farm struct*' and agricultur* and (energy or (sector* NEAR/2 (VAD or employment or wage*)))) OR TS=('farm speciali*' and agricultur* and (energy or (sector* NEAR/2 (VAD or employment or wage*)))) OR TS=('farm size*' and agricultur* and (energy or (sector* NEAR/2 (VAD or employment or wage*)))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	8 August 2023	31	3
Income & work: **findings from here are used under social equity and farm resilience**	TS=('farm struct*' and agricultur* and (income or (income NEAR work))) OR TS=('farm speciali*' and agricultur* and (income or (income NEAR work))) OR TS=('farm size*' and agricultur* and (income or (income NEAR work))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	9 August 2023	199	17
Farm resilience	TS=('farm struct*' and agricultur* and resilien*) OR TS=('farm speciali*' and agricultur* and resilien*) OR TS=('farm size*' and agricultur* and resilien*) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	9 August 2023	24	4
Total			**696**	55

Table A4. Field structural change search queries and results.

	Full search query	Date of last search	Records found	Relevant studies
Biodiversity	TS=((‘field shape’ or ‘parcel shape’ or ‘patch shape’) and agricultur* and (biodiversity or (biodiversity NEAR/2 loss) or ‘genetic diversity’ or ‘functional diversity’ or ‘biosphere integrity’ or (extinction NEAR/2 rate) or (species NEAR/2 variability))) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and (biodiversity or (biodiversity NEAR/2 loss) or ‘genetic diversity’ or ‘functional diversity’ or ‘biosphere integrity’ or (extinction NEAR/2 rate) or (species NEAR/2 variability))) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and (biodiversity or (biodiversity NEAR/2 loss) or ‘genetic diversity’ or ‘functional diversity’ or ‘biosphere integrity’ or (extinction NEAR/2 rate) or (species NEAR/2 variability))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	9 August 2023	119	30
Climate	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and (‘climate change’ or ‘greenhouse gas*’ or ‘global warming’)) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and (‘climate change’ or ‘greenhouse gas*’ or ‘global warming’)) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and (‘climate change’ or ‘greenhouse gas*’ or ‘global warming’)) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	10 August 2023	31	3
Nutrient flows	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and ((usage or use or appl*) NEAR/2 (nitrogen or phosph* or fertilizer))) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and ((usage or use or appl*) NEAR/2 (nitrogen or phosph* or fertilizer))) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and ((usage or use or appl*) NEAR/2 (nitrogen or phosph* or fertilizer))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	11 August 2023	23	7
Land use	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and (‘forest cover’ or (land NEAR/2 conver*) or deforestation or ‘land use change’)) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and (‘forest cover’ or (land NEAR/2 conver*) or deforestation or ‘land use change’)) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and (‘forest cover’ or (land NEAR/2 conver*) or deforestation or ‘land use change’)) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	14 August 2023	39	2
Water use	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and ((groundwater or freshwater or ‘blue water’ or ‘surface water*’) NEAR (withdraw* or extract* or use))) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and ((groundwater or freshwater or ‘blue water’ or ‘surface water*’) NEAR (withdraw* or extract* or use))) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and ((groundwater or freshwater or ‘blue water’ or ‘surface water*’) NEAR (withdraw* or extract* or use))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	14 August 2023	5	1
Chemical pollution (novel entities)	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and (‘chemical pollut*’ or ‘novel entities’ or chlorofluorocarbon or pesticide or microplastic* or ‘heavy metal’)) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and (‘chemical pollut*’ or ‘novel entities’ or chlorofluorocarbon or pesticide or microplastic* or ‘heavy metal’)) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and (‘chemical pollut*’ or ‘novel entities’ or chlorofluorocarbon or pesticide or microplastic* or ‘heavy metal’)) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	15 August 2023	36	1

Table A4. Continued

	Full search query	Date of last search	Records found	Relevant studies
Aerosol loading	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and (aerosol or (air NEAR/4 pollut*) or (partic* NEAR/2 (pollution or matter)))) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and (aerosol or (air NEAR/4 pollut*) or (partic* NEAR/2 (pollution or matter)))) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and (aerosol or (air NEAR/4 pollut*) or (partic* NEAR/2 (pollution or matter)))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	14 August 2023	5	2
Nutrition security	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and (food or undernourish* or hung*)) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and (food or undernourish* or hung*)) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and (food or undernourish* or hung*)) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	16 August 2023	81	3
Health	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and health) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and health) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and health) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	15 August 2023	11	5
Social equity	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and (gender or (gender NEAR/2 equality) or educat* or *literacy or ‘social equity’)) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and (gender or (gender NEAR/2 equality) or educat* or *literacy or ‘social equity’)) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and (gender or (gender NEAR/2 equality) or educat* or *literacy or ‘social equity’)) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	15 August 2023	0	0
Economy	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and (energy or (sector* NEAR/2 (VAD or employment or wage*)))) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and (energy or (sector* NEAR/2 (VAD or employment or wage*)))) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and (energy or (sector* NEAR/2 (VAD or employment or wage*)))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	16 August 2023	0	0
Income & work: **findings from here are used under social equity and farm resilience**	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and (income or (income NEAR work))) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and (income or (income NEAR work))) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and (income or (income NEAR work))) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	15 August 2023	21	9
Farm resilience	TS=((‘field shape’ or ‘parcel shape’) and agricultur* and resilien*) OR TS=((‘field size’ or ‘parcel size’) and agricultur* and resilien*) OR TS=((‘field structur*’ or ‘parcel structur*’) agricultur* and resilien*) AND WC=(Agriculture, Multidisciplinary OR Agricultural Economics & Policy)	15 August 2023	7	0
Total			378	63

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