Supplementary material

Developing context-specific frameworks for integrated sustainability assessment of agricultural intensity change: an application for Europe

Appendix A. Identifying mechanisms of agricultural intensity change in Europe (Step 1)

The main mechanisms of agricultural intensity change operating in Europe were identified by conducting an extensive literature review, combined with inductive content analysis [1], [2]. We searched on Scopus and ISI Web of Knowledge databases for peer-reviewed articles describing increases or decreases in the output/input ratio (i.e., productivity, resource-use efficiency and profitability) of agricultural systems in European agriculture. Accordingly, the following search string was applied:

agricultur AND Europe* AND (((increas* OR decreas*) W/3 productivity) OR ((increas* OR decreas*) W/3 profit*) OR ((increas* OR decreas*) W/3 efficiency))* [1]

The search results of the two databases were then merged, and duplicates were removed. The unique results were then reordered by number of citations. The selection of articles was then narrowed down after screening for their title, abstract and full texts. The following eligibility criteria were applied:

- peer-reviewed and in English language;
- describe cases of agricultural intensity change at the field scale and/or farm level;
- refer to cases occurring in Europe (including trans-continental and global studies in which European cases are described);
- explicitly refer the adjustments in management intensity and/or landscape structure attributes that led to changes in agronomic productivity, resource-use efficiency and/or profitability, either observed in the past or expected in the future.

The articles were screened following a descending order of the number of citations, until 100 articles fulfilling the eligibility criteria were selected. For each selected article, we reviewed the described cases in which changes in productivity, efficiency, or profit where reported, and which adjustments in farm (management) attributes contributed to this. The snowballing technique was used whenever the cases identified in the selected articles referred to studies providing relevant additional information. Based on these cases, we iteratively developed a typology of agricultural intensity change mechanisms and identified the farm (management) attributes used to describe them. The typology was developed through inductive content analysis, a method that utilises an iterative process of abstraction to reduce and group data, so that groups of concepts, categories or themes can be identified. In particular, we read each case/article several times, in order to first identify condensed meaning units (i.e., a description of a particular process of intensity change), and then identify codes (i.e., attributes of intensity change mentioned in the condensed meaning units). Finally, we iteratively defined categories (i.e., mechanisms of agricultural intensity change) based on recurrent combinations of condensed meaning units and codes. The results are presented in Table A.1 with the respective references, and summarized in Table 1, in the main text. Based on these results, we defined sets of key attributes as *Agricultural intensity* themes, sub-themes and indicators (Table 2, in the main text).

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[1] This search string refers to one applied for literature searches in Scopus. For the one applied in ISI Web of Knowledge, the operator W/3 was replaced with NEAR/3

Table A.1: Mechanisms of agricultural intensity change identified in Europe, and respective references

Mechanisms of intensity change	Attributes of intensity change	Description	References
Land management intensity	Animal productivity Economic output Livestock density Grazing period length	Increasing animal productivity, and/or economic output by adjusting livestock density and/or grazing period length.	[3]–[16]
	Crop/grassland yield Nutrient efficiency Economic output Frequency of field operations	Increasing crop/grassland yield, economic output and/or nutrient efficiency by adjusting the frequency of field management operations (e.g. seed bed preparation, soil tillage, crop sowing/planting, weed removal, grassland mowing, orchard pruning, soil drainage, burning grassland shrubs that are non-palatable for livestock).	[5], [7], [9], [17]–[37]
	Crop/grassland yield Economic output Cropping frequency Fallow cycle frequency Crop/sowing density Intercropping	Increasing crop yields, and/or economic output by adjusting the crop rotation cycles (i.e. cropping frequency, fallow cycles) and/or cropping intensity (i.e. crop/sowing density, intercropping).	[6], [21], [27], [28], [38]–[41]
Capital intensity	Crop yield Animal productivity Economic output Investments on machinery and equipment	Increase crop yield, animal productivity, and/or economic output by adjusting investments on machinery and equipments in the farm, such as machinery for field operations (e.g. mechanic plough, cultivator, harrow, seed broadcaster, harvester, fertiliser spreader, pesticide sprayer, mower, baler), automatic feeders, milking robots, automatic water points, sensors, and drones.	[5], [10], [11], [18], [21]–[24], [27], [29]–[31], [33], [35], [39], [41]–[55]
	Crop/grassland yield Animal productivity Economic output Area equipped for irrigation Investments on irrigation equipment Water use efficiency	Increasing crop/grassland yield, animal productivity, and/or economic output by adjusting the amount of farm area equipped with irrigation infrastructure, and/or increasing water use efficiency by investing on water saving technologies (e.g. drip-irrigation, controlled deficit irrigation, shading covers over on-farm ponds, replacement of old open-channel distribution networks with more efficient pressurised distribution systems).	[18], [21], [23], [24], [35], [41], [44], [46], [55]–[62]
	Economic output Investments on farm buildings and facilities Investment on farm infrastructure	Increasing crop yield, animal productivity, and/or economic output by adjusting investments on farm buildings and facilities (e.g. greenhouses, stables, silos, warehouses, and waste treatment facilities) and/or other infrastructure (e.g. land improvements, roads, fences, renewable energy).	[4]–[6], [9], [16], [18], [19], [25], [30], [35], [38], [41], [44], [50], [54], [55], [58], [60], [63]–[65]
	Animal productivity Economic output Herd size Breeding livestock Milking livestock Livestock replacement rate	Increasing animal productivity and/or economic output by adjusting the number of animal assets in the farm (e.g. overall herd size, breeding and milking livestock), and/or their respective replacement rate.	[3], [4], [6], [7], [9], [10], [13], [16], [19], [50], [66]
	Crop yield Economic output Economic added-value Permanent crop area Permanent crop density	Increasing crop yield, economic output, and economic added-value by adjusting the area of the farm with permanent crops (fruit orchards, olive groves, vineyards, etc.) and/or its density.	[6], [18], [23], [24], [29], [35]
Input-use intensity	Crop/grassland yield Nutrient efficiency Economic output Economic added- value Yield variability Fertiliser use Fertiliser composition	Increasing crop/grassland yield, nutrient efficiency, economic output, economic added-value and/or reducing yield variability by adjusting the levels and composition of fertiliser inputs (organic and synthetic).	[5], [10], [11], [15], [18]–[20], [22]–[24], [26]–[39], [41], [43]–[45], [47], [49], [52], [58], [60], [67]–[75]
	Animal productivity Economic output Economic added-value Animal health inputs	Increasing animal productivity by adjusting the use of animal health inputs (e.g. vaccines and antibiotics).	[14], [30], [76]
	Crop yield Input use efficiency Economic output Economic added-value	Increasing crop yield, input efficiency, economic output, economic added-value and/or reducing crop yield variability by adjusting the levels of pesticide use (organic and synthetic), and respective toxicity.	[5], [11], [13], [18], [21], [23], [24], [27]–[31], [35], [37], [39], [41], [43], [44], [46]–[48], [67], [77], [78]

Mechanisms of intensity change	Attributes of intensity change	Description	References
	Yield variability Pesticide use Pesticide toxicity		
	Crop/grassland yield Energy efficiency Economic output Economic added-value Energy use	Increase crop yield, animal productivity, economic output, economic added-value and/or energy efficiency by adjusting energy use (i.e., fuel, electricity, etc.) for machinery used in field operations (e.g. soil tilling, harvesting, application of inputs) and functioning of buildings and facilities (e.g. farmhouse, storage, feedlots, milking facilities).	[18], [21], [22], [24], [26], [30], [31], [33], [35], [49], [56], [58], [60], [63], [65], [70], [75], [79]
	Crop/grassland yield Animal productivity Economic output Economic added-value Water efficiency Yield variability Water use	Increasing crop yield, animal productivity, economic output, economic added-value, water use efficiency and/or reducing yield variability by adjusting water use inputs in the farm.	[18], [21], [24], [29], [31], [32], [34], [35], [41], [44], [57]–[59], [62]–[64], [67], [72], [80]–[82]
	Animal productivity Feed efficiency Economic output Economic added-value Feed intake Feed composition Input self-sufficiency	Increasing animal productivity, feed efficiency, economic output and/or economic added-value by adjusting the intake and composition of animal feed, including forage (e.g. grass, legumes, shrubs) and fodder (e.g. hay, straw, silage, grains, high-protein feed concentrates), and/or the ratio between purchased and farm-grown feed.	[4]–[7], [9], [10], [12], [13], [15], [19], [30], [39], [43]–[45], [64], [66], [83]
	Crop/grassland yield Animal productivity Economic output Economic added-value Seed inputs Input self-sufficiency	Increasing crop yield, economic output and economic added-value by adjusting the use of seed inputs and the ratio between purchased seeds and seeds grown in the farm.	[30], [44]
Labour intensity	Crop yield Animal productivity Economic output Economic added-value Labour input Labour efficiency Family labour Hired labour Permanent labour Seasonal labour Retention rate of hired labour	Increasing crop yield, animal productivity, economic output and/or labour efficiency by adjusting the use of labour input in the farm, including family labour and hired labour (permanent and seasonal), and respective retention rate of hired labour.	[4]–[6], [10], [12], [18], [23], [24], [26], [29], [30], [35], [39], [44], [45], [47]–[51], [55], [66], [84]–[86]
Farm consolidation	Economic output Economic added-value Farm area size Farm economic size Ownership structure	Achieving increasing returns to scale/size (i.e. increasing economic output while simultaneously reducing average total cost per output unit) through farm size enlargement (e.g. acquiring and/or renting agricultural land from other farms).	[4]–[6], [10], [11], [13], [18], [23], [24], [26], [27], [29], [30], [39], [41], [43], [44], [50], [51], [55], [64], [84]–[89]
	Economic output Economic added-value Agricultural field size Agricultural land-use composition Semi-natural habitat composition Agricultural field size Semi-natural habitat patch size Density of landscape elements Density of historical/cultural landmarks Distance of agricultural fields to the farmhouse	Achieving increasing returns to scale/size (i.e. increasing economic output while simultaneously reducing average total cost per output unit) through landscape simplification (e.g. increasing field size by removing semi-natural habitat patches, single trees and landscape elements such as hedgerows, tree lines, single trees, stone walls, historical/cultural landmarks etc.) and/or land consolidation (e.g. reallocating land to make the distribution of agricultural fields more compact and closer to the farmhouse).	[3]–[5], [11], [25], [27], [28], [41], [50], [87], [90]

Mechanisms of intensity change	Attributes of intensity change	Description	References
Farm specialisation / diversification	Crop yield Economic output Economic added-value Crop types and varieties Crop rotation	Increasing crop yield, economic output and/or economic added-value by specialising on a limited number of crop types or varieties.	[3], [5], [7], [30], [39], [41], [43], [55], [67], [88], [91], [92]
	Animal productivity Economic output Livestock species and breed varieties Livestock development stages	Increasing animal productivity and/or economic output by specialising on a limited number of livestock species, breeds and/or stages of animal development.	[4], [6], [55]
	Economic output Farming activities	Increasing economic output by specialising on a limited number of farming activities (e.g. livestock production, cultivation of arable crops, fruits or vegetables).	[4], [6], [11], [43], [51], [75], [84], [86], [88], [91]
	Total output Total output variability Farming activities Crop types and varieties Livestock species and breed varieties	Increasing total output and/or reducing total output variability through economies of scope, by engaging in several farming activities, often complementary (e.g. mixed farming systems).	[6], [26], [30], [35], [43], [85], [86]
	Crop/grassland yield Yield variability Total output Output variability Nutrient efficiency Input self-sufficiency Nr. of crop types and varieties Crop rotation Share of agricultural land use	Increasing crop yield, total output, reducing yield/output variability, improving nutrient efficiency, and/or increasing input self-sufficiency through economies of scope, by growing several types of crops/livestock, often complementary (e.g. nutrient fixating crops, cover crops, different types of forage crops).	[6], [12], [26], [30], [35], [36], [43], [70], [93]–[100]
Regional specialisation and concentration	Total output Economic added-value Total output Agricultural land-use composition	Increasing economic/total output and/or economic added-value through agglomeration economies, due to clustering of similar farm activities in regions where industrial/logistic hubs for processing, transporting or marketing agricultural products exist (e.g. dairy industry, vegetable oil production, harbours, horticulture auctions), leading to more stable markets for inputs and outputs, decreasing transaction costs, and improved access to knowledge and labour.	[11], [43], [67], [75], [86], [101]
Vertical integration	Economic added-value Output variability Value-chain position Contract farming Processed products By-products	Increasing economic added-value (e.g. by reducing transaction costs) and output variability by adjusting the positioning of the farm in the supply chain, through contract farming (e.g. forward pricing contracts), consolidation of processing (e.g. olive oil, cheese, wine) and marketing operations (e.g. short supply chains such as direct marketing), and/or valorisation of by-products (e.g. fertiliser and energy production).	[6], [26], [29], [30], [38], [43], [51], [79], [84], [86], [88], [92], [101]–[108]
Knowledge intensity	Crop yield Animal productivity Economic output Economic added-value Farmer education and training Workers training Consultation with advisory/extension services	Increasing crop yield, animal productivity, economic output and/or economic added-value by acquiring knowledge and skills on improved management practices (including marketing and human resource management) through education and training (for both farmer managers and workers), and/or consultation with advisory/extension services.	[10], [13], [23], [26], [30], [42], [43], [50], [51], [55], [58], [66], [92], [109]
Improved information management	Crop yield Animal productivity Economic output Economic added-value ICT services use frequency Computer literacy	Increasing crop yield, animal productivity, input-use efficiency, and/or economic output, by adjusting planning (e.g. seeding, harvesting, weeding), process controlling (e.g. milking operations, fencing, adjustment of temperature and ventilation in animal facilities and greenhouses), application of consumable inputs (e.g. fertiliser, pesticides, water), and/or marketing strategies (e.g. output sales and input acquisition) through the use of information and communications technology (ICT).	[13], [26], [38], [42], [48], [51], [53], [54], [57], [58], [60], [61], [78], [80], [84], [109]–[112].
Crop/breed change and product differentiation	Crop yield Animal productivity Economic output Economic added-value Input efficiency	Increasing crop yield, animal productivity, economic output, economic added-value, and/or input/pesticide/water efficiency, by switching to crop varieties and livestock breeds with higher productivity (e.g. due to improved tolerance to dense sowing and increased number of rows, more efficient nutrient uptake, resistance to diseases), better product quality and/or higher market value (e.g. due to higher nutritional value, local food specialty).	[5], [12], [16], [18], [19], [30], [37]–[39], [67], [81], [82], [84], [86], [88], [92], [101], [113]–[117]

Mechanisms of intensity change	Attributes of intensity change	Description	References
	Fertiliser efficiency Water use efficiency Crop types and varieties Livestock species and breed varieties		
	Economic output Economic added-value Organic farming Protected designation of origin Voluntary sustainability standards	Increasing economic output and/or economic added-value by adhering to added-value niche markets through certification schemes such as organic farming, protected designation of origin (PDO) and/or voluntary sustainability standards (VSS).	[16], [26], [29], [30], [43], [51], [67], [88], [101], [106], [109], [118]
Income diversification	Economic output Economic added-value Total output variability Non-farming income Diversity of income sources	Increasing economic output, economic added-value and/or reducing total output/income variability by engaging in on-farm non-agricultural activities (agri-tourism, gastronomy, recreational activities) and/or renting assets (e.g. idle farm equipment, land for wind/solar power production).	[3], [4], [6], [26], [43], [50], [51], [67], [92], [101], [109], [119]
	Off-farm income Diversity of income sources	Increasing income and/or reducing income variability by engaging in off-farm employment.	[3], [4], [6], [13], [23], [26], [30], [43], [51], [55], [87], [101], [109], [119]
	Economic output Total output variability Subsidies Diversity of income sources	Increasing economic output and reducing output/income variability by adopting agro-environmental practices that are subsidised through financial compensation schemes (e.g. Ecological Focus Area).	[4], [6], [26], [29], [30], [33], [35], [82], [109], [120], [121]
Cooperation	Economic output Economic added-value Membership in professional organisations Membership in resource management organisations Membership in social organisations	Achieving increasing returns to scale/size (i.e. increasing economic output while simultaneously reducing average total cost per output unit) and/or realising economies of scope (i.e. reducing total costs of providing the services of a sharable input into two or more product lines are less than the total costs of providing these services for each product line separately) through strategies based on social capital, such as building supportive social and economic networks for exchanging services and assets (e.g. labour, manure, pastureland, farming materials), and/or developing institutional arrangements (e.g. cooperatives) for joint governance of resources and infrastructure (e.g. irrigation network), knowledge (e.g. better access to information and technical advice), value chains and marketing strategies (e.g. lower input costs and higher market prices through increased bargaining power).	[6], [10], [13], [23], [26], [35], [43], [50], [102], [104], [109], [122]

Appendix B. Identifying the effects of agricultural intensity change on ecosystem service provision in Europe (Step 2)

The effects of agricultural intensity change in the provision of ecosystem services in Europe were identified though literature review, combined with deductive content analysis [123]. Firstly, we searched on Scopus and ISI Web of Knowledge for peer-reviewed articles describing cases where intensity change affected ecosystem service provision in Europe. We used the IPBES Nature's Contributions to People framework (NCP, see Díaz et al. [124] as a heuristic for identifying different types of ecosystem services (see Table B.1 for an overview of the definition of different NCP types and reporting categories). However, since NCP is a relatively recent concept, we also added keywords related to "ecosystem services". We particularly focused on review/synthesis articles, using the following search string:

agricultur AND europe* AND (intensi OR intensif*) AND ("ecosystem services" OR "nature's contributions to people" OR NCP) AND (impact* or effect*) AND (synthesis OR review*)*

The search results of the two databases were then merged, and duplicates were removed. The selection of articles was then narrowed down after screening for their title, abstract and full texts. The following eligibility criteria were applied:

- Peer-reviewed and in English language;
- describe cases where a mechanism of intensity change identified in Table A.1 affected the provision of an ecosystem service described in Table B.1;
- refer to cases occurring in Europe (including trans-continental and global studies in which European cases are described).

The snowballing technique was then used, whenever the cases identified in the selected articles did not provide enough information to fully infer on the mechanism of intensity change and/or on the respective effects on ecosystem service provision. We read each selected case/article several times, and iteratively identified through deductive content analysis the sets of attributes of ecosystem service provision affected by the mechanisms of intensity change identified in Step 2 (Table A.1). In particular, the attributes were identified by using the NCP reporting categories as a pre-defined set of categories for identifying condensed meaning units (i.e. a description of a particular effect of intensity change on ecosystem service provision) and respective codes (i.e. the attributes of ecosystem service provision mentioned in the condensed meaning units). We iteratively defined sets of attributes, scales and socio-ecological processes based on recurrent combinations of condensed meaning units and codes. The results of the literature review were then coded in a matrix mapping the effects of each mechanism of intensity change in each ecosystem service category. In particular, for each cell we described the effects, and the attributes of ecosystem service that are affected by a particular mechanism of intensity change, the scale at which they are affected, and the socio-ecological processes through which they are affected. These results are presented in Tables B.2, B.3 and B.4, with the respective references. Based on these results, for each *Ecosystem service provision* theme and sub-theme, we defined a set of key attributes as indicators (Table 3, in the main text).

Table B.1 – Nature Contributions to People (NCP) types and reporting categories (adapted from [124])

NCP types	NCP reporting categories	Definition
Regulating NCP	NCP 1 - Habitat creation and maintenance	The formation and continued production, by ecosystems or organisms within them, of ecological conditions necessary or favorable for living beings of direct or indirect importance to humans. Growing sites for plants, nesting, feeding, and mating sites for animals, resting and overwintering areas for migratory mammals, birds and butterflies, roosting places for agricultural pests and disease vectors, nurseries for juvenile stages of fish, habitat creation at different soil depths by invertebrates.
	NCP 2 - Pollination	Facilitation by animals of movement of pollen among flowers and dispersal of seeds, larvae or spores of organisms beneficial or harmful to humans.
	NCP 3 - Regulation of air quality	Regulation (by impediment or facilitation) by ecosystems, of CO2/O2 balance, O3, sulphur oxide, nitrogen oxides (NOx), volatile organic compounds (VOC), particulates, aerosols, allergens. Filtration, fixation, degradation or storage of pollutants that directly affect human health or infrastructure.
	NCP 4 - Regulation of climate	Climate regulation by ecosystems (including regulation of global warming) through: positive or negative effects on emissions of greenhouse gases (e.g. biological carbon storage and sequestration; methane emissions from wetlands); positive or negative effects on biophysical feedbacks from vegetation cover to atmosphere, such as those involving albedo, surface roughness, long-wave radiation, evapotranspiration (including moisture-recycling) and cloud formation; direct and indirect processes involving biogenic volatile organic compounds (BVOC), and regulation of aerosols and aerosol precursors by terrestrial plants and phytoplankton.
	NCP 5 - Regulation of ocean acidification	Regulation, by photosynthetic organisms (on land or in water), of atmospheric CO2 concentrations and seawater pH, which affects associated calcification processes by many marine organisms important to humans (such as corals)
	NCP 6 - Regulation of freshwater quantity, location and timing	Regulation, by ecosystems, of the quantity, location and timing of the flow of surface and groundwater used for drinking, irrigation, transport, hydropower, and as the support of non-material contributions. Regulation of flow to water-dependent natural habitats that in turn positively or negatively affect people downstream, including via flooding (wetlands including ponds, rivers, lakes, swamps). Modification of groundwater levels, which can ameliorate dryland salinization in unirrigated landscapes.
	NCP 7 - Regulation of freshwater and coastal water quality	Regulation through filtration of particles, pathogens, excess nutrients, and other chemicals, by ecosystems or particular organisms, of the quality of water used directly (e.g. drinking, swimming) or indirectly (e.g. aquatic foods, irrigated food and fiber crops, freshwater and coastal habitats of heritage value).
	NCP 8 - Formation, protection and contamination of soils and sediments	Formation and long-term maintenance of soil structure and processes by plants and soil organisms. Includes: physical protection of soil and sediments from erosion, and supply of organic matter and nutrients by vegetation; processes that underlie the continued fertility of soils important to humans (e.g. decomposition and nutrient cycling); filtration, fixation, attenuation or storage of chemical and biological pollutants (pathogens, toxics, excess nutrients) in soils and sediments.
	NCP 9 - Regulation of hazards and extreme events	Amelioration, by ecosystems, of the impacts on humans or their infrastructure caused by e.g. floods, wind, storms, hurricanes, heat waves, tsunamis, high noise levels, fires, seawater intrusion, tidal waves.
	NCP 10 - Regulation of detrimental organisms and biological processes	Regulation, by organisms, of pests, pathogens, predators or competitors that affect humans (materially and nonmaterially), or plants or animals of importance for humans. Also the direct detrimental effect of organisms on humans or their plants, animals or infrastructure.
Material NCP	NCP 11 - Energy	Production of biomass-based fuels, such as biofuel crops, animal waste, fuelwood, agricultural residue pellets, peat.
	NCP 12 - Food and feed	Production of food from wild, managed, or domesticated organisms, such as fish, bushmeat and edible invertebrates, beef, poultry, game, dairy products, edible crops, wild plants, mushrooms, honey. Production of feed (forage and fodder) for domesticated animals (e.g. livestock, work and support animals, pets) or for aquaculture.
	NCP 13 - Materials, companionship and labour	Production of materials derived from organisms in cultivated or wild ecosystems, for construction, clothing, printing, ornamental purposes (e.g. wood, peat, fibers, waxes, paper, resins, dyes, pearls, shells, coral branches). Live organisms being directly used for decoration (i.e. ornamental plants, birds, fish in households and public spaces), company (e.g. pets), transport, and labour.
	NCP 14 - Medicinal, biochemical and genetic resources	Production of materials derived from organisms (plants, animals, fungi, microbes) used for medicinal, veterinary and pharmacological (e.g. poisonous, psychoactive) purposes. Production of genes and genetic information used for plant and animal breeding and biotechnology.
Non-material NCP	NCP 15 - Learning and inspiration	Provision, by landscapes, seascapes, habitats or organisms, of opportunities for the development of the capabilities that allow humans to prosper through education, acquisition of knowledge and development of skills for well-being. Information, and inspiration for art and technological design.
	NCP 16 - Physical and psychological experiences	Provision, by landscapes, seascapes, habitats or organisms, of opportunities for physically and psychologically beneficial activities, healing, relaxation, recreation, leisure, tourism and aesthetic enjoyment based on the close contact with nature (e.g. hiking, recreational hunting and fishing, birdwatching, snorkelling, diving, gardening).
	NCP 17 - Supporting identities	Landscapes, seascapes, habitats or organisms being the basis for religious, spiritual, and social-cohesion experiences: provisioning of opportunities by nature for people to develop a sense of place, belonging, rootedness or connectedness, associated with different entities of the living world (e. g. cultural, sacred and heritage landscapes, sounds, scents and sights associated with childhood experiences, iconic animals, trees or flowers); basis for narratives, rituals and celebrations provided by landscapes, seascapes, habitats, species or organisms; source of satisfaction derived from knowing that a particular landscape, seascape, habitat or species exists.

Table B.2: Effects of mechanisms of agricultural intensity change in the provision of habitat creation and maintenance (NCP 1), pollination (NCP 2), air quality regulation (NCP 3) and climate regulation (NCP 4) in Europe. For each ecosystem service category, the affected attributes are <u>underlined</u>, the levels and/or scales at which they are affected are in **bold**, and the socio-ecological processes through which they are affected are in *italics*.

Mechanism of intensity change	NCP 1 - Habitat creation and maintenance	NCP 2 - Pollination	NCP 3 - Air quality regulation	NCP 4 - Climate regulation
Land management intensity	Changes in land management intensity affect <u>habitat availability</u>, <u>connectivity</u>, <u>fragmentation</u> and <u>quality</u> for different types of flora and fauna species at the **landscape scale**, through changes in *ecosystem functioning*, *species-habitat interactions* and *biological movements*. Particularly: • more frequent field operations, long grazing periods and higher stocking density rates affect the habitat availability and quality for birds, invertebrates and mammal species, by altering native plant growth, vegetation height and structure, botanical diversity and availability of flower resources, and consequently the availability of habitat for food and cover [125]. • Soil drainage affects wetland habitat quality for related bird species, including the soil penetrability for probing birds, and hence their access to invertebrate prey [125][41] • Abandonment allows re-establishment of native habitats in some areas, but it also results in loss and fragmentation of habitat for butterflies, plants, and farmland birds in need of open farmland [125] [126] [3] [127] [41] • Increased fallow cycles provide greater habitat availability and quality (e.g. increased variety and amount of food and cover throughout the year) [125] • Increased sowing densities lead to denser and more homogeneous sward structures, sequestering resources and modifying habitat availability and quality for plants, invertebrates and birds [28][128] Changes in land management intensity leads to changes in <u>net primary production</u> of agroecosystem habitats at the **landscape scale**, through changes in *ecosystem functioning* and *biogeochemical cycles*, which in turn affects the availability of resources such as plant biomass and fruits for birds, mammals and butterflies [129] [130]	Changes in land management intensity affect <u>pollination potential</u> (i.e. the abundance and diversity of pollinator species, and respective composition, structure and stability of pollinator communities) at the **field and landscape scales**, through changes in *ecosystem functioning*, *species-habitat interactions* and *biological movements*. Particularly: • increased livestock density, grazing period length, frequency of field operations, soil drainage and reduction of fallow cycles may cause the alteration of plant-species interactions and availability of food resources, direct pollinator mortality, and destruction/disturbance of underground nests and potential nesting sites of pollinators [125], [131] [132] [133] [28] [134] [135] • increased fallow cycles contribute to the availability of food resources and nesting habitat for pollinators [125] [133]		Changes in land management intensity affect the <u>soil's carbon storage potential</u> at the **field and landscape scales**, through changes in *biogeochemical cycles*. Particularly: • increased livestock density, grazing period length and soil drainage in poorly drained mineral soils can lead to significant losses of topsoil organic content, reducing carbon storage potential [136][137] • the transition from tilled arable land to no-tillage or conservation tillage systems increase soil's carbon storage potential [138] • the reversion of agricultural land to uncultivated grassland contributes to increased carbon sequestration potential [125] • agricultural abandonment leads to the accumulation of woody above-ground biomass, thus increasing carbon sequestration potential [139]
Capital intensity	Changes in capital intensity affect <u>habitat availability</u> and <u>habitat quality</u>, and/or <u>habitat fragmentation</u> at the **landscape scale**, through changes in *ecosystem functioning*, *species-habitat interactions* and *biogeochemical flows*. Particularly: • Draining wetlands and temporary ponds, or converting them to permanent irrigation reservoirs results in loss of habitat availability and habitat quality for a range of specialised organisms, such as amphibians and crustaceans [125] • Damming for irrigation changes the natural character of streams and rivers considerably, causing habitat			

Mechanism of intensity change	NCP 1 - Habitat creation and maintenance	NCP 2 - Pollination	NCP 3 - Air quality regulation	NCP 4 - Climate regulation
	fragmentation, and/or loss of habitat availability and habitat quality for freshwater species [125] • Loss of habitat availability and habitat quality in typical agro-silvo-pastoral landscapes of Spain (dehesas) and Portugal (montados) due to the large-scale deployment of irrigation infrastructure [125]			
Input-use intensity	Changes in input-use intensity affect habitat availability and habitat quality at the **landscape scale**, through changes in *ecosystem functioning*, *species-habitat interactions*, *biogeochemical cycles* and *pollutant flows*. Particularly: • increased application of fertilizers and herbicides affect the quality of habitats adjacent to fields, such as field margins and ditch banks [125] [28] [127] [41] • High ammonia and nitrogen dioxide emissions resulting from excessive fertiliser application may lead to increased nitrogen deposition and affect sensitive vegetation and habitat quality elsewhere [125]. Changes in input-use intensity lead to changes in net primary production of agroecosystem habitats at the **landscape scale**, through changes in *ecosystem functioning* and *biogeochemical cycles*, which in turn affects the availability of resources such as plant biomass and fruits for birds, mammals and butterflies [129] [130]	Changes in input-use intensity affect pollination potential, (the abundance and diversity of pollinator species, and respective composition, structure and stability of pollinator communities) at the **field and landscape scales**, through changes in *ecosystem functioning*, *species-habitat interactions*, *biological movements* and *pollutant flows*. Particularly: • Application of broad-spectrum insecticides increases pollinator mortality [131] as well as a range of other sub-lethal effects, such as physiological, morphological (e.g. bee worker size) and behavioural (e.g. foraging) changes affecting pollination services [133] [135] [132] [140] [141]. These effects can be caused by direct exposure and by airborne drift of insecticides applied in distant locations [125] • Increased application of herbicides reduces the availability and diversity of flowering plants providing pollen and nectar [131][132] and weed flowers providing foraging resources for wild and managed pollinators [133] [135] • Increased application of inorganic fertilisers can reduce the abundance and diversity of less competitive wild and weedy plant species, and alter the morphology, nectar chemistry and phenology of flowers, thereby altering plant–pollinator interactions [133] [135]		
Farm consolidation	Farm consolidation affects habitat availability, connectivity, fragmentation and quality for different types of flora and fauna species at the **landscape scale**, through changes in *ecosystem functioning*, *species-habitat interactions* and *biological movements*. Particularly: • Landscape simplification through enlargement field size, and removal of (semi-)natural habitat patches (e.g. natural grasslands and meadows, wetlands) and linear elements (e.g. field boundaries, hedgerows, tree lines, ditch margin vegetation, riparian strips and, flower strips) leads to loss and/or fragmentation of semi-natural habitats [125][142][28] [143][41]. • Conversely, decreasing field size and restoring and/or maintaining non-crop areas and linear elements can provide support for improving habitat availability, connectivity and overall quality [144] [145] [146]	Farm consolidation affects pollination potential (i.e. the abundance and diversity of pollinator species, and respective composition, structure and stability of pollinator communities) at the **field and landscape scales**, through changes in *ecosystem functioning*, *species-habitat interactions* and *biological movements*. Particularly: • Increasing field sizes, removing (semi-)natural habitats (e.g. natural grasslands and meadows, wetlands)and landscape element s(e.g. field boundaries, hedgerows, tree lines, ditch margin vegetation, riparian strips and, flower strips) and linear elements (field boundaries, hedgerows, tree lines, ditch margin vegetation, riparian strips and, flower strips) disrupts pollinator species, particularly by altering their local abundance, composition and diversity, due to loss of wild vegetation and consequent reduction of food resources, reduction of areas where bees can nest, altered pollinator networks (e.g. distance between florally rich locations and nests), reduced larval host plants for butterflies, and less-varied microhabitats for egg laying and larval development [131][130], [147][148] [132] [133] [149] [150] [135]	Farm consolidation affects air pollution retention capacity at the **landscape scale**, through changes in *pollutant flow* and *biological movements*. Particularly: • the removal of vegetation elements and patches reduces the ability to intercept/remove air pollutants (e.g. pesticide drift, pathogens and fine particulate matter [154] [155] [125] [156]	Farm consolidation affects carbon sequestration potential at the **field and landscape scales**, through changes in *biogeochemical cycles*. Particularly: • Removal of habitat patches and linear elements reduces potential for carbon sequestration [146] [157] [158] Farm consolidation affect micro-climatic conditions by altering evapotranspiration, albedo, temperature regulation and humidity regulation at the **field and landscape scales**, through changes in *biogeochemical cycles*. Particularly: • removal of natural vegetation reduces evapotranspiration and increases albedo [154] • Removal of riparian trees may affect water temperature, due to reduced shading [159] • Conversely, maintaining hedges, wooded banks, forests and permanent grasslands support the regulation of temperature and humidity [5] [125] [155]

Mechanism of intensity change	NCP 1 - Habitat creation and maintenance	NCP 2 - Pollination	NCP 3 - Air quality regulation	NCP 4 - Climate regulation
		• Habitat fragmentation resulting from farm consolidation can harm interactions that plants have with seed dispersers and other mutualists [131] • Conversely, decreasing field size and restoring and/or maintaining non-crop areas and linear elements can directly increase habitat connectivity, thus improving floral and nesting resources for pollinator diversity and reduce flight distances [133] [151] [152] [153] [132]		
Farm specialisation / diversification	Farm specialisation/diversification affects habitat availability, connectivity, fragmentation and quality for different types of flora and fauna species at the **landscape scale**, through changes in *ecosystem functioning*, *species-habitat interactions* and *biological movements*. Particularly: • farm specialization (monocultural farming, separation of pastoral and arable farming systems) affects landscape composition and reduces habitat availability and quality, and availability food resources over the medium term for birds, fish, plants, mammals and invertebrates [155][125][133][146] [41] • farm diversification can provide habitats for species of different ecological profile. For example, the existence of permanent and temporary grasslands within arable farming diversifies available habitats, by providing habitats suitable to grassland specialists and resources in specific periods of the year for generalist species that would suffer from the temporal discontinuity of resources in crop fields [137] [125] [130][155][160] Farm specialisation/diversification affects landscape heterogeneity, with effects on net primary production and temporal stability at the **landscape scale**, through changes in *ecosystem functioning* and *biogeochemical cycles* [161]	Farm specialisation/diversification affects pollination potential (i.e. the abundance and diversity of pollinator species, and respective composition, structure and stability of pollinator communities) at the **field and landscape scales**, through changes in *ecosystem functioning*, *species-habitat interactions* and *biological movements*. Particularly: • farm specialization (monocultural farming, separation of pastoral and arable farming systems) reduces floral diversity overall habitat resources for pollinators, consequently reducing the diversity of pollinating insects [131] [133] [162] [135] [163] • Farm diversification (e.g. crop-livestock mixtures, agroforestry, crop rotations including flowering crops, legumes and cover crops) can support pollinator communities by enhancing floristic diversity, habitats and continuity of food resources (seasonal and spatial) for many pollinator species, even in landscapes with little semi-natural habitats [162][132] [133] [137] [156][160]		Farm specialisation/diversification affects carbon sequestration potential at the **field and landscape scales**, through changes in *biogeochemical cycles*. Particularly: • soil carbon sequestration potential can be increased through planting deep rooted plants such as agroforestry, use of improved crop rotations in which carbon inputs are increased over a rotation, and use of cover crops during fallow periods to provide year-round carbon inputs [136][160]
Regional specialisation and concentration	Regional specialisation and concentration affect habitat availability, connectivity, fragmentation and quality for different types of flora and fauna species at the **landscape scale**, through changes in *ecosystem functioning*, *species-habitat interactions* and *biological movements*. Particularly: • the resulting homogenisation of the landscape reduces habitat availability, quality and connectivity, and availability food resources over the medium term for birds, fish, plants, mammals and invertebrates [155][125][133][146] [41] Regional specialisation affects landscape heterogeneity, with effects on net primary production and temporal stability at the **landscape scale**, through changes in *ecosystem functioning* and *biogeochemical cycles* [161]	Regional specialisation and concentration affect pollination potential (i.e. the abundance and diversity of pollinator species, and respective composition, structure and stability of pollinator communities) at the **landscape scale**, through changes in *ecosystem functioning*, *species-habitat interactions* and *biological movements*. Particularly: • farm specialization (monocultural farming, separation of pastoral and arable farming systems) reduces floral diversity overall habitat resources for pollinators, consequently reducing the diversity of pollinating insects [131] [133][162][135][163]		

Table B.3: Effects of mechanisms of intensity change in the provision of water quantity regulation (NCP 6), water quality regulation (NCP 7), soil regulation (NCP 8), extreme events regulation (NCP 9) and detrimental organisms regulation (NCP 10) in Europe. For each ecosystem service category, the affected attributes are underlined, the levels and/or scales at which they are affected are in **bold**, and the socio-ecological processes through which they are affected are in *italics*.

Mechanism of intensity change	**NCP 6 - Water quantity regulation**	**NCP 7 - Water quality regulation**	**NCP 8 - Soil regulation**	**NCP 9 - Extreme events regulation**	**NCP 10 - Detrimental organisms regulation**
Land management intensity	Changes in land management intensity affect water flow regulation capacity at the **landscape scale**, through changes in *biogeochemical cycles*. Particularly: • lower infiltration rates associated with soil compaction, due to increased frequency of field operations, high livestock density and increased grazing period lead to reduced soil water storage capacity, increased surface runoff and reduced groundwater recharge [125][164] [136] [155] • increased adoption of field drains leads to sedimentation of water reservoirs, contributing to reduced water storage capacity [125]	Changes in land management intensity affect water pollution filtration capacity at the **landscape scale**, through changes in *biogeochemical cycles* and *pollutant flows*. Particularly: • lower infiltration rates associated with soil compaction, due to increased frequency of field operations, high livestock density, and increased grazing period, lead to reduced filtration capacity due to rapid transport of nutrients, pesticides, and sediment to surface waters [125] [136][137][41] • the reversion of agricultural land to uncultivated grassland may result in local improvement in filtration capacity [125] • increased adoption of field drains leads to reduced water filtration capacity [125]	Changes in land management intensity affect soil erosion regulation capacity, soil nutrient fixation capacity, and sediment retention capacity at the **field and landscape scales**, through changes in *biogeochemical cycles*, *ecosystem functioning*, and *species-habitat interactions*. Particularly: • increased frequency of field operations, high livestock density, increased grazing period, increased cropping frequency and reduced fallow periods affect the ability of the soil for filtering and retain pollutants, sediments and nutrients, and to avoid soil erosion [159] [125], [165] [136] [155] [41] [137] • Soil compaction due to increased frequency of field operations, high livestock density, increased grazing period, reduces abundance of microfauna maintaining soil structure, and affects microbial community structure, thus reducing soil erosion regulation capacity and soil nutrient fixation capacity [41] [156][146] • Conversely, no-till farming and minimum tillage increase soil bulk density and promote soil microfauna, thus reducing soil erosion and improving soil nutrient retention [125] [133][41] [156] [146] • Increased vegetation cover due to agricultural abandonment may protect soil from erosion. However, the increased risk of fire may also increase, exposing the soil to erosion [126] [41] [166]	Changes in land management intensity affect flood regulation capacity at the **landscape scale**, through changes in *biogeochemical cycles*. Particularly: • soil compaction, due to increased frequency of field operations, high livestock density, and increased grazing period, increases flooding [125] [164] [155] Changes in land management intensity affects fire regulation capacity at the **landscape scale,** through changes in *ecosystem functioning* and *biogeochemical cycles*. Particularly: • increased vegetation cover due to agricultural abandonment may increase risk of fire [126] [166] [41] [139] • more frequent orchard pruning reduces fire risk [167]	Changes in land management intensity affect natural pest control potential at the **field and landscape scales,** through changes in *ecosystem functioning*, *species-habitat interactions* and *biological movements*. Particularly: • tillage practices affect soil microbial community composition and activities, and influences the soil's ability to supress pests and diseases [168] [136], while conservation tillage supports natural pest control communities [169]
Capital intensity	Changes in capital intensity affect water flow regulation capacity at the **landscape scale**, through changes in *biogeochemical cycles*. Particularly: • drainage of peatlands and wetlands reduce water storage capacity [136] • lower infiltration rates associated with soil compaction due to use of machinery lead to reduced soil water storage capacity, increased surface runoff and reduced groundwater recharge [164] [136] [41]	Changes in capital intensity affect water pollution filtration capacity at the **landscape scale**, through changes in *biogeochemical cycles* and *pollutant flows*. Particularly: • drainage of wetlands (including unimproved pasture or even small patches of wet soils in the corners of fields) reduces water filtration capacity [155] [151] [41] • lower infiltration rates associated with soil compaction due to use of machinery lead to reduced soil water storage capacity,	Changes in capital intensity affect soil erosion regulation capacity, soil nutrient fixation capacity, and sediment retention capacity at the **field and landscape scales,** through changes in *biogeochemical cycles*, *ecosystem functioning*, and *species-habitat interactions*. Particularly: • Soil compaction due use of heavy machinery affects the ability of the soil for filtering and retain pollutants, sediments and	Changes in capital intensity affect flood regulation capacity and fire regulation capacity at the **landscape scale,** through changes in *ecosystem functioning* and *biogeochemical cycles*. Particularly: • soil compaction due use of heavy machinery affects the ability of the soil to regulate floods[136] • wetland drainage can increase fire risk [136] and reduce ability to regulate floods [146]	

Mechanism of intensity change	**NCP 6 - Water quantity regulation**	**NCP 7 - Water quality regulation**	**NCP 8 - Soil regulation**	**NCP 9 - Extreme events regulation**	**NCP 10 - Detrimental organisms regulation**
		increased surface runoff and reduced groundwater recharge [164] [136] [41]	nutrients, and to avoid soil erosion [136] [41] • Soil compaction due to use of heavy machinery reduces abundance of microfauna maintaining soil structure, and affects microbial community structure, thus reducing soil erosion regulation capacity and soil nutrient fixation capacity [41]		
Input-use intensity			Changes in input-use intensity affect soil erosion regulation capacity, soil nutrient fixation capacity, and sediment retention capacity at the **field and landscape scales,** through changes in *biogeochemical cycles*, *ecosystem functioning* and *species-habitat interactions*, and *pollutant flows*. Particularly: • Increased fertiliser use and irrigation may affect the chemical and physical properties of the soil, including acidification, increase in salinization and decrease in organic matter, leading to increased risk of soil erosion [125] [170] [136] • application of slurry affects soil micro-biology by introducing antibiotics from veterinary medicines, resulting in a shift in the fungal: bacteria ratio, thus affecting soil nutrient fixation capacity [125] [170] [136]		Changes in input-use intensity affect natural pest control potential at the **field and landscape scales,** through *pollutants flows* changes in *ecosystem functioning* and *species-habitat interactions*. Particularly: • Increased use of pesticides reduces the abundance, diversity, activity and food resources of natural pest predators and other non-target species, potentially leading to the emergence of new pests. [125] [136] [28] [41] [146] [171] • high crop productivity due to fertilizer use favours pest outbreaks [130]
Farm consolidation	Farm consolidation affects water flow regulation capacity at the **landscape scale**, through changes in *biogeochemical cycles*. Particularly: • removal of vegetation cover and linear elements affect the ability to regulate the amount, and stability of water flows [125] [146] [164] [155] [172][143] [173]	Farm consolidation affects water pollution filtration capacity at the **landscape scale**, through changes in *biogeochemical cycles* and *pollutant flows*. Particularly: • removal of vegetation cover and linear elements affect the ability to retain nitrates, phosphates, pollutants and sediments [125] [146] [159] [155][41] [151] [143] [172]	Farm consolidation affects soil erosion regulation capacity, soil nutrient fixation capacity, and sediment retention capacity at the **field and landscape scales,** through changes in *biogeochemical cycles*. Particularly: • removal of vegetation cover and linear elements increases erosion risk, and reduces the retention of nutrients and sediments [125][155] [41] [157] [151][143]	Farm consolidation affects flood regulation capacity, fire regulation capacity, and wind regulation capacity at the **landscape scale,** through changes in *biogeochemical cycles*. Particularly: • removal of vegetation cover and linear elements increases flooding risk, and deteriorates the capacity to regulate fire risk and wind speed [125] [146] [164] [155] [173]	Farm consolidation affects affect natural pest control potential at the **field and landscape scales,** through changes in *ecosystem functioning* and *species-habitat interactions*. Particularly, • enlarging field size, and removal of vegetation cover and linear elements may disrupt processes of biological pest control, as these areas are sources for agents of biological control, pests and pathogens, and support a considerable number of associated species. Simplification of agricultural landscapes can thus either reduce or enhance pest pressure, depending on the habitat preferences and mobility of the relevant organisms, but often leads to reduction of natural pest control [130], [147] [174][175] [176] [170][177] [146][150] [171]
Farm specialisation / diversification	Farm specialisation/diversification affects water flow regulation capacity at the **landscape scale**, through changes in *biogeochemical cycles*. Particularly: • increasing the diversity of plants on the crop rotation (e.g. cover crops, legumes, mixed arable-livestock systems) and rooting depths (e.g. agroforestry) increases soil water-	Farm specialisation/diversification affects water pollution filtration capacity at the **landscape scale**, through changes in *biogeochemical cycles* and *pollutant flows*. Particularly: • increasing the diversity of plants on the crop rotation (e.g. cover crops, legumes, mixed arable-livestock systems) and rooting depths (e.g. agroforestry) improves the ability to	Farm specialisation/diversification affects soil erosion regulation capacity, soil nutrient fixation capacity, and sediment retention capacity at the **field and landscape scales** through changes in *biogeochemical cycles* and *species-habitat interactions*. Particularly: • increasing the diversity of plants on the crop rotation (e.g. cover crops, legumes, mixed arable-livestock systems) and rooting depths	Farm specialisation/diversification affects flood regulation capacity at the **landscape scale,** through changes in *biogeochemical cycles.* Particularly: • increasing the diversity of plants on the crop rotation (e.g. cover crops, legumes, mixed arable-livestock systems) and rooting depths (e.g. agroforestry) improves the water	Farm specialisation/diversification affects natural pest control potential at the **field and landscape scales,** through changes in ecosystem *functioning* and *species-habitat interactions*. Particularly: • Increased intraspecific crop genetic diversity enhances tolerance to from emergent pests and diseases [178][146]

Mechanism of intensity change	**NCP 6 - Water quantity regulation**	**NCP 7 - Water quality regulation**	**NCP 8 - Soil regulation**	**NCP 9 - Extreme events regulation**	**NCP 10 - Detrimental organisms regulation**
	holding capacity through adsorption [146] [155][136][41][160].	reduce the delivery of nutrients, pathogens and pollutants to water, by reducing leaching through adsorption and increased microbial activity [155][136] [156] [41] [146] [137] [160].	(e.g. agroforestry) improves erosion regulation and the retention of nutrients and sediments, by increasing infiltration rate through improved soil structure, organic matter content and beneficial biota (e.g. earthworms) [155][136] [156] [41] [146] [137] [160]	holding capacity of the soil, reducing the flooding risk downstream [155].	• Diversity of crops and habitats (e.g. wildflower strips) enhances the diversity and abundance of natural enemy populations (e.g. beetles, birds and other predators) controlling insect pests and viruses transmitted by insects. Enhanced abundance and diversity of natural enemies, however, do not necessarily provide enhanced pest control, since pest densities may also respond positively to diversity of habitats [133][28] [155][130] [156] [174][146][160].
Regional specialisation and concentration	Regional specialisation and concentration affects water flow regulation capacity at the **landscape scale**, through changes in *biogeochemical cycles*. Particularly: • reducing diversity of habitats such as pastures, meadows, wetlands, woodlots and water bodies reduces the capacity of the farming landscape for hydrological regulation [155].	Regional specialisation and concentration affects water pollution filtration capacity at the **landscape scale**, through changes in *biogeochemical cycles* and *pollutant flows*. Particularly: • reducing the diversity of habitats such as pastures, meadows, wetlands, woodlots and water bodies reduces the ability of the farming landscape to regulate of water quality [155].		Regional specialisation and concentration affects flood regulation capacity at the **landscape scale,** through changes in *biogeochemical cycles*. Particularly: • reducing diversity of habitats such as pastures, meadows, wetlands, woodlots and water bodies reduces the capacity of the farming landscape for hydrological regulation, increasing the flooding risk downstream [155]	Regional specialisation and concentration affects natural pest control potential at the **landscape scale,** through changes in ecosystem *functioning*, *species-habitat interactions and biological movements*. Particularly: • reducing diversity of habitats in the landscape leads to a decline on the diversity and abundance of natural enemy populations (e.g. beetles, birds and other predators) controlling insect pests and viruses transmitted by insects [133][28] [155][130] [156] [174][146][160].

Table B.4: Effects of mechanisms of agricultural intensity change in the provision of energy production (NCP 11), food and feed production (NCP 12), learning and inspiration (NCP 15), physical and psychological experiences (NCP 16) and supporting identity services (NCP 17) in Europe. For each ecosystem service category, the affected attributes are <u>underlined</u>, the levels and/or scales at which they are affected are in **bold**, and the socio-ecological processes through which they are affected are in *italics*.

Mechanism of intensity change	NCP 11 - Energy production	NCP 12 - Food and feed production	NCP 15 - Learning and inspiration	NCP 16 - Physical and psychological experiences	NCP 17 - Supporting identities
Land management intensity	Changes in land management intensity affect <u>potential bioenergy crop yields</u> at the **field and landscape scales**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly: • increased frequency of field operations, cropping frequency, sowing density and soil drainage contribute to increased crop yields [179][180] [136] • soil erosion and compaction due to more frequent field operation and livestock density reduces crop yields and crop quality, due to waterlogging, impaired root growth, reduced earthworm abundance and activity, and changes in microbial community structure due anaerobic conditions and [125][136] [7] [155] [41] • Large quantities of manure due to high livestock density can lead to the release of high levels of gases that are precursors to ozone, which in turn is associated with increased plant damage and direct crop loss [155] • livestock density, grazing period length, frequency of field operations, soil drainage and fallow cycle frequency affect pollinator [125], [131] [132] [133] [28] [134] [135], and natural pest control communities [168] [136][169], which in turn affect crop productivity [146] [181] [151] [152] [150] [133]	Changes in land management intensity affect <u>potential crop yield for food crops</u> and <u>potential crop yield for feed crops</u> at the **field and landscape scales**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly: • increased frequency of field operations, cropping frequency, sowing density and soil drainage contribute to increased crop yields [179][180] [136] • soil erosion and compaction due to more frequent field operation and livestock density reduces crop yields and crop quality, due to waterlogging, impaired root growth, reduced earthworm abundance and activity, and changes in microbial community structure due anaerobic conditions and [125][136] [7] [155] [41] • Large quantities of manure due to high livestock density can lead to the release of high levels of gases that are precursors to ozone, which in turn is associated with increased plant damage and direct crop loss [155] • livestock density, grazing period length, frequency of field operations, soil drainage and fallow cycle frequency affect pollinator [125], [131] [132] [133] [28] [134] [135], and natural pest control communities [168] [136][169], which in turn affect crop productivity [146] [181] [151] [152] [150] [133] • Mowing frequency affects fodder quality [129] • decreasing livestock density or grazing period length decreases productivity per unit of area, but fine tuning of the timing of grazing makes it possible to limit the negative effects on production (temporary removal of livestock from some plots at flowering peak) [137]	Changes in land management intensity affect the <u>landscape educational value</u> at the **landscape scale**, through changes in *human-nature interactions* and *social relationships*. Particularly, abandonment of traditionally managed landscapes results in the loss of traditional skills and local knowledge [41][127][5][126]	Changes in land management intensity affect the <u>landscape aesthetical value</u> and <u>landscape recreational value</u> at the **landscape scale**, through changes in *human-nature interactions, social relationships, human-livestock interactions, and ecosystem functioning, biological movements* and *habitat-species interactions.* Particularly: • abandonment of traditionally managed landscapes decreases their recreation and aesthetical values due to deterioration or removal of farm buildings and landscape mosaics and loss of cultural heritage value [5] [126] [41][166] [156] • Conversely, rewilding of abandoned areas can lead to increased recreation value (e.g. for tourism and hunting) due to the return of species benefitting from abandonment (e.g. large mammals such as wolves and bears) [182] • Increased livestock density can decrease landscape aesthetical value due to damage on landscape elements such terraces and stonewalls [7] • grassland mowing affects landscape aesthetical value, by affecting species diversity, flowering phenology and litter mass [129]	Changes in land management intensity affect the <u>cultural heritage value</u> and <u>landscape spiritual value</u> at the **landscape scale**, through changes in *human-nature interactions, social relationships, human-livestock interactions, ecosystem functioning* and *habitat-species interactions*. Particularly, the abandonment of traditionally managed landscapes and/or increased livestock density towards a shift from pastoral livestock systems to intensive livestock production results in the loss of cultural heritage (e.g. songs, tales, handicrafts, gastronomy, festivals, practices, constructions and local breeds), regional identity, sense of belonging and connectedness [41] [127] [5] [126] [183] [127] [139][137] [7]
Capital intensity	Changes in capital intensity affect <u>potential bioenergy crop yields</u> at the **field and landscape scales**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly:	Changes in capital intensity affects <u>potential crop yield for food crops</u> and <u>potential crop yield for feed crops</u> at the **field and landscape scales**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*.. Particularly:	Changes in capital intensity affect the <u>landscape educational value</u> at the **landscape scale**, through changes in *human-nature interactions, social relationships*, *human-livestock interactions*, and *ecosystem functioning*. Particularly:	Changes in capital intensity affect the <u>landscape aesthetical value</u> and <u>landscape recreational value</u> at the **landscape scale**, through changes in *human-nature interactions, social relationships, human-livestock interactions, ecosystem functioning* and *habitat-species interactions*. Particularly:	Changes in capital intensity affect the <u>cultural heritage value</u> and <u>landscape spiritual value</u> at the **landscape scale**, through changes in *human-nature interactions, social relationships, human-livestock interactions, ecosystem functioning* and *habitat-species interactions*. Particularly, the shift from traditional pastoral

Mechanism of intensity change	NCP 11 - Energy production	NCP 12 - Food and feed production	NCP 15 - Learning and inspiration	NCP 16 - Physical and psychological experiences	NCP 17 - Supporting identities
	• increased machinery use and irrigation area contributes to increased crop yields [179][180] [136] • soil compaction due to use of heavy machinery reduces crop yields and crop quality, due to waterlogging, impaired root growth, reduced earthworm abundance and activity, and changes in microbial community structure due anaerobic conditions [125][136] [7] [155] [41]	• increased machinery use and irrigation area contribute to increased crop yields [179][180] [136] • soil compaction due to use of heavy machinery reduces crop yields and crop quality, due to waterlogging, impaired root growth, reduced earthworm abundance and activity, and changes in microbial community structure due anaerobic conditions [125][136] [7] [155] [41]	• the replacement of historic buildings with modern facilities results in the loss of architectural features with educational value [41] [127][5][126][41] • Conversely, the renovation of historical buildings and grey linear elements (e.g. stone walls) increases the landscape educational value [143][184] • the shift from traditional pastoral systems with local breeds to intensive livestock production results in a in a loss of opportunities for educational activities [137][183]	• the replacement of historic buildings and orchards with modern facilities (e.g. greenhouses, stables), and shift from traditional pastoral systems to intensive livestock production reduces the landscape aesthetical value. [143][184] [185] • Conversely, the renovation of historical buildings and grey linear elements (e.g. stone walls) increases the landscape aesthetical and recreational values [143][184] • The deployment of irrigation infrastructure affects the landscape aesthetical value [125]	systems to intensive livestock production, and replacement of related historical buildings, results in the loss of cultural heritage (e.g. gastronomy, celebrations, practices, constructions and local breeds), regional identity, sense of belonging and connectedness [5][183][143] [184][137]
Input-use intensity	Changes in input-use intensity affect <u>potential bioenergy crop yields</u> at the **field and landscape scales**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly: • the use of fertilisers, pesticides, water for irrigation, and energy for field operations and irrigation contributes to increases in crop yields [179][180] [136] [186] [187] [28] [5] [188] [155] • Adjustment of nutrient inputs can improve plant growth which increases organic matter returns to the soil, which in turn can improve soil fertility[136] • increased irrigation contributes to soil degradation, due accumulation of salts in the root zone, consequently compromising crop yields in the long term [125] [136] • increase use of pesticides and fertilisers affect pollinator [131][133] [135] [132] [140] [141] and natural pest control communities [125] [136] [28] [41] [146] [130], which in turn affect crop productivity [146] [181] [151] [152] [150] [133]	Changes in input-use intensity affect <u>potential crop yield for food crops</u> and <u>potential crop yield for feed crops</u> at the **field and landscape scales**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly: • the use of fertilisers, pesticides, water for irrigation, and energy for field operations and irrigation contributes to increases in crop yields [179][180] [136] [186] [187] [28] [5] [188] [155] • Adjustment of nutrient inputs can improve plant growth which increases organic matter returns to the soil, which in turn can improve soil fertility [136] • increased irrigation contributes to soil degradation, due accumulation of salts in the root zone, consequently compromising crop yields in the long term [125] [136] • increase use of pesticides and fertilisers affect pollinator [131][133] [135] [132] [140] [141] and natural pest control communities [125] [136] [28] [41] [146] [130], which in turn affect crop productivity [146] [181] [151] [152] [150] [133][171]	Changes in input-use intensity affect the <u>landscape educational value</u> at the **landscape scale**, through changes in *human-nature interactions, social relationships*, *human-livestock interactions*, and *ecosystem functioning.* Particularly, the shift from traditional pastoral systems to intensive livestock production with increased use of feed concentrates results in a loss of opportunities for educational activities [183] [137]	Changes in input-use intensity affect the <u>landscape aesthetical value</u> and <u>landscape recreational value</u> at the **landscape scale**, through changes in *human-nature interactions, social relationships, human-livestock interactions, ecosystem functioning* and *habitat-species interactions.*. Particularly, the shift from pastoral systems to intensive livestock production with increased use of feed concentrates reduces the landscape aesthetical and recreational values [183] [137]	Changes in input-use intensity affect the <u>cultural heritage value</u> and <u>landscape spiritual value</u> at the **landscape scale**, through changes in *human-nature interactions, social relationships, human-livestock interactions, ecosystem functioning* and *habitat-species interactions*. Particularly, the shift from pastoral systems to intensive production with increased use of feed concentrates results in the loss of cultural heritage, sense of belonging and connectedness [183] [137]
Farm consolidation	Farm consolidation affects <u>potential bioenergy crop yields</u> at the **field and landscape scales**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly: • increasing field size and farm size enhances the use of machinery, leading to increases in crop productivity [125][5][186] [179][180] • removal of vegetation cover and linear elements affect the ability to regulate the amount, and stability of water flows [125] [146] [164] [155] [172][143] [173][155], which in turn contribute to soil erosion and	Farm consolidation affects <u>potential crop yield for food crops</u> and <u>potential crop yield for feed crops</u> at the **field and landscape scales**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly: • increasing field size and farm size enhances the use of machinery, leading to increases in crop productivity [125] [5][186] [179][180] • removal of vegetation cover and linear elements affect the ability to regulate the amount, and stability of water flows [125] [146] [164] [155] [172][143] [173][155], which in turn contribute to soil erosion and	Farm consolidation affects <u>landscape educational value</u> at the **landscape scale**, through changes in *human-nature interactions* and *social relationships,* and *ecosystem functioning*. Particularly, the homogenisation and fragmentation of the landscape through removal of natural vegetation and landscape elements results in a loss of educational values [5][189] [143] [183] [137]	Farm consolidation affect the <u>landscape aesthetical value</u> and <u>landscape recreational value</u> at the **landscape scale**, through changes in *human-nature interactions, social relationships, ecosystem functioning* and *habitat-species interactions.*. Particularly, the homogenisation and fragmentation of the landscape through removal of natural vegetation and landscape elements reduces the aesthetical and recreational values [5] [155] [172] [151] [189] [143] [183] [137] [7]	Farm consolidation affect <u>cultural heritage value</u> and <u>landscape spiritual value</u> at the **landscape scale**, through changes in *human-nature interactions, social relationships, ecosystem functioning* and *habitat-species interactions*. Particularly, the homogenisation and fragmentation of the landscape through removal of natural vegetation and landscape elements affects the cultural heritage, regional identity, sense of belonging and connectedness [5] [189] [143] [137] [183] [7]

Mechanism of intensity change	NCP 11 - Energy production	NCP 12 - Food and feed production	NCP 15 - Learning and inspiration	NCP 16 - Physical and psychological experiences	NCP 17 - Supporting identities
	waterlogging [125][155] [41] [157] [151][143], leading to reduced crop production [155] [41] • removal of natural vegetation and landscape elements affect pollinator [131][130], [147][148] [132] [133] [149] [150] [135][151] [152] [153] and natural pest control communities [130], [147] [174][175] [176] [170][177] [146][150], which in turn affect crop productivity [146] [181] [151] [152] [150] [133]	waterlogging [125][155] [41] [157] [151][143], leading to reduced crop production [155] [41] • removal of natural vegetation and landscape elements affect pollinator [131][130], [147][148] [132] [133] [149] [150] [135][151] [152] [153] and natural pest control communities [130], [147] [174][175] [176] [170][177] [146][150] [171], which in turn affect crop productivity [146] [181] [151] [152] [150] [133][171]			
Farm specialisation / diversification	Farm specialisation/diversification affects potential bioenergy crop yields at the **field and landscape scales**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly: • Crop specialisation enables higher crop yields and standards of quality and uniformity [5] • crop rotations (including rotations with cover crops and legumes) and mixed systems (arable-livestock, agroforestry) substantially reduce long-term yield losses [98] [151][160] • farm specialization/diversification affect the ability to regulate the amount, and stability of water flows [146][155][136][41][160], which in turn contribute to soil erosion and waterlogging [125] [155] [41] [157] [151][143], leading to reduced crop production [155] [41] • farm specialization/diversification affect pollinator [131] [133] [162] [135] [163][162][132] [137] [156][160] and natural pest control communities [178] [133][28] [155][130] [156] [174][146][160], which in turn affect crop productivity [146] [181] [151] [152] [150] [133]	Farm specialisation/diversification affects potential crop yield for food crops and potential crop yield for feed crops at the **field and landscape scales**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly: • Crop specialisation enables higher crop yields and standards of quality and uniformity [5] • crop rotations (including rotations with cover crops and legumes) and mixed systems (arable-livestock, agroforestry, grasslands with mixed species) substantially reduce long-term yield losses [98] [151][160] [137] • farm specialization/diversification affect the ability to regulate the amount, and stability of water flows [146][155][136][41][160], which in turn contribute to soil erosion and waterlogging [125] [155] [41] [157] [151][143], leading to reduced crop production [155] [41] • farm specialization/diversification affect pollinator [131] [133] [162] [135] [163][162][132] [137] [156][160] and natural pest control communities [178] [133][28] [155][130] [156] [174][146][160], which in turn affect crop productivity [146] [181] [151] [152] [150] [133]	Farm specialisation/diversification affects landscape educational value at the **landscape scale**, through changes in *human-nature interactions, social relationships*, *human-livestock interactions*, and *ecosystem functioning*. Particularly: • transitions from agrosilvopastoral systems to specialised industrial livestock production leads to loss of traditional ecological knowledge [7] • specialisation in local breeds provides educational value in terms breeding and processing skills [183]	Farm specialisation/diversification affects landscape aesthetical value and landscape recreational value at the **landscape scale**, through changes in *human-nature interactions, social relationships, human-livestock interactions, ecosystem functioning* and *habitat-species interactions*.. Particularly, • transitions from agrosilvopastoral systems to specialised livestock production leads to loss of landscape aesthetics [7]. • Mixed farming systems are associated with higher recreational and aesthetical values [155] [151] [125] [130] [156] [137] [143] [189] • specialisation in local breeds enhances the landscape recreational value [183] [190]	Farm specialisation/diversification affects cultural heritage value and landscape spiritual value at the **landscape scale**, through changes in *human-nature interactions, social relationships, human-livestock interactions, ecosystem functioning* and *habitat-species interactions*. Particularly, • transitions from agrosilvopastoral systems to specialised livestock production leads to loss of cultural heritage [7]. • Mixed farming systems are associated with higher recreational and aesthetical values [155] [151] [125] [130] [156] [137] [143] [189] • specialisation in local breeds is associated with cultural heritage (breeding, practices, processing of products, gastronomy, festivals), enhancing regional identiy, sense of belonging and connectedness [183] [190]
Regional specialisation and concentration	Regional specialisation and concentration affects potential bioenergy crop yields at the **landscape scale**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly: • regional specialisation affects the ability of the landscape to regulate the amount, and stability of water flows [146][155][136][41][160], which in turn contribute to soil erosion and waterlogging [125] [155] [41] [157] [151][143], leading to reduced crop production [155] [41]	Regional specialisation and concentration affects potential crop yield for food crops and potential crop yield for feed crops at the **landscape scale**, through changes in *ecosystem functioning*, *biological movements*, *species-habitat interactions* and *biogeochemical cycles*. Particularly: • regional specialisation affect the ability of the landscape to regulate the amount, and stability of water flows [146][155][136][41][160], which in turn contribute to soil erosion and waterlogging [125][155] [41] [157] [151][143], leading to reduced crop production [155] [41]	Regional specialisation affects landscape educational value at the **landscape scale**, through changes in *human-nature interactions, social relationships*, *human-livestock interactions*, and *ecosystem functioning*. Particularly: • transitions from agrosilvopastoral systems to specialised industrial livestock production leads to loss of traditional ecological knowledge [7] • the specialisation in local breeds provides educational value in terms breeding and processing skills ([183]	Regional specialisation and concentration affects landscape aesthetical value and landscape recreational value at the **landscape scale**, through changes in *human-nature interactions, social relationships, human-livestock interactions, ecosystem functioning* and *habitat-species interactions*. Particularly, • transitions from agrosilvopastoral systems to specialised livestock production leads to loss of landscape aesthetics [7]. • Mixed farming landscapes are associated with higher recreational and aesthetical values [155] [151] [125] [130] [156] [137] [143] [189]	Regional specialisation and concentration affects cultural heritage value and landscape spiritual value at the **landscape scale**, through changes in *human-nature interactions, social relationships, human-livestock interactions, ecosystem functioning* and *habitat-species interactions*. Particularly, • transitions from agrosilvopastoral systems to specialised livestock production leads to loss of cultural heritage [7]. • Mixed farming landscapes are associated with higher recreational and aesthetical values [155] [151] [125] [130] [156] [137] [143] [189]

Mechanism of intensity change	NCP 11 - Energy production	NCP 12 - Food and feed production	NCP 15 - Learning and inspiration	NCP 16 - Physical and psychological experiences	NCP 17 - Supporting identities
	• regional specialisation affects pollinator [131] [133] [162] [135] [163][162][132] [137] [156][160] [163] and natural pest control communities [178] [133][28] [155][130] [156] [174][146][160], which in turn affect crop productivity [146] [181] [151] [152] [150] [133] [163] [160]	• regional specialisation affect pollinator [131] [133] [162] [135] [163][162][132] [137] [156][160] [163] and natural pest control communities [178] [133][28] [155][130] [156] [174][146][160], which in turn affect crop productivity [146] [181] [151] [152] [150] [133] [163] [160]		• specialisation in local breeds enhances the landscape recreational value [183] [190]	• specialisation in local breeds is associated with cultural heritage (breeding, practices, processing of products, gastronomy, festivals), enhancing regional identiy, sense of belonging and connectedness [183] [190]

Appendix C. Identifying the effects of agricultural intensity change on sustainability outcomes in Europe (Step 3)

The effects of agricultural intensity change on sustainability outcomes in Europe were identified through literature review combined with deductive content analysis [123]. We searched on Scopus and ISI Web of Knowledge for peer-reviewed articles and reports describing how different intensification mechanisms affect sustainability outcomes in Europe. We used the SDG framework as a heuristic for defining the keyword search strings for sustainability outcomes. Similarly to Blicharska et al. [191] and McElwee et al. [192], search strings were tailored to each SDG, rather than using terminology strictly taken from the SDG framework (for example, "income" and "poverty", rather than "SDG 1" or "End poverty"). In particular, for each SDG we adopted keywords listed in the SDG literature search queries developed by the Aurora Universities Network [193]. For an overview of the search strings used in the literatures searches, see Table C.1.

Table C.1: Search strings used for literature searches on the effects of agricultural intensity change on SDG-related sustainability outcomes in Europe

SDG	Search string
SDG 1 – No Poverty	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND (income OR poverty)
SDG 2 – Zero Hunger	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND (hunger OR "food security")
SDG 3 – Good health and wellbeing[2]	(agricultur* AND europe* AND (intensity OR intensif* OR intensive))) AND ("human health" OR "mental health" OR "wellbeing" OR "well-being" OR "mortality" OR "death*" OR "illness" OR "injury" OR "suicide*")
SDG 5 – Gender equality	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND ("gender" OR "gender equality" OR "gender inequality" OR ((women OR female OR sexual) AND discrimination) OR ((women OR female) AND (("household work" OR "domestic work" OR "unpaid work") OR ("equal opportunities" OR "unequal opportunities"))))
SDG 6 – Clean water	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND ("drinking water" OR "water pollution" OR "water contamination" OR "water availability" OR "water scarc*" OR "water short*")
SDG 7 – Clean Energy	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND ("energy security" OR (energy AND (affordab* OR reliab* OR renewable*)))
SDG 8 – Decent work and economic growth	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND ("economic growth" OR GDP OR "gross domestic product" OR job* OR touris* OR employment OR unemployment OR (rights AND (worker* OR labour OR labor)) OR "migrant worker*" OR "seasonal worker*" OR "forc* labo*" OR "human traffic*" OR slave*)
SDG 10 – Reduced inequalities	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND ("income* equal*" OR "income* inequal*" OR "income* distribution")
SDG 11 – Sustainable communities	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND (settlement* OR housing OR heritage OR "air quality" OR "population growth" OR "migration")
SDG 12 – Responsible consumption and production	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND ((sustainab* AND (consum* OR produc*)) OR "footprint") AND ("animal welfare")
SDG 13 – Climate action	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND ("climat* change" OR "global warming" OR "greenhouse gas*" OR GHG*)
SDG 15 – Life on land	(agricultur* AND europe* AND (intensity OR intensif* OR intensive)) AND (biodiversity OR forest* OR deforest* OR "land degradation")

The search results of the two databases were then merged, and duplicates were removed. The selection of articles was then narrowed down after screening for their title, abstract and full texts. The following eligibility criteria were applied:

- Peer-reviewed and in English language;
- describe cases where a mechanism of intensity change identified in Table A.1 affected the a sustainability outcome related to an SDG;
- refer to cases occurring in Europe (including trans-continental and global studies in which European cases are described).

[2] SDG 3 was supplemented with searches on PubMed, to obtain a more comprehensive coverage of health-related literature

The snowballing technique was then used whenever the cases identified in the selected articles did not provide enough information to fully infer on the mechanism of intensity change and/or on the respective effects on sustainability outcomes. The academic database searches were then supplemented by searches for grey literature via web search engines and organisational websites. Finally, the authors checked their own collections for eligible papers to supplement the automatic search. We read each selected case/article several times, and iteratively identified through deductive content analysis the sets of sustainability attributes affected by the mechanisms of intensity change identified in Step 2 (Table A.1.). In particular, the attributes were identified by using the SDG goals and targets as a pre-defined set of categories for identifying condensed meaning units (i.e. a description of a particular effect of agricultural intensity change on sustainability outcomes) and respective codes (i.e. the attributes of sustainability mentioned in the condensed meaning units). We iteratively defined sets of attributes, scales and socio-ecological processes based on recurrent combinations of condensed meaning units and codes. The results of the literature review were then coded in a matrix mapping the effects of each intensity change mechanism on each sustainability dimension (i.e. SDG). In particular, for each cell we describe the effects, and the attributes of sustainability that are affected by a particular intensity change mechanism, the scale at which they are affected, and the socio-ecological processes through which they are affected. These results are presented in Tables C.2, C.3 and C.4, with the respective references. Based on these results, for each *Sustainability outcome* theme and sub-theme, we defined a set of key attributes as indicators (Table 4 in the main text).

Table C.2: Effects of mechanisms of agricultural intensity change on sustainability outcomes related to SDG 1 (End poverty), SDG 2 (Zero hunger), SDG 3 (Health and well-being) and SDG 5 (Gender equality) in Europe. For each sustainability theme, the affected attributes are underlined, the levels and/or scales at which they are affected are in **bold**, and the socio-ecological processes through which they are affected are in *italics*.

Mechanism of intensity change	1 NO POVERTY	2 NO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY
Land management intensification	Changes in land management intensity affect income level, income stability; farm viability, farm adaptability at the **farm level and regional scale**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. Particularly: • changes in agronomic productivity, efficiency and profitability affect net revenues, and consequently income levels and farm viability (see in Table A.1 for references on land management intensity) • in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or increased costs to maintain it [194][125][146] • higher variable costs resulting from more intensive land management may contribute to increased exposure to external shocks (e.g. price fluctuations of agricultural commodities inputs, extreme events and crop failures)[146][194]	Changes in land management intensity affect food availability, food affordability, food self-sufficiency, food supply stability, food safety and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • increased agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability, affordability and supply stability in distant regions connected through trade flows [195] [196] [197] [198] • more intensive production makes the food system more vulnerable to shocks (e.g. price fluctuations of agricultural commodities inputs, extreme events and crop failures), potentially affecting food availability, affordability, and supply stability in the short-term [199] • in the long term, negative effects on regulating and material ES (see Appendix B.2) may lead to lower productivity and/or increased costs to maintain it, thus affecting food availability, affordability and supply stability [194][125][146] • High livestock density, and resulting concentration of waste, creates favourable conditions for pathogens to adapt and spread at a rapid pace, contribute to the outbreak of zoonotic animal diseases, which can passed to humans through food consumption, thus affecting food safety [200][201][202]	Changes in land management intensity affect mental health, physical injuries, occupational risk of respiratory illnesses and occupational exposure to zoonotic diseases at the **farm level**, through changes in *social relationships*, *livestock-human interactions*, *pollutant flows* and *pathogens flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • High livestock density and resulting concentration of waste, creates favourable conditions for pathogens to adapt and spread at a rapid pace, contribute to the outbreak of zoonotic animal diseases, which can passed to workers interacting with the animals [204] [205] • High livestock density leads to higher emission of harmful gases (e.g. ammonia), organic dust and fine particles, increasing the risk of chronic and acute respiratory illnesses [204] [206] [207] [205] [155] • More time spent in field operation leads to more isolation, increasing risk of depression for farmers and households [208] • Farm workers – and particularly seasonal and migrant workers with poor training – face some of the highest risks of physical injury relating to equipment use in field operations and livestock handling, with fatalities primarily occurring due to machinery-related incidents [200] • heavy orkload due to more frequent field operation may lead to lack of free time and overwork-related stress affecting mental health of farmers and workers [209] [210][208] [203][211][212][200] Changes in land management intensity affect environmental exposure to pesticides, exposure to nitrates in drinking water, environmental risk of respiratory illnesses and environmental exposure to zoonotic diseases at the **community level**, through changes in *pollutant flows, pathogens flows* and water flows. Particularly: • High livestock density and resulting concentration of waste, creates favourable conditions for pathogens to adapt and spread at a rapid pace, contributing to the outbreak of zoonotic animal diseases, which can be passed to surrounding communities through airborne particulate matter carried by the wind [204] [205]	

Mechanism of intensity change	1 NO POVERTY	2 NO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY
			• High livestock density leads to higher emission of harmful gases (e.g. ammonia), organic dust and fine particles, increasing the risk of chronic and acute respiratory illnesses to surrounding rural communities [204][206] [207] [205][155] • High livestock density leads to increased manure production, potentially leading to high concentration of nitrates in surrounding freshwater resources used as drinking water, potentially causing health issues in rural communities [213][200][214] Changes in land management intensity affect prevalence of food-borne diseases at the **regional scale**, through *commodity flows*. • High livestock density, and resulting concentration of waste, creates favourable conditions for pathogens to adapt and spread at a rapid pace, contribute to the outbreak of zoonotic animal diseases, which can passed to humans through food consumption [200][201][202]	
Capital intensity	Changes in capital intensity affect income level, income stability; farm viability, farm adaptability and farm autonomy at the **farm level and regional scale**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. Particularly: • changes in agronomic productivity, efficiency and/or profitability affect net revenues, and consequently income levels and farm viability (see Table A.1 for references on capital intensity) • in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or increased costs to maintain it [194][125][146] • Higher fixed and variable costs resulting from high capital intensity may contribute to increased exposure to external shocks (e.g. price fluctuations of agricultural commodities and inputs, extreme events and crop failures) [146][194] [5][55] [54] [6][215]	Changes in capital intensity affect food availability, food affordability, food self-sufficiency, supply stability and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • Increased agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [196] [197] [216] [198] • more intensive production makes the food system more vulnerable to shocks (e.g. price fluctuations of agricultural commodities inputs, extreme events and crop failures) [199] • in the long term, negative effects on regulating and material ES (see Appendix B.2) may lead to lower productivity and/or increased costs to maintain it, thus affecting food availability, affordability and supply stability [194][125][146] • Large herd sizes confined in stables, and resulting concentration of waste, creates favourable conditions for pathogens to adapt and spread at a rapid pace, contribute to the outbreak of zoonotic animal diseases, which can passed to humans through food consumption, thus affecting food safety [200][201][202]	Changes in capital intensity affect mental health, physical injuries, occupational risk of respiratory illnesses and occupational exposure to zoonotic diseases at the **farm level**, through changes in *social relationships*, *livestock-human interactions*, *monetary flows*, *pollutant flows* and *pathogens flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • High levels of indebtedness resulting from investments on capital assets, coupled with irregular cash flows and volatile crop and input prices, and problems with machinery malfunction and animal health, may cause psychological distress and mental health disorders on farmers and their families [209], [217].[210][218] [208][203][200] • Increased mechanisation may lead to more isolation, increasing risk of depression for farmers and households [208] • greenhouse workers are more exposed by potential risks to their health, including heat stress, noise, lighting, and poor ventilation [219] • large herd sizes confined in stables, and resulting concentration of waste, creates favourable conditions for pathogens to adapt and spread at a rapid pace, contribute to the outbreak of zoonotic animal diseases, which can passed to workers interacting with the animals [204] [205] • Large herd sizes confined in stables leads to higher emission of harmful gases (e.g. ammonia), organic dust	Changes in capital intensity affect women unemployment and women migration at the **regional scale**, through changes in *social relationships* and *migration flows*. Particularly, the increase in rural unemployment due to substitution of labour by capital, combined with unbalanced responsibilities in terms of household caring duties, results in both higher unemployment and migration rates for women in rural communities. [220]–[223].

Mechanism of intensity change	1 NO POVERTY	2 NO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY
			and fine particles, increasing the risk of chronic and acute respiratory illnesses [204][206] [207] [205] [155] • Farm workers – and particularly seasonal and migrant workers with poor training – face some of the highest risks of physical injury relating to equipment use in field operations and livestock handling, with fatalities primarily occurring due to machinery-related incidents [200] Changes in capital intensity affect exposure to nitrates in drinking water, environmental risk of respiratory illnesses and environmental exposure to zoonotic diseases at the **community level**, through changes in *pollutant flows*, *pathogens flows* and *water flows*. Particularly: • large herd sizes confined in stables, and resulting concentration of waste, creates favourable conditions for pathogens to adapt and spread at a rapid pace, contributing to the outbreak of zoonotic animal diseases, which can be passed to surrounding communities through airborne particulate matter carried by the wind [204] [205] • large herd sizes confined in stables leads to higher emission of harmful gases (e.g. ammonia), organic dust and fine particles, increasing the risk of chronic and acute respiratory illnesses to surrounding rural communities [204][206][207] [205][155] • large herd sizes confined in stables lead to increased manure production, potentially leading to high concentration of nitrates in surrounding freshwater resources used as drinking water, potentially causing health issues in rural communities [213][200][214] Changes in capital intensity affect prevalence of food-borne diseases at the **regional scale**, through *commodity flows*. • large herd sizes confined in stables, and resulting concentration of waste, creates favourable conditions for pathogens to adapt and spread at a rapid pace, contribute to the outbreak of zoonotic animal diseases, which can passed to humans through food consumption [200][201][202]	
Input-use intensity	Changes in input-use intensity affect income level, income stability; farm viability, farm adaptability and farm autonomy at the **farm level and regional scale**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. Particularly: • changes in agronomic productivity, efficiency and/or profitability affect net revenues, and consequently income levels and farm viability (see Table A.1 for references on input-use intensity)	Changes in input-use intensity affect food availability, food affordability, food self-sufficiency, supply stability, food safety, nutrition security and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • Increased agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and	Changes in input-use intensity affect mental health, physical injuries, occupational exposure to pesticides occupational risk of respiratory illnesses and occupational exposure to zoonotic diseases at the **farm level**, through changes in *social relationships*, *livestock-human interactions*, *monetary flows*, *pollutant flows* and *pathogens flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203]	

Mechanism of intensity change	1 NO POVERTY	2 NO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY
	• in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or increased costs to maintain it [194][125][146] • Higher variable costs resulting from more intensive input-use may contribute to increased exposure to external shocks (e.g. price fluctuations of agricultural commodities and consumable inputs, extreme events and crop failures)[146][194] [5][55] [54] [6][215] [156] [224] [225] [226] [215] • Conversely, modest and targeted use of inputs and/or optimizing use of on-farm available resources (e.g. nutrients from manure, home-grown feed production) may improve average productivity, income stability and farm autonomy in the long-term [187] [188][227]	affordability in distant regions [195] [196] [197] [216] [198] • more intensive production makes the food system more vulnerable to shocks (e.g. price fluctuations of agricultural commodities inputs, extreme events and crop failures) [199] • in the long term, negative effects on regulating and material ES (see Appendix B.2) may lead to lower productivity and/or increased costs to maintain it, thus affecting food availability, affordability and supply stability [194][125][146] • increased use of imported feed for meat and milk production affects self-sufficiency in import countries, and nutrition security in export countries [155] [188][228] [197], [229] • fatty acid composition and antioxidant content of meat and milk from grass fed systems are more favourable for human health than from systems based on intensive use of feed inputs [188][155] • use of fertilisers, pesticides and animal health inputs (vaccination, antibiotics and medicines animal diseases) affects food safety by increasing exposure to heavy metals and toxic chemical residues, and promoting antimicrobial resistance [136] [201][200] [230] [231] [232][233] [234] [235] [236][227]	• Increased health risks (dermatological, gastrointestinal, neurological, carcinogenic, respiratory, reproductive, and endocrine effects) and mortality for farmers, workers and their families (including spontaneous abortions) due to acute accidental exposure through unintentional pesticide poisoning, and chronic occupational exposure during preparation, storage and application of pesticides, or by contact with pesticide residues on the crop or soil, and cleaning-up of spraying equipment [237] [234], [238] [231] • Increased use of antibiotics in livestock production may promote antibiotic-resistant bacteria, potentially leading to the outbreak of zoonotic diseases affecting farm workers [204] [205] [204] [206][227] Changes in input-use intensity affect <u>environmental exposure to pesticides</u>, <u>exposure to nitrates in drinking water</u>, and <u>environmental exposure to zoonotic diseases</u> at the **community level**, through changes in *pollutant flows*, *pathogens flows* and *water flows*. Particularly: • Increased health risks of rural communities due to increased environmental exposure to pesticides (particularly women and children - accumulation in adipose tissue, leading to breast cancer and toxic levels in breastfeeding milk), as a result of pesticide drift to surrounding residential areas and contamination of drinking water sources [231][239] [240][241][242] [243], [244] • Increased health risks of rural communities (birth defects, infant methemoglobinemia, endocrine, neurological and carcinogenic effects) due to increased exposure to nitrates in public drinking water, as a result of increased use and runoff of inorganic fertilisers and manure [245][200] [213].[200][214] • Increased use of antibiotics in livestock production may promote antibiotic-resistant bacteria, potentially leading to the outbreak of zoonotic diseases, which can be passed to surrounding communities through airborne particulate matter carried by the wind [204] [205] [204] [206][227] • The application of manure and sewage sludge introduces antibiotics from veterinary and human medicines, which can then be leached to drinking water sources, potentially leading to the development of antibiotic-resistant bacteria affecting surrounding communities [125] [155] • Increased application of manure and phosphate fertilizer can lead to increased health risks (e.g. cancer) due to environmental exposure in drinking water to toxic levels of heavy metals (mercury, copper, zinc) [235] [236][200]	

Mechanism of intensity change	1 NO POVERTY	2 NO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY
			Changes in input-use intensity affect dietary exposure to pesticide residues and heavy metals and prevalence of food-borne diseases at the **regional scale**, through *commodity flows*. Particularly: • Increased use of pesticides can lead to acute and chronic health risks to consumers due dietary exposure to pesticide residues in processed and unprocessed food [231]–[234] • Increased use of manure and phosphate fertilizer can lead to increased health risks (e.g. cancer) due to dietary exposure to toxic levels of heavy metals (mercury, copper, zinc, cadmium) in food consumption [230][235][236][200] • Increased use of antibiotics in livestock production may promote antibiotic-resistant bacteria, potentially leading to the outbreak of zoonotic diseases, which can be passed to consumers through food consumption [227]	
Labour intensity	Changes in labour intensity affect income level, income stability, farm viability and farm adaptability at the **farm level and regional scale**, and poverty at the **regional scale**, through changes in *commodity flows* and *monetary flows*. Particularly: • Adjustments in hired and family labour change agronomic productivity, efficiency and/or profitability, thus affecting net margins, and consequently income levels and farm viability (see Table A.1 for references on labour intensity) • Farms with larger requirements for hired labour are more dependent on labour availability and developments in the labour market [221] • technology-oriented agriculture leads to higher labour costs, due to requirements for highly-skilled labour [221] • seasonality of work represents higher risk of poverty for farm workers [222]	Changes in labour intensity affect food availability, food affordability, food self-sufficiency, supply stability and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • Increased agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [196] [197] [216] [198] • more intensive production makes the food system more vulnerable to shocks (e.g. price fluctuations of agricultural commodities and inputs, disruptions in labour availability, extreme events and crop failures) [199]	Changes in labour intensity affect mental health and physical injuries at the **farm level**, through changes in *social relationships*, *livestock-human interactions*, and *monetary flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • Farm workers – and particularly seasonal and migrant workers with poor training – face some of the highest risks of physical injury relating to equipment use in field operations and livestock handling [200] • greenhouse workers are more exposed by potential risks to their health, including heat stress, noise, lighting, and poor ventilation [219] • Heavy workload may lead to lack of free time and overwork-related stress affecting mental health of farmers and workers [209] [210][208] [203][211][212][200]	Changes in labour intensity affect women unemployment and women migration at the **regional scale**, through changes in *social relationships* and *migration flows*. Particularly, the increase in rural unemployment due to substitution of labour by capital, combined with unbalanced responsibilities in terms of household caring duties, results in both higher unemployment and migration rates for women in rural communities. [220]–[223]
Farm consolidation	Farm consolidation affects income level, income stability, farm viability, farm adaptability and farm autonomy at the **farm level and regional scale**, through changes in *commodity flows* and *monetary flows*. • changes in agronomic productivity, efficiency and/or profitability affect net revenues, and consequently income levels and farm viability (see Table A.1 for references on farm consolidation) • in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or increased costs to maintain it [194][125][146] • Larger farm sizes are more likely to be viable [215] [156] [246] [224] [215] [55], while small-scale traditional farms are more adaptable and can better cope with external shocks (e.g. price fluctuations of agricultural	Farm consolidation affects food availability, food affordability, food self-sufficiency, supply stability, nutrition security and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • Increased agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [196] [197] [198] • more intensive production makes the food system more vulnerable to shocks (e.g. price fluctuations of agricultural commodities inputs, extreme events and crop failures) [199] • in the long term, negative effects on regulating and material ES (see Appendix B.2) may lead to lower	Farm consolidation affects mental health at the **farm level**, through changes in *social relationships*, *human-nature interactions*, and *monetary flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • diverse, aesthetically attractive landscapes provide well-being to farmers and visitants [248]	Farm consolidation affects women unemployment and women migration at the **regional scale**, through changes in *social relationships* and *migration flows*. Particularly, the increase in rural unemployment due to farm consolidation, combined with unbalanced responsibilities in terms of household caring duties, results in both higher unemployment and migration rates for women in rural communities. [220]–[223]

Mechanism of intensity change	1 NO POVERTY	2 NO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY
	commodities and consumable inputs, extreme events and crop failures) than modern intensive farms [186]	productivity and/or increased costs to maintain it, thus affecting food availability, affordability and supply stability [194][125][146] • increases in farm size and field size often results in a shift from crops that are more suitable to be grown in smaller plots (e.g. vegetables, fruits, and some roots and tubers) to crops that are more easily cultivated with mechanised techniques (cereals, sugar and oil crops), thus potentially decreasing the supply of highly nutritious food groups [247].		
Farm specialisation / diversification	Farm specialisation/diversification affects income level, income stability, farm viability, farm adaptability and farm autonomy at the **farm level and regional scale**, through changes in *commodity flows* and *monetary flows*. Particularly: • Changes agronomic productivity, efficiency and/or profitability due to specialisation/diversification affect net margins, and consequently income levels and farm viability (see Table A.1 for references on farm specialisation/diversification) • in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or increased costs to maintain it [194][125][146] [249] • specialisation in limited number of activities may contribute to increased vulnerability to external shocks (e.g. price volatility, extreme events) and reduced adaptability [249] [194][125][146] [5][55][215] [92] • diversified farms can better adapt to external shocks [186] [249][160] • complementary activities may lead to reduction of marginal costs, and consequently increase net income levels, farm stability and/or farm autonomy [221] [156] [6]	Farm specialisation/diversification affects food availability, food affordability, food self-sufficiency, supply stability, nutrition security and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • structural changes in agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [197] • more specialised food production leads to more homogeneous food supplies worldwide (thus affecting food nutrition), decreases self-sufficiency, and makes the food system more vulnerable to shocks (e.g. price fluctuations of agricultural commodities inputs, extreme events and crop failures) [199] [247], [250], [251][252], particularly due to changing risks of synchronous crop failures in breadbasket regions [253], [254] • in the long term, effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or on the costs to maintain it, thus affecting food availability, affordability and supply stability [194][125][146] • countries/regions that diversify in a coherent way improve their self-sufficiency and food security, but at the expense of global crop production efficiency [252]	Farm specialisation/diversification affects mental health at the **farm level**, through changes in *social relationships*, *human-nature interactions*, and *monetary flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • diverse, aesthetically attractive landscapes provide well-being to farmers and visitants [248] • specialised farms are less able to accommodate external shocks, and the resulting financial constraints increase risk of depression and suicide rate [218]	
Regional specialisation and concentration	Regional specialisation and concentration affects income level, income stability, farm viability, farm adaptability and farm autonomy at the **regional scale**, through changes in *commodity flows* and *monetary flows*. Particularly: • Increased economic productivity and profitability due to cost savings resulting from agglomeration economies may lead to higher net revenues, and consequently higher income levels and farm viability (see references for regional specialisation and concentration in Table A.1) • in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or increased costs to maintain it [194][125][146][249]	Regional specialisation and concentration affects food availability, food affordability, food self-sufficiency, supply stability, nutrition security and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • structural changes in agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [197] [198] • structural specialisation of food production leads to more homogeneous food supplies worldwide (thus affecting food nutrition), decreases self-sufficiency, and makes the	Regional specialisation and concentration affects mental health at the **farm level**, through changes in *social relationships*, *human-nature interactions*, and *monetary flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • diverse, aesthetically attractive landscapes provide well-being to farmers and visitants [248] • specialised farms are less able to accommodate external shocks, and the resulting financial constraints increase risk of depression and suicide rate [218]	

Mechanism of intensity change	1 NO POVERTY	2 NO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY
	• moderate sectoral specialisation in a region may be beneficial for income levels, stability and farm viability, while high specialisation may have a negative effect due to competitive pressures [215] • diversified farms within a specialised region can better adapt to external shocks (e.g. price fluctuations of agricultural commodities and consumable inputs, extreme events and crop failures) [186] [249][160]	food system more vulnerable to shocks (e.g. price fluctuations of agricultural commodities inputs, extreme events and crop failures) [199] [247], [250], [251][252], particularly due to changing risks of synchronous crop failures in breadbasket regions [253], [254] • countries/regions that diversify in a coherent way improve their self-sufficiency and food security, but at the expense of global crop production efficiency [252] • in the long term, effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or on the costs to maintain it, thus affecting food availability, affordability and supply stability [194][125][146]		
Vertical integration	Vertical integration affects income level, income stability, farm viability, farm adaptability and farm autonomy at the **farm level and regional scale**, through changes in *commodity flows* and *monetary flows*. Particularly, the degree to which farms are engaged with short marketing channels, agrofood industries (e.g. through supply of inputs, product sales and contract farming), product processing/marketing, and by-product valorisation, affects net revenues, and consequently income levels and farm viability, and ability to adjust to external shocks (see in Table A.1 for references on vertical integration)	Vertical integration affects food availability, food affordability, food self-sufficiency, supply stability, and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • structural changes in agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [197]	Vertical integration affects mental health at the **farm level**, through changes in *social relationships*, and *monetary flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • Increased paperwork involved in contracts is a source of stress [210], [218][208] [203] [212]	
Knowledge intensification	Changes in knowledge intensity affects income level, income stability, farm viability, farm adaptability and farm autonomy at the **farm level and regional scale**, through changes in *commodity flows* and *monetary flows*. Particularly, education levels and usage of extension services are associated with higher and more stable income levels, and vice-versa [55] [225] [92](see also Table A.1 for references on knowledge intensity)	Changes in knowledge intensity affects food availability, food affordability, food self-sufficiency, supply stability, and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • changes in agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [197]	Changes in knowledge intensity affect mental health at the **farm level**, through changes in *social relationships*, and *monetary flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203]	
Improved information management	Improved information management affects income level, income stability, farm viability, farm adaptability and farm autonomy at the **farm level and regional scale**, through changes in *commodity flows* and *monetary flows*. Particularly: • the use of ICT enables to increase net revenues by making more efficient use of resources, inputs and labour, and reducing weather risks [53][226] (see also Table A.1 for references on improved information management) • high investment costs may lead to high indebtedness, thus affecting farm autonomy [54]	Improved information management affects food availability, food affordability, food self-sufficiency, supply stability, food safety and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • structural changes in agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [197] [198] • reduced use of inputs enabled by precision farming contributes to food safety [255]	Improved information management affects mental health at the **farm level**, through changes in *social relationships*, and *monetary flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • precision farming can reduce mental workload, thus reducing stress [256]	
Crop/breed change and	Crop/breed change and product differentiation affects income level, income stability, farm viability, farm adaptability and farm autonomy at the **farm level and**	Crop/breed change and product differentiation affects food availability, food affordability, food self-sufficiency, supply stability, food safety and overall food security at the	Crop/breed change and product differentiation affects mental health at the **farm level**, through changes in *social relationships*, and *monetary flows*. Particularly:	

Mechanism of intensity change	1 NO POVERTY	2 NO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY
product differentiation	**regional scale**, through changes in *commodity flows* and *monetary flows*. Particularly: • changes in agronomic productivity, efficiency and/or profitability affect net revenues, and consequently income levels and farm viability (see Table A.1 for references on crop/breed change and product differentiation) • niche/labelled product may allow for higher net revenues with lower yields [246] [186] [257][156][188]	**regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • structural changes in agronomic productivity, efficiency, profitability and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [197][246] [188] [198] • reduced use of inputs enabled by organic farming contributes to food safety [255]	• Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • Increased paperwork, forms and legislation due to certification is a source of stress [210], [218][208] [203] [212]	
Income diversification	Income diversification affects income level, income stability, farm viability, farm adaptability and farm autonomy at the **farm level and regional scale**, through changes in *commodity flows* and *monetary flows*. Particularly: • Complementary non-farming activities on and off the farm reduce vulnerability to external shocks (e.g. price fluctuations of agricultural commodities and consumable inputs, extreme events and crop failures), thus increasing farm stability and adaptability [221] [156] [225] [258] [101] [92] (see also Table A.1 for references on income diversification) • financial support (e.g. CAP subsidies) may secure income stability, farm viability and adaptability in the short-term, but in the long-term in decreases farm autonomy [186] [6][55] [225] [259] [7]	Income diversification affects food availability, food affordability, food self-sufficiency, supply stability, and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • structural changes in agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [197]	Income diversification affects mental health at the **farm level**, through changes in *social relationships*, and *monetary flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • Increased paperwork, forms and legislation (e.g. for applying for subsidy schemes) is a source of stress [210], [218] [210], [218][208] [203] [212]	
Cooperation	Cooperation affects income level, income stability, farm viability, farm adaptability and farm autonomy at the **farm level and regional scale**, through changes in *commodity flows* and *monetary flows*. Particularly: • Participation in farming associations contributes to improve access to funding, reduce costs related to red tape and bureaucracy [260] [261], and to learn/adopt improved technologies and market opportunities [262] [226] [225]. • Informal labour- and resource-sharing systems allow small farms to remain viable [6]	Cooperation affects food availability, food affordability, food self-sufficiency, supply stability, and overall food security at the **regional scale** and in **distant regions**, through changes in *material ES*, *regulating ES*, *commodity flows* and *monetary flows*. • structural changes in agronomic productivity, efficiency and stability of production within a region contributes to food availability, affordability, supply stability and self-sufficiency within a region, and food availability and affordability in distant regions [195] [197] [198]	Cooperation affects mental health at the **farm level**, through changes in *social relationships*, and *monetary flows*. Particularly: • Farmers that are able to successfully increase production are more satisfied with their working day and income and more determined to continue production [203] • Participation in social networks promotes farmers health and well-being by addressing helplessness, hopelessness, stress, burnout, avoiding social isolation and promoting self-efficacy [260][208], [211], [212], [218]	

Table C.3: Effects of mechanisms of agricultural intensity change on sustainability dimensions related to SDG 6 (Clean water and sanitation), SDG 7 (Affordable and clean energy), SDG 8 (Decent work and economic growth) and SDG 10 (Reduced inequality) in Europe. For each sustainability dimension, the affected attributes are underlined, the levels and/or scales at which they are affected are in **bold**, and the socio-ecological processes through which they are affected are in *italics*.

Mechanism of intensity change	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	10 REDUCED INEQUALITIES
Land management intensity	Changes in land management intensity affect freshwater quantity and freshwater quality at the **landscape and regional scales**, through changes in *water flows*, *pollutant flows*, *pathogen flows* and *ES regulating water and soil*. Particularly: • Increased livestock density leads to higher production of manure and soil compaction, leading to emission and deposition of ammonia, as well as run-off and leaching of nutrients and sediments into local and downstream surface freshwater bodies and groundwater aquifers, decreasing water quality as a result of eutrophication, acidification, presence high nitrate concentration levels, sedimentation of reservoirs, residues of veterinary medicines, bacteria and soil colloids [213][263] [125] [136][200] [155] [41] [188] [159] • Soil drainage and soil compaction due to more frequent field operations with machinery, promote run-off and leaching of nitrogen and other water-soluble compounds (e.g. pesticides) to watercourses, thus leading to deterioration of water quality [125] • soil drainage leads to sedimentation of water reservoirs, contributing to reduced water storage capacity [125]	Changes in land management intensity affect energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264] • in the long term, effects on regulating and material ES (see Appendix B.2) may changes in productivity and/or increased costs to maintain it [194][125][146], thus affecting energy security	Changes in land management intensity affect economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES*. Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [221], [265] [183] [7] • in the long term, effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or increased costs to maintain it, [194][125][146], thus affecting agricultural economic output • Effects on non-material ES may have an impact on the tourism sector in the region [5] [126] [41][166] [156] [127] [139][137] [7] [183] • Agricultural abandonment decreases the economic output of agricultural and employment opportunities in the region[182][221] • Conversely, rewilding of abandoned areas can lead to increased recreation value due to the return of species benefitting from abandonment (e.g. large mammals such as wolves and bears), therefore increasing tourism [182]	Changes in land management intensity affect income inequality, income stability, farm adaptability and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES and material ES*. Particularly: • negative effects on regulating and material ES resulting from intensive land management (see Appendix B.2) in large farms may be externalised to surrounding smallholder farms with less capacity to adapt. [146]
Capital intensity	Changes in capital intensity affect freshwater quality at the **landscape and regional scales**, through changes in *water flows*, *pollutant flows*, *pathogen flows* and *ES regulating water and soil*. Particularly: • Large herd sizes confined in stables leads to higher production of manure leading to emission and deposition of ammonia, as well as run-off and leaching of nutrients into local and downstream surface freshwater bodies and groundwater aquifers, decreasing water quality as a result of eutrophication, acidification, presence high nitrate concentration levels, sedimentation of reservoirs, residues of veterinary medicines, and bacteria [213][263] [125] [136][200] [155] [41] [188][213][263] [125] [136][200] [155] [41] [188] [159] • Soil compaction due to use of heavy machinery promotes run-off and leaching of nitrogen and other water-soluble compounds (e.g. pesticides) to watercourses, thus leading to deterioration of water quality [125]	Changes in capital intensity affect energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264] • in the long term, effects on regulating and material ES (see Appendix B.2) may changes in productivity and/or increased costs to maintain it [194][125][146], thus affecting energy security	Changes in capital intensity affect economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES*. Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [221], [265] [183] [7] • the substitution of labour by capital (e.g. due to mechanisation) may contribute to a loss of job opportunities in a region [221] [222] [7] • in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or increased costs to maintain it,	Changes in capital intensity affect income inequality, income stability, farm adaptability, farm autonomy and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly • Higher fixed and variable costs resulting from high capital intensity may contribute to increased exposure to external shocks (e.g. price fluctuations of agricultural commodities and inputs, extreme events and crop failures), particularly for small farms under competitive pressures in a region [146][194] [5][55] [54] [6][215][266] [267] • negative effects on regulating and material ES resulting from capital intensification (see Appendix B.2) in large farms may be externalised to surrounding small farms with less capacity to adapt. [146] • small farms in a region may not be able to remain viable given the inability to compete with larger capital-

Mechanism of intensity change	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	10 REDUCED INEQUALITIES
			[194][125][146], thus affecting agricultural economic output • Effects on non-material ES have an impact on the tourism sector in the region [41] [127][5][126][41] [143][184] [137][183]	intensive farms driving commodity prices down [222] [55] [53] [223] [266] [267] • small farmers are more likely to have credit constraints, which often impedes investments on capital assets [223]
Input-use intensity	Changes in input-use intensity affect freshwater availability and freshwater quality at the **landscape and regional scales**, through changes in *water flows*, *pollutant flows*, *pathogen flows* and *ES regulating water and soil*. Particularly: • Application of fertilisers, pesticides and antibiotics may lead to deterioration of local and downstream surface freshwater bodies and groundwater aquifers quality due to eutrophication, acidification, high concentration of nitrates, phosphates, toxic chemicals, veterinary medicines and heavy metals [268][269][263][270], [271][159] [125] [136] [155] [41] [188] [272][273] [274] • Nitrogen and phosphorus losses from manure to water bodies can be reduced by tailoring nitrogen and phosphorus content of animal feed [125] • Increased irrigation decreases the availability of water for other human uses, and contributes to decreased water quality of aquifers (e.g. salinization), rivers and wetlands [125] [136] [41]	Changes in input-use intensity affect energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264] • in the long term, effects on regulating and material ES (see Appendix B.2) may changes in productivity and/or increased costs to maintain it [194][125][146], thus affecting energy security	Changes in input-use intensity affect economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES*. Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [221], [265] [183] [7] • in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes in productivity and/or increased costs to maintain it, [194][125][146], thus affecting agricultural economic output • Effects on non-material ES have an impact on the tourism sector in the region [41] [127][5][126][41] [143][184] [137][183]	Changes in input-use intensity affect income inequality, income stability, farm adaptability, and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • negative effects on regulating and material ES resulting from input-use intensification (see Appendix B.2) in large farms may be externalised to surrounding small farms with less capacity to adapt. [146] • Higher variable costs resulting from more intensive input-use may contribute to increased exposure to external shocks (e.g. price fluctuations of agricultural commodities and consumable inputs, extreme events and crop failures), particularly for small farms under competitive pressures in a region [146][194] [5][55] [54] [6][215] [156] [224] [225] [266] [267] • small farms in a region may not be able to remain viable given the inability to compete with larger, more productive input-intensive farms driving commodity prices down [222] [55] [266] [267]
Labour intensity		Changes in labour intensity affect energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *material ES*. Particularly: • Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264]	Changes in labour intensity affect economic output of agriculture, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, and *people movements*. Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [221], [265] [183] [7] • the substitution of labour by capital (e.g. due to mechanisation) may contribute to a loss of employment opportunities [221] [222] [7] • Labour-intensive farms (e.g. fruit and vegetable production) create employment opportunities, with overexploitation, human rights violations, limited health protection, and low wages being often reported [199], [221], [222], [275]–[279] [275], [277], [279]–[281] [222] [282]	Changes in labour intensity affect poverty at the **community level and regional scale**, through changes in *monetary flows*. Particularly: • the restructuration of the farming sector towards decreasing labour inputs, and decreasing wages for seasonal workers are drivers for increased poverty in rural communities, with seasonality of work representing a high risk of social exclusion for farm workers [222] [282]
Farm consolidation	Farm consolidation affects freshwater availability and freshwater quality at the **landscape and regional scales**, through changes in *water flows*, *pollutant flows*, *pathogen flows* and *ES regulating water and soil*. Particularly, the removal of natural vegetation and landscape elements	Farm consolidation affects energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly:	Farm consolidation affect economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES*. Particularly:	Farm consolidation affects income inequality, income stability, farm adaptability, farm autonomy and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly:

Mechanism of intensity change	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	10 REDUCED INEQUALITIES
	decreases the filtration and water-holding capacity of the landscape [125] [146][164] [155] [172][143] [173] [159] [151] [172]	• Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264] • in the long term, effects on regulating and material ES (see Appendix B.2) may changes in productivity and/or increased costs to maintain it [194][125][146], thus affecting energy security	• changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [221], [265] [183] • in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes productivity and/or increased costs to maintain it, [194][125][146], thus affecting agricultural economic output • Effects on non-material ES have an impact on the tourism sector in the region [5][189] [143] [183] [137] [155] [172] [151] [7]	• Larger farm sizes are more likely to be viable [215] [156] [246] [224] [215] [55] [267], while small-scale traditional farms are more adaptable and can better cope with external shocks (e.g. price fluctuations of agricultural commodities and consumable inputs, extreme events and crop failures) than modern intensive farms [186] [267] • negative effects on regulating and material ES resulting from farm consolidation (see Appendix B.2) in large farms may be externalised to surrounding small farms with less capacity to adapt. [146] • small farms in a region may not be able to remain viable given the inability to compete with larger e farms driving commodity prices down [222] [55] [223] [266] [267] • small farms are more likely to have credit constraints, which often impedes investments on land [223] • Large farms are often able to influence land rental prices and rental contract conditions, which distorts land markets for land, and may undermine the competitiveness of surrounding small farms[223]
Farm specialisation / diversification	Farm specialisation/diversification affects freshwater availability and freshwater quality at the **landscape and regional scales**, through changes in *water flows*, *pollutant flows*, *pathogen flows* and *ES regulating water and soil*. Particularly, increasing the diversity of plants on the crop rotation and rooting depths increases the filtration and water-holding capacity of the landscape [146][155][136][41][160][137]	Farm specialisation/diversification affect energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264] • in the long term, effects on regulating and material ES (see Appendix B.2) may changes in productivity and/or increased costs to maintain it [194][125][146], thus affecting energy security	Farm specialisation/diversification affect economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES*. Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [43] [221], [265] [183] • in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes productivity and/or increased costs to maintain it, [194][125][146], thus affecting agricultural economic output • Effects on non-material ES having an impact on the tourism sector in the region [7] [183] [155] [151] [130] [156] [137] [143] [189] [190]	Farm specialisation/diversification affects income inequality, income stability, farm adaptability, and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • negative effects on regulating and material ES resulting from farm specialisation (see Appendix B.2) in large farms may be externalised to surrounding small farms with less capacity to adapt [146]. • specialisation in limited number of activities may contribute to increased vulnerability to external shocks (e.g. price volatility, extreme events) and reduced adaptability [249] [194][125][146] [5][55][215] [92] [267] • diversified farms can better adapt to external shocks [186] [249][160] [267]
Regional specialisation and concentration	Regional specialisation and concentration affects freshwater availability and freshwater quality at the **landscape and regional scales**, through changes in *water flows*, *pollutant flows*, *pathogen flows* and *ES regulating water and soil*. Particularly: • increasing the diversity of plants on the crop rotation and rooting depths increases the filtration and water-holding capacity of the landscape [146][155][136][41][160][137] • regional specialisation and concentration of livestock production leads to higher production of manure and soil compaction, leading to emission and deposition of	Regional specialisation and concentration affect energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264] • in the long term, effects on regulating and material ES (see Appendix B.2) may changes in productivity and/or	Regional specialisation and concentration affect economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES*. Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry),	Regional specialisation and concentration affects income inequality, income stability, farm adaptability, and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • negative effects on regulating and material ES resulting from regional specialisation (see Appendix B.2) may be externalised to surrounding small farms with less capacity to adapt [146]. • diversified farms within a specialised region can better adapt to external shocks (e.g. price fluctuations of

Mechanism of intensity change	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	10 REDUCED INEQUALITIES
	ammonia, as well as run-off and leaching of nutrients and sediments into local and downstream surface freshwater bodies and groundwater aquifers, decreasing water quality as a result of eutrophication, acidification, presence high nitrate concentration levels, sedimentation of reservoirs, residues of veterinary medicines, bacteria and soil colloids [213][263] [125] [136][200] [155] [41] [188] [159]	increased costs to maintain it [194][125][146], thus affecting energy security • Increased manure availability in regions specialised in livestock production can also allow for the production of biogas, thus increasing bioenergy availability [283]	and to employment opportunities in the region [221], [265] [183] • in the long term, potential effects on regulating and material ES (see Appendix B.2) may lead to changes productivity and/or increased costs to maintain it, [194][125][146], thus affecting agricultural economic output • Effects on non-material ES have an impact on the tourism sector in the region [7] [183] [155] [151] [125] [130] [156] [137] [143] [189] [190] • Regional specialisation in limited number of activities may contribute to increased vulnerability to external shocks (e.g. price volatility, extreme events) and reduced adaptability, with potential impacts on the rural economy [249] [194][125][146] [5][55][215] [92]	agricultural commodities and consumable inputs, extreme events and crop failures) [186] [249][160]
Crop/breed change and product differentiation		Crop change affects energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264]	Crop/breed change and product differentiation affect economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES.* Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [43] [221], [265] [183] • regional products and local breeds contribute to the tourism sector [43] [183] [137] [109]	Crop/breed change and product differentiation affect income inequality, income stability, farm adaptability, and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES.* Particularly: • niche/labelled product may allow for higher net revenues with lower yields [246] [186] [257][156][188]
Vertical integration		Vertical integration affects energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264] • Increased manure availability in regions specialised in livestock production can also allow for the production of biogas, thus increasing bioenergy availability Valorisation of animal waste through anaerobic digestion allows to produce methane that can be used as fuel [125] [283], thus increasing bioenergy availability	Vertical integration affect economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES.* Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [221], [265] [183] • short marketing channels (e.g. market places, direct producer-consumer circuits, farm sales, producer shops) contribute to the regional economic output [183]	Vertical integration affects income inequality, income stability, farm adaptability, and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES.* Particularly: • small farms have a weaker bargaining power in the supply chain, with regard to large buyers of farm output such as wholesalers and supermarkets [223][284]
Knowledge intensity		Changes in knowledge intensity affect energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability	Changes in knowledge intensity affect economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES.* Particularly:	Changes in knowledge intensity affect income inequality, income stability, farm adaptability, and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES.* Particularly: • farm visits by expert personnel such as engineers, agronomists or veterinarians are expensive (unless made

Mechanism of intensity change	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	10 REDUCED INEQUALITIES
		within a region, and in distant regions connected through trade flows [198][264]	• changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [221], [265] [183]	by state-paid extension services), and therefore access to knowledge is more limited to small farms than large farms [223]
Improved information management	Improved information management affects freshwater availability and freshwater quality at the **landscape and regional scales**, through changes in *water flows* and *pollutant flows*. Particularly: • Precision farming and water-saving irrigation technologies (e.g. drip irrigation) can reduce water use for irrigation, and thus reduce pressures on water availability [53] [285] • precision farming allows to optimise inorganic N application and reduce nitrate pollution to water bodies, thus reducing pressures on water quality [125] availability [53] [285]	Improved information management affects energy security at the **regional scale** and **in distant regions**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264]	Improved information management affects economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES*. Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [221], [265] [183] • while a number of manual and repetitive tasks may be replaced by automation, skilled and cognitive agricultural jobs might increase with precision farming and digitalisation [221], [286] [53]	Improved information management affects income inequality, income stability, farm adaptability, farm autonomy, and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • high costs and limited knowledge and skills can limit the adoption of technology by small farms, and consequently the access to the novel technologies may remain restricted to large industrialized farms [53] [223] [54] • small farms are more likely to have credit constraints, which often impedes investments on technology [223]
Income diversification		Income diversification affects energy security at the **regional scale** and in **distant regions**, through changes in commodity flows, monetary flows, regulating ES and material ES. Particularly: • Changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264]	Income diversification affects economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES*. Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [221], [265] [183] • on-farm agritourism and gastronomy activities contribute to economic output and employment opportunities in the tourism sector [43][183][137]	Income diversification affects income inequality, income stability, farm adaptability, farm autonomy, and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • Complementary non-farming activities on and off the farm reduce vulnerability to external shocks (e.g. price fluctuations of agricultural commodities and consumable inputs, extreme events and crop failures), thus increasing farm stability and adaptability [221] [156] [225] [258] [101] [92] (see also Table A.1 for references on income diversification) • financial support (e.g. CAP subsidies) may secure income stability, farm viability and adaptability in the short-term, but in the long-term in decreases farm autonomy [186] [6][55] [225]
Cooperation		Cooperation affects energy security at the **regional scale** and in **distant regions**, through changes in commodity flows, monetary flows, regulating ES and material ES. Particularly: • changes in productivity and efficiency of bioenergy crop production affect energy availability and affordability within a region, and in distant regions connected through trade flows [198][264]	Cooperation affects economic output of agriculture, economic output of tourism, total regional economic output and regional unemployment at the **regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES, material ES* and *non-material ES*. Particularly: • changes in productivity and profitability contribute to changes in economic output of the agricultural sector, and to other related sectors (e.g. input suppliers, agricultural services, supply chains and food processing industry), and to employment opportunities in the region [43][221], [265] [183]	Cooperation affects income inequality, income stability, farm adaptability, and poverty at the **community level and regional scale**, through changes in *commodity flows*, *monetary flows*, *regulating ES* and *material ES*. Particularly: • local organisation can help small farms to build capacity in order to address social inclusion issues more effectively [222] • Participation in cooperatives can improve bargaining power of small family farms [223] [284]

Mechanism of intensity change	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	10 REDUCED INEQUALITIES
			• involvement of farmers in local associations contributes to their social capital, potentially having a positive effect on their side businesses and thus contributing to the region's economic output [43]	

Table C.4: Effects of mechanisms of agricultural intensity change on sustainability dimensions related to SDG 11 (Sustainable cities and communities), SDG 12 (Sustainable production and consumption), SDG 13 (Climate action) and SDG 15 (Sustainable terrestrial ecosystems) in Europe. For each sustainability dimension, the affected attributes are <u>underlined</u>, the levels and/or scales at which they are affected are in **bold**, and the socio-ecological processes through which they are affected are in *italic*.

Mechanism of intensity change	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND
Land management intensity	Changes in land management intensity affect <u>social cohesion</u>, <u>quality of life</u>, <u>sense of place</u>, <u>rural population</u>, and <u>air quality</u> at the **community level and regional scales,** through changes in *migration flows*, *social relationships*, *human-nature interactions* and *pollutant flows*. Particularly: • noise and foul odour due to high livestock density decreases quality of life in surrounding communities [183][183] • Negative effects of changes in land management intensity on regulating and non-material ES (see Appendix B.2) decrease recreational, aesthetical and cultural heritage value of the landscape, thus affecting sense of place and overall quality of life [287][288] [127] [5] [183] • high livestock density leads to increased emissions of ammonia and particulate matter, thus decreasing air quality in the surrounding communities [155] [200][263] [125] • soil erosion due to increased frequency of field operations and high livestock density can contribute to poorer air quality, particularly when the bare soil surfaces are exposed to strong winds [155] • agricultural abandonment results in migration to urban centers, leading shrinking and ageing of the rural population and potentially compromising social cohesion [41] [182] [125][289]	Changes in land management intensity affect <u>animal health and welfare</u> at the **farm level and regional scales**, through changes in *human-livestock interactions*. Particularly: high livestock density can cause extensive discomfort and health problems to animals [188] [290] [291][292][293] Changes in land management intensity affect <u>land footprint</u>, <u>water footprint</u>, <u>material footprint</u> and <u>nutrient footprint</u> at the **regional scales and in distant regions**, through *commodity flows*. Changes in agricultural productivity and resource use affect land, water and nutrient footprint of crop and livestock production, both in producer regions and in distant consumer regions connected through trade flows [294][295]–[301][302]	Changes in land management intensity affect <u>carbon footprint</u> at the **farm level, and regional and global scales**, through changes in *greenhouse gases flows*. Particularly: • Increased livestock density leads to higher GHG emissions resulting from livestock enteric fermentation [303] [155] [125] and from manure production [304], [305] [155] [125][306] • Increased frequency of field operations with machinery increases direct GHG emissions from fuel combustion[41] Changes in land management intensity affect <u>soil nitrous oxide emissions</u> at the **agricultural field and landscape scales**, through changes in *greenhouse gases flows*. Particularly: • draining organic soils in peatlands/wetlands leads to the decomposition of organic matter, resulting in carbon dioxide and nitrous oxide emissions [136] [307][308][309][304][310] • subsoil compaction due to increased frequency of field operations with heavy machinery and higher livestock density can lead to increased soil water content, which in turn can give rise to nitrous oxide emissions [136] [137] [125] [310][310][311] Changes in land management intensity affect <u>carbon storage</u> at the **agricultural field and landscape scales**, through changes in *greenhouse gases flows* and *climate regulation ES*. Particularly: • increased livestock density, grazing period length and soil drainage in poorly drained mineral soils reduces soil carbon stock due to losses of topsoil organic content [136] [137] • the accumulation of woody above-ground biomass due to agricultural abandonment increases carbon stocks [139], but in turn may also increase the risk of wild fires, leading to the release of carbon emissions [126]	Changes in land management intensity affect <u>land degradation</u> at the **agricultural field and regional scales**, through changes in *ecosystem functioning*; *pollutant flows* and *regulating ES*. • More frequent field operations, higher livestock density and longer grazing periods contribute to land degradation through soil erosion, compaction and/or acidification [312][194][136][7] [41] Changes in land management intensity affect <u>deforestation</u> and <u>ecosystem degradation</u> at the **landscape, regional and in distant regions**, through changes in *ecosystem functioning*; *pollutant flows* and *regulating ES*. • High livestock density contributes to high atmospheric nitrogen levels, leading to exceedance of critical nitrogen deposition load in surrounding ecosystems [200][263] [136] [41] Changes in land management intensity affect <u>water biodiversity</u>, <u>soil biodiversity</u> and <u>above-ground biodiversity</u> at the **agricultural field, landscape, regional and global scales and in distant regions**, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES*.. • Soil compaction due to more frequent field operations, high livestock density and longer grazing periods reduces abundance of soil microfauna [41] • increased nitrogen levels in the soil due to high livestock density affect soil microbial community (bacteria and fungi) [313]–[315], increase in earthworm abundance but reduce earthworm species richness [41] • Increased field operation frequency (e.g. mowing) and high nitrogen emissions due to high livestock density decreases plant species richness, grasslands included [134] [316] [155] [125] [317][318] • Livestock density, grazing period length, frequency of field operations (ploughing, mowing, mechanical weeding, harvesting), sowing density and fallow cycle frequency affect the abundance and richness of terrestrial insects, birds and mammals, by altering food, and nesting resources, trampling risk, and exposure to predators [125] [155][132] [126] [28] [41] [317][318] • Agricultural abandonment allows for rewilding, but can also lead decrease in abundance of birds adapted to open farmland [125] [317][318]

Mechanism of intensity change	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND
				• Drainage of arable farm fields affect adjacent wet grassland habitats, leading to a decline in abundance and diversity of associated birds, plants and invertebrates [41] [125] Changes in land management intensity affect functional biodiversity at the landscape scale, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES*. • high livestock densities contribute to alterations in the grassland habitat properties, making them structurally more uniform by reducing botanical diversity and changing vegetation height and structure [125] [155] • high livestock density, long grazing periods and/or more frequent field operations contribute to high nitrogen emissions and increased runoff induced by soil compaction, resulting in more frequent eutrophication events, which lead to changes in the plant community structure of aquatic habitats [125]
Capital intensity	Changes in capital intensity affect social cohesion, quality of life, sense of place, rural population, and air quality at the **community level and regional scales,** through changes in *migration flows*, *social relationships*, *human-nature interactions* and *pollutant flows*. Particularly: • noise and foul odour due to high livestock density decreases quality of life in surrounding communities [183][183] • Negative effects of capital intensification on regulating and non-material ES (see Appendix B.2) decrease recreational, aesthetical and cultural heritage value of the landscape, thus affecting sense of place and overall quality of life [287][288] [127] [5] [183] • Larger herd sizes confined in stables lead to increased emissions of ammonia and particulate matter, thus decreasing air quality in the surrounding communities [155] [200][263] [125] • soil erosion due to use of heavy machinery can contribute to poorer air quality, particularly when the bare soil surfaces are exposed to strong winds [155] • higher unemployment rate resulting from substitution of labour by capital results in migration to urban centers, leading shrinking and ageing of the rural population and potentially compromising social cohesion [41] [182] [126] [125] [289]	Changes in capital intensity affect animal health and welfare at the **farm level and regional scales**, through changes in *human-livestock interactions*. Particularly: Confining large herds inside stables can cause extensive discomfort and health problems to animals, depending on space available per animal, outdoor access, equipment for regulation of temperature and ventilation, floor and bedding materials, and feed supplying facilities [188] [290] [291][292][293] Changes in capital intensity affect land footprint, water footprint, material footprint and nutrient footprint at the **regional scales and in distant regions**, through *commodity flows*. Changes in agricultural productivity and resource use affect land, water and nutrient footprint of crop and livestock production, both in producer regions and in distant consumer regions connected through trade flows [294][295]–[301][302]	Changes in capital intensity affect carbon footprint at the **farm level, and regional and global scales**, through changes in *greenhouse gases flows*. Particularly, • Larger herd size leads to higher GHG emission intensity from livestock enteric fermentation [303] [155] [125], and from manure production [304], [305] [155] [125] [306] • Energy use for operation of facilities and machinery increases GHG emissions [41] Changes in land management intensity affect soil nitrous oxide emissions at the **agricultural field and landscape scales**, through changes in *greenhouse gases flows*. Particularly, • Wetland drainage leads to increased nitrous dioxide emissions [309] [136] • Irrigation on well-drained soils increases nitrous oxide emissions [309] [41] [310] [311] • The use of heavy machinery can lead to subsoil compaction, which in turn can lead to increased soil water content, which in turn can give rise to nitrous oxide emissions[136] [137] [125] [310][310] [311]	Changes in capital intensity affect land degradation at the **agricultural field and regional scales**, through changes in *ecosystem functioning*, *pollutant flows* and *regulating ES*. • Use of heavy machinery contributes to land degradation through soil erosion and/or compaction [312] [194] [136] [7] [41] Changes in capital intensity affect deforestation and ecosystem degradation at the **landscape, regional and in distant regions**, through changes in *ecosystem functioning*, *pollutant flows* and *regulating ES*. • Nitrogen emissions from large livestock herds contribute to high atmospheric nitrogen levels, leading to exceedance of critical nitrogen deposition load in surrounding ecosystems [200][263] [136][155] [41] Changes in capital intensity affect water biodiversity, soil biodiversity and above-ground biodiversity at the **agricultural field, landscape, regional and global scales and in distant regions**, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES*.. • Soil compaction resulting from the use of heavy machinery reduces abundance of soil microfauna, and reduces the abundance and activity of earthworms [41] • increased nitrogen levels due to emissions from large livestock herds contribute to increases in earthworm abundance while reducing earthworm species richness [134], affects soil microbial community (bacteria and fungi) [313]–[315], decreases plant species richness, grasslands included [316] [155] [125], and affects species

Mechanism of intensity change	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND
				composition in aquatic habitats, e.g. by contributing to excessive algae growth, leading to depletion of oxygen from water bodies, and subsequent death of aquatic invertebrates, fish and other aquatic animals [41] [136] • Large livestock herds affect the abundance and richness of terrestrial insects, (migratory) birds and mammals, by altering food and nesting resources and increasing the risk of trampling [125] [155][132] [126] [28] [41] [317][318] • Drainage of water bodies and wet grassland habitats, and damming and canalisation of rivers for irrigation leads to a decline in abundance and diversity of associated birds, plants, amphibians and invertebrates [41][125] • Large-scale conversion of open arable and pastoral landscapes into vineyards and irrigated olive orchards affects the abundance and diversity of open farmland specialist species [125] • Irrigated rice plantations can contribute to increases in the local diversity of aquatic invertebrates and the birds feeding on them, including breeding, wintering and migratory birds [41] Changes in capital intensity affect <u>functional biodiversity</u> at the **landscape scale**, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES*. • Large livestock herds contribute to alterations in the grassland habitat properties, making them structurally more uniform by reducing botanical diversity and changing vegetation height and structure [125][155] • nitrogen emissions from large livestock herds contribute to more frequent eutrophication events, leading to changes in plant community structure of aquatic habitats [125]
Input-use intensity	Changes in input-use intensity affect <u>social cohesion</u>, <u>quality of life</u>, <u>sense of place</u> and <u>air quality</u> at the **community level and regional scales,** through changes in *social relationships*, *human-nature interactions* and *pollutant flows*. Particularly: • foul odour due to applications of fertiliser decreases quality of life in surrounding communities [183][183] • Negative effects of input-use intensification on regulating and non-material ES (see Appendix B.2) decrease recreational, aesthetical and cultural heritage value of the landscape, thus affecting sense of place and overall quality of life [287][288] [127] [5] [183] • Fertiliser and pesticide applications decrease air quality in the surrounding communities [155] [125] [188] [200]	Changes in input-use intensity affect <u>animal health and welfare</u> at the **farm level and regional scales**, through changes in *human-livestock interactions*. Particularly: Changes in feed composition and use of antibiotics affect health problems to animals [188][290][319][320][321] Changes in input-use intensity affect <u>land footprint</u>, <u>water footprint</u>, material <u>footprint</u> and <u>nutrient footprint</u> at the **regional scales and in distant regions**, through *commodity flows*. Changes in agricultural productivity and resource use affect land, water and nutrient footprint of crop and livestock production, both in producer regions and in distant consumer regions connected through trade flows [294][295]–[301][302]	Changes in input-use intensity affect <u>carbon footprint</u> at the **farm level, and regional and global scales**, through changes in *greenhouse gases flows*. Particularly, • Energy use for operation of facilities and machinery increases directs GHG emissions, while increased use of consumable inputs (fertilisers, pesticides, feed concentrates) leads to higher indirect GHG emissions resulting from their production and transport [41] [155] Changes in input-use intensity affect <u>soil nitrous oxide emissions</u> at the **agricultural field and landscape scales**, through changes in *greenhouse gases flows*. • Water use for irrigation on well-drained soils increases nitrous oxide emissions [309] [41] [311]	Changes in input-use intensity affect <u>land degradation</u> at the **agricultural field and regional scales**, through changes in *ecosystem functioning*; *pollutant flows* and *regulating ES*. • Use of fertilisers and pesticides contributes to soil degradation through soil acidification and contamination [312][194][136] [41] • Increased use of water for irrigation contributes to land degradation through soil secondary salinization, particularly in dry regions with high salt content in the subsoil [136] Changes in input-use intensity affect <u>deforestation</u> and <u>ecosystem degradation</u> at the **landscape, regional and in distant regions**, through changes in *ecosystem functioning*; *pollutant flows* and *regulating ES*.

Mechanism of intensity change	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND
			• Increased emissions of nitrous oxide as a by-product of nitrogenous fertiliser applications [304] [136] [155] [311] [125] • Irrigation on well-drained soils increases nitrous oxide emissions [309] [41] [310] [311]	• Fertiliser use, as well the production of fertiliser itself, contributes to increased atmospheric nitrogen levels, leading to exceedance of critical nitrogen deposition load in surrounding ecosystems [200][263] [136][155][41][125] [188] [136] • Increased use of imported feed concentrates drives agricultural expansion in feed exporter regions, leading to deforestation [296], [322] Changes in input-use intensity affect <u>water biodiversity</u>, <u>soil biodiversity</u> and <u>above-ground biodiversity</u> at the **agricultural field, landscape, regional and global scales and in distant regions**, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES*.. • Increased fertiliser use leads to increases in earthworm abundance while reducing earthworm species richness [134], and affects soil microbial community (bacteria and fungi) [313]–[315], • increased use of fertilizers and herbicides results in dominance of competitive flora species and loss of wild plant species in grasslands and in habitats adjacent to arable fields (e.g. field margins and ditch banks), especially those adapted to conditions of intermediate fertility, thus decreasing plant species richness, and affecting the abundance and richness of terrestrial insects, (migratory) birds and mammals, by altering their food and nesting resources [125] [155][132] [127] [126] [28] [41], [316] [155] [125][323] [317][318][324] • increased use of broad spectrum insecticides affects the composition and abundance of invertebrates communities, thus affecting the availability of food resources for birds [41] [125] [325] [323][317][318] • Increased pesticide and fertiliser use increases the concentration of pollutants such as nitrates, phosphates, toxic chemicals and heavy metals in surrounding aquatic habitats, thus affecting the abundance and diversity of aquatic species, amphibian species and other taxa higher on the food web [125] [268][136] • Increased water use for irrigation reduces water availability in surrounding aquatic ecosystems, leading to a decline in abundance and diversity of associated birds, plants and invertebrates [41] [125] • Increased use of antibiotics affects pasture invertebrate assemblages (e.g. non-target dung invertebrates), and indirectly other taxa higher on the food web [125] Changes in input-use intensity <u>affect functional biodiversity</u> at the **landscape scale**, through changes in

Mechanism of intensity change	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND
				ecosystem functioning; *species migration flows*, *pollutant flows* and *regulating ES*. • Increased fertiliser and herbicide use lead to alterations in grassland and surrounding semi-natural habitat properties, by reducing the abundance and diversity of less competitive wild and weedy plant species, and alter the morphology, nectar chemistry and phenology of flowers [125] [133] [135][155] [28] • Eutrophication and acidification of aquatic habitats due to nitrogen deposition and runoff resulting from fertiliser use leads to changes in plant community structure [125]
Labour intensity	Changes in labour intensity affect social cohesion, quality of life, and rural population, at the **community level and regional scales,** through changes in *migration flows* and *social relationships*. Particularly: • higher unemployment rate resulting from substitution of labour by capital results in migration to urban centers, leading shrinking and ageing of the rural population and potentially compromising social cohesion [41] [182] [126] [125] [289] • seasonality of work can represent a high risk of social exclusion for farm workers [222] • Labour-intensive farms (e.g. fruit and vegetables production) employ mainly seasonal workers of migrant origin, with precarious housing conditions, and social exclusion being often reported [199], [221], [222], [275]–[279] [275], [277], [279]–[281] [222] [282]			
Farm consolidation	Farm consolidation affect social cohesion, quality of life, sense of place, rural population, and air quality at the **community level and regional scales,** through changes in *migration flows*, *social relationships*, *human-nature interactions* and *pollutant flows*. Particularly: • Negative effects of farm consolidation on regulating and non-material ES (see Appendix B.2) decrease recreational, aesthetical and cultural heritage value of the landscape, thus affecting sense of place and overall quality of life [287][288] [127] [5] [183] • the assimilation of small farms into larger ones may contribute to community disintegration and migration [125] [5] [183] • removal of natural vegetation and landscape elements can reduce the ability to regulate soil erosion and air quality, thus contributing to poor air quality due to the dispersal of particulate matter when bare soil surfaces of are exposed to strong winds[155]	Farm consolidation affects land footprint, water footprint, material footprint and nutrient footprint at the **regional scales and in distant regions**, through *commodity flows*. Changes in agricultural productivity and resource use affect land, water and nutrient footprint of crop and livestock production, both in producer regions and in distant consumer regions connected through trade flows [294][295]–[301][302]	Farm consolidation affects carbon storage at the **field and landscape scales**, through changes in *climate regulation ES*. Particularly: • Removal of semi-natural vegetation patches and landscape linear elements decreases carbon stocks [146] [157] [158] Farm consolidation affects soil nitrous oxide emissions at the **agricultural field and landscape scales**, through changes in *greenhouse gases flows*. Particularly, • Grass strips, hedgerows and tree strips contribute to reduce nitrous oxide emissions [157]	Farm consolidation affects land degradation at the **agricultural field and regional scales**, through changes in *ecosystem functioning*; *pollutant flows* and *regulating ES*. • Increasing field size and removing of semi-natural vegetation patches and linear elements contributes to land degradation by decreasing the ability to regulate soil erosion [125][155] [41] Farm consolidation affects deforestation and ecosystem degradation at the **landscape, regional and in distant regions**, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES*. • Increase in farming area for agricultural expansion contributes to deforestation [326] Farm consolidation affects water biodiversity, soil biodiversity and above-ground biodiversity at the **agricultural field, landscape, regional and global scales and in distant regions**, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES*. • Field size and the existence/removal of semi-natural vegetation patches and landscape elements reduces

Mechanism of intensity change	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND
				habitat availability, quality and connectivity, thus being a major determinant of terrestrial fauna and flora biodiversity, including the abundance and richness of soil microbial and macrofauna communities, and insect, plant, (migratory) birds and mammal species [125][130][327] [41] [132] [28] [328] [329] [315] [317][318] Farm consolidation affects functional biodiversity at the **landscape scale**, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES.* • Landscape simplification through removal of semi-natural vegetation patches and landscape elements leads to decrease in habitat diversity [125][130][327] [41]
Farm specialisation / diversification	Farm specialisation / diversification affect social cohesion, quality of life, and sense of place, at the **community level and regional scales,** through changes in *human-nature interactions* and *pollutant flows*. Particularly: • the effects of farm specialisation/diversification on regulating and non-material ES (see Appendix B.2) lead to changes in the recreational, aesthetical and cultural heritage value of the landscape, thus affecting sense of place and overall quality of life [287][288] [127] [5] [183]		Farm specialisation/diversification affect carbon storage at the **field and landscape scales**, through changes in *greenhouse gases flows* and *climate regulation ES.* Particularly, • practices such as agroforestry, crop rotations in which carbon inputs are increased over time, and use of cover crops contribute to increases in carbon stocks [136][160]	Farm specialisation/diversification affects land degradation at the **agricultural field and regional scales**, through changes in *ecosystem functioning*, *pollutant flows* and *regulating ES.* • increasing the diversity of plants on the crop rotation (e.g. cover crops, legumes, mixed arable-livestock systems) and rooting depths (e.g. agroforestry) decreases land degradation by improving erosion regulation [155][136] [156] [41] [146] [137] [160] Farm specialisation/diversification affects water biodiversity, soil biodiversity and above-ground biodiversity at the **agricultural field, landscape and regional scales**, through changes in *ecosystem functioning*; *pollutant flows* and *regulating ES.* • Agroforestry systems increase the abundance of bird species by supporting a diversity of fruits [130] • crop rotation in grasslands leads to a decline of butterflies associated primarily with permanent grasslands [125] • mixed arable-livestock systems and rotations with legume crops enhance the abundance and richness of beetle, plant and farmland bird species [125] [28] [134] • crop rotations with cover crops promote invertebrate communities [125] • the separation of pastoral and arable farming systems leads to declines in bird populations in both arable and grassland landscapes [125] [317][318] • farm specialization reduces the availability of food resources for birds, fish, plants, mammals and invertebrates [155][125][133][146] [41] [317][318] • the presence of heterogeneous crop mosaics affects positively the abundance and diversity of arthropods, plants, birds and mammals [329] [125] [317][318] • farm diversification can provide habitats for species of different ecological profile. For example, the existence of

Mechanism of intensity change	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND
				permanent and temporary grasslands within arable farming diversifies available habitats, by providing habitats suitable to grassland specialists and resources in specific periods of the year for generalist species that would suffer from the temporal discontinuity of resources in crop fields [137][125] [130][155][160] [317][318] Farm specialisation/diversification affects functional biodiversity at the **landscape scale**, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES*. • the specialisation and separation of pastoral and arable farming systems reduces habitat diversity in agricultural landscapes [125] • the presence of heterogeneous crop mosaics affects positively multi-trophic diversity [329]
Regional specialisation and concentration	Regional specialisation and concentration affects social cohesion, quality of life, and sense of place, at the **community level and regional scales,** through changes in *social relationships*, *human-nature interactions, pollutant flows.* Particularly: • the negative effects of regional specialisation on regulating and non-material ES (see Appendix B.2) decrease the recreational, aesthetical and cultural heritage value of the landscape, thus affecting sense of place and overall quality of life [287][288] [127] [5] [183] • specialisation in local breeds and crop varieties, and the cultural heritage associated with it, contributes to social cohesion and sense of place [183] • regional specialisation and concentration of livestock production leads to higher production of manure and soil compaction, leading to emission of ammonia and particulate matter, thus decreasing air quality in the surrounding communities [155] [200][263] [125]			Regional specialisation and concentration affects land degradation at the **regional scale**, through changes in *ecosystem functioning*, *pollutant flows* and *regulating ES*. • increasing the diversity of plants on the crop rotation (e.g. cover crops, legumes, mixed arable-livestock systems) and rooting depths (e.g. agroforestry) decreases land degradation by improving erosion regulation [155][136] [156] [41] [146] [137] [160] Regional specialisation and concentration affects water biodiversity, soil biodiversity and above-ground biodiversity at the **landscape and regional scales**, through changes in *ecosystem functioning*; *species migration flows, pollutant flows* and *regulating ES*.. • Agroforestry systems increase the abundance of bird species by supporting a diversity of fruits [130] • crop rotation in grasslands leads to a decline of butterflies associated primarily with permanent grasslands [125] • mixed arable-livestock systems and rotations with legume crops enhance the abundance and richness of beetle, plant and farmland bird species [125] [28] [134] • crop rotations with cover crops promote invertebrate communities [125] • the specialisation and separation of pastoral and arable farming systems leads to declines in bird populations in both arable and grassland landscapes [125] • the presence of heterogeneous crop mosaics affects positively the abundance and diversity of arthropods, plants, birds and mammals [329] [125] Farm specialisation/diversification affects functional biodiversity at the **landscape scale**, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES*.

Mechanism of intensity change	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	15 LIFE ON LAND
				• the specialisation and separation of pastoral and arable farming systems reduces habitat diversity in agricultural landscapes [125] • the presence of heterogeneous crop mosaics affects positively multi-trophic diversity [329]
Crop/breed change and product differentiation	Crop/breed change and product differentiation affect social cohesion, and sense of place, at the **community level and regional scales,** through changes in *social relationships*. Particularly: • regional products, and the cultural heritage associated with it, contributes to social cohesion and sense of place [183]			Crop/breed change and product differentiation affects soil biodiversity and above-ground biodiversity at the **agricultural field, landscape, and regional scales**, through changes in *ecosystem functioning*; *species migration flows*, *pollutant flows* and *regulating ES*. • Adopting organic farming increases species richness of microbes, arthropods, plants and birds [330] [28]
Vertical integration	Vertical integration affects social cohesion, and sense of place, at the **community level and regional scales,** through changes in *social relationships*. Particularly: short marketing channels (e.g. market places, direct producer-consumer circuits, farm sales, producer shops) contribute to the territory's social cohesion and sense of place. Conversely, highly integrated, standardized agriculture structured around supply chains leads to disconnection among local actors [183]			
Income diversification	Income diversification affects social cohesion and sense of place at the **community level and regional scales,** through changes in *social relationships*. Particularly: Non-farming activities such gastronomy, artisanal crafts and festivals contribute to the territory's social cohesion and sense of place [183]			
Cooperation	Cooperation affects social cohesion, and sense of place at the **community level and regional scales,** through changes in *social relationships*. Particularly: Participation in local organisations promotes farmers sense of place and social cohesion by enabling social learning, shared social norms, promoting reciprocity and reducing social conflicts [260][262] [183] [261]			

Appendix D. Selecting metrics for SI indicators in Europe (Step 4)

D.1. Search strategy for literature and online databases

We reviewed existing literature and publicly available online databases to identify applicable methods and available data sources to measure the indicators identified in Steps 1-3. For the literature review, we searched Scopus, ISI Web of Knowledge and Google Scholar for three overarching branches of literature: sustainability assessment of agriculture, agricultural (land-use) intensification, and sustainable intensification (Table D.1). The authors also checked their own collections for eligible papers and reports to supplement the automatic search. A combination of scientific articles and grey literature was gathered based on these searches. We did not perform a systematic review; instead, we screened the publications and selected them according to a number of eligibility criteria, including relevant title and abstract, and whether they explicitly proposed, utilised or reviewed approaches to measure indicators relevant to agricultural intensity, ecosystem service provision, and/or sustainability outcomes. Full texts were screened to meet these criteria by looking for assessment frameworks, indicators, and/or methods to derive indicator metrics. When a given indicator theme was not sufficiently covered by these literature branches (e.g. social cohesion), we performed dedicated literatures searches.

Table D.1: Search strings used for literature searches on SI indicator metrics

Branch of Literature	Search strings
sustainability assessment of agriculture	assess* AND sustainab* AND agriculture*;
agricultural (land-use) intensification	agricultur* intensi* OR landuse intensi* AND (assess* OR evaluat* OR measur*);
sustainable intensification of agriculture	((sustainable AND intensification AND agriculture) OR sustainable intensification OR ecological intensification) AND (assess* OR evaluat* OR measur*);

In addition, we also reviewed online data portals from international agencies and organisations (Table D.2) and searched for relevant indicators with pan-European coverage. Finally, based on the selected articles and data portals, we assigned indicator metrics at different scales and levels of organisation for all considered indicators (see Section D.2).

Table D.2: Reviewed online data portals

Data portal	Website
Biodiversity Indicators Partnership (BIP)	https://bipdashboard.natureserve.org/SelectIndicator.html
Emissions Database for Global Atmospheric Research (EDGAR)	https://data.jrc.ec.europa.eu/collection/edgar
European Environment Agency (EEA)	https://www.eea.europa.eu/ims
European Soil Data Centre (ESDAC)	https://esdac.jrc.ec.europa.eu/
EU CAP Common Monitoring and Evaluation Framework (CMEF-CAP)	https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cmef_en
EU Farm Accountancy Data Network (FADN)	https://agridata.ec.europa.eu/extensions/FarmEconomyFocus/FADNDatabase.html
EUROSTAT	https://ec.europa.eu/eurostat/web/main/data/database
FAO-AQUASTAT	https://www.fao.org/aquastat/en/databases/
FAOSTAT	https://www.fao.org/faostat/en/#data
FAO-SDG indicators	http://www.fao.org/sustainable-development-goals/indicators/en/
Global Food Security Index (GFSI)	https://impact.economist.com/sustainability/project/food-security-index/
Global Health Observatory (GHO)	https://www.who.int/data/gho/data/indicators
Living Planet Index (LPI) database	https://livingplanetindex.org/data_portal
World Animal Protection (WAP)	https://api.worldanimalprotection.org/
World Bank data	https://data.worldbank.org/indicator
WHO Mortality Database (WHO-MD)	https://www.who.int/data/data-collection-tools/who-mortality-database
UN-SDG indicators	https://unstats.un.org/sdgs/dataportal/database

D.2. Indicator framework for SI assessment in Europe

Table D.3: *Agricultural intensity* indicator metrics

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale	Regional scale	Global scale
Management intensity	Land management	Livestock density	• LU / ha [331]	• LU / ha [331]	• average LU / ha [331] • LU / ha [332], [333]	• LU / ha (EUROSTAT)	• Total nr. of livestock units
		Grazing period length	• Grazing season length [8]	• Grazing season length [8]	Grazing season length [8]		
		Cropping frequency	• Crop rotation period [334]		• Nr. of cropped years ., 2016) • Crop duration ratio [335] • Nr. of harvests per year [335]	• % arable land with crop rotation (EUROSTAT) • Cropland harvest frequency [336] • Harvest gap [336]	• Cropland harvest frequency [336] • Harvest gap [336]
		Fallow cycle frequency	• Crop rotation period [334] • Fallow cycles [335]	• % Fallow area / Set aside (FADN)	• Fallow cycles [335]	• Fallow area / set aside (EUROSTAT)	
		Frequency of field operations	• Nr. of years between grassland reseeding events [337] • % drained area [338] • % pruned orchard area [167] • Maintenance of terraces (% terraced area) • Tillage in spring (% area) [167]		• Crop duration ratio [335] • Mowing events per growing season [339]–[341] • % drained area [338], [342] • Frequency of tillage and ploughing [341]	• % land with conventional, conservational and zero tillage (EUROSTAT)	
		Crop rotation	• Crop rotation scheme [343]			• Predominant crop rotation scheme [343]	
		Sowing density	• Plant density [344] • Plant spacing heterogeneity [344]				
		Intercropping	• Crop share in substitutive arrangements [345]	• Area under intercropping [345]			
	Fixed capital assets	Irrigation area / Irrigation equipment		• % Irrigated area [338] • Cost per unit irrigated area [56]	• % irrigated area [338] • % irrigated area and area equipped with irrigation [346]	• % Irrigable area (EUROSTAT) • Irrigated area (FAO-AQUASTAT) • Area equipped with irrigation (FAO-AQUASTAT)	• Irrigated area (FAO-AQUASTAT) • Area equipped with irrigation (FAO-AQUASTAT)

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale	Regional scale	Global scale
		Buildings and infrastructure / Machinery and equipment		• Machinery assets (FADN) • Building assets (FADN) • Expenses in machineries and buildings (FADN) • Depreciation of buildings [167] • Equipment fixed costs [167] [347] • Equipment variable costs [167] [347] • Total cost of agricultural machine [54] • Mechanisation index [348]		• Machinery assets (FADN) • Building assets (FADN) • Expenses in machineries and buildings (FADN) • Nr. of machines / ha (EUROSTAT)	
		Permanent crop area / density		• Assets in land, permanent crops & quotas / ha (FADN) • Maintenance of orchards and terraces [167] • Depreciation on plantation investment [347]		• Assets in land, permanent crops & quotas / ha (FADN) • Land area per orchard and vineyard type (EUROSTAT)	
		Land ownership structure		• Share of land rented in relation to total land area (FADN) [349] • Communal grazing areas [349]		• Share of land rented (FADN)	
		Herd size		• Number of animals, per species [348] • Total livestock units (FADN)		• Total livestock units (FADN)	
		Breeding livestock		• Assets in breeding animals (FADN)		• Assets in breeding animals (FADN)	
		Milking livestock		• Dairy cows (FADN) • Sheep and goats (FADN)		• Dairy cows (FADN) • Sheep and goats (FADN)	
		Livestock replacement		• Replacement rate [348]			
	Consumable inputs	Fertiliser use / composition	• N input per fertiliser type [331]	• Fertilizer costs (FADN) • % intensively fertilized arable area (>150 kg N/ha/year) [350]	• average N input per fertiliser type [331]	• Sales of manufactured fertilizers EUR • Consumption of inorganic fertilizers kg (EUROSTAT) • Fertilizer costs (FADN)	

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale	Regional scale	Global scale
		Pesticide use / toxicity	• No. of applications [331] • Kg active ingredients/ha [347]	• Treatment index [351] • Pesticide costs (FADN) • Crop protection costs (FADN) • active ingredients/ha [347]	• average no. of applications [331] • No. of applications [352]	• Pesticide costs (FADN) • Crop protection costs (FADN) • Pesticides sales (EUROSTAT) • No. of applications [352]	
		Seeds inputs		• Seed costs (FADN)		• Seed costs (FADN)	
		Feed intake / composition		• % total flock energy requirements from grazing [349] • Feed costs (FADN) • Grass stored as hay [348] • Forage crops (FADN) • Feed composition [320]		• Feed costs (FADN) • Forage crops (FADN)	
		Animal health inputs use		• Veterinary products [334] • Veterinary assistance [348]			• Antibiotics use mg / kg meat (World Bank)
		Water use	• Water use [331]	• Water use [331] • Annual relative irrigation supply [56]	• Water use [346] • Water consumption [353] • Water abstraction by river basin district (EUROSTAT)	• Volume of freshwater use in agriculture [354] • Water use (EUROSTAT)	• Global withdrawals of water for agriculture (FAO-AQUASTAT) • Global human consumption of water (World Bank)
		Energy use		• Cumulative energy demand MJ [355] • Expenses in energy (FADN) •		• Energy consumption by agriculture MJ/ha (EUROSTAT) • Expenses in energy (FADN)	• Global energy use in agriculture (FAOSTAT) • Global energy use (World Bank)
	Labour	Labour input		• Annual work units (FADN)		• Annual work units (FADN) • Agricultural labour input index (EUROSTAT)	
		Family labour		• Family labour input (FADN)		• Family work units (FADN)	
		Hired labour		• Hired labour input (FADN) • Wages paid (FADN) • Contract work (FADN)		• Hired labour input (FADN) • Wages paid (FADN) • Contract work (FADN)	
		Permanent/seasonal labour		• Seasonal hired labour [282] • Share of permanent hired labour in total labour required [225]			
		Employee turnover		• Employee turnover [347]			
	Social capital	Membership in organisations		• Active Participation in agricultural organisations • Active participation in government agencies [355]		• Participation in formal or informal voluntary activities or active citizenship (EUROSTAT)	

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale	Regional scale	Global scale
				• Membership to non-agricultural organisations [356] • Social capital index [262]		• Number of projects undertaken jointly by associations, environmental organisations and local government [167]	
	Human capital	Farmer / employees education and training		• Share of employees with vocational training [355] • Participation in training events [355] • Training provision [347] • Skill and qualifications [347]		• % farmers with agricultural training (EUROSTAT)	
		Consultation with advisory /extension services		• Advisory services [349] • Access to extension			
	Farming diversity	Crop types and varieties		• Nr. of crops [357] • Nr. of local/rare crop varieties [356] [357] • Diversity of perennial crops [334]		• % CAP beneficiaries to crop diversification due to greening • % land subject to crop diversification due to greening • Nr. of crops (FADN) • Shannon–Wiener's index of crop diversity [162]	
		Livestock species and breed varieties		• Number of local/rare livestock breed varieties [349], [356] • Nr of breeds [357]	• Nr of breeds [357]	• Proportion of local breeds at risk of extinction (FAO-SDG)	
		Stages of livestock development				• Livestock units per farm type (EUROSTAT)	
	Income sources	Non-farming activities		• % work other gaining activities (FADN) • % output other gaining activities (FADN) • % agritourism output (FADN)		• % work other gaining activities (FADN) • % output other gaining activities • % agritourism output (FADN)	
		Off-farm activities		• % off-farm income [349]			
		Income diversity		• Herfindahl index [91] • Share of total household income derived from off/non-farm activites [225] • Number of different income sources[349]			
		Subsidies		• Compensatory payments and area payments (FADN)		• Compensatory payments and area payments (FADN) • Total subsidies on crops (FADN)	

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale	Regional scale	Global scale
				• Total subsidies on crops (FADN) • Total subsidies on livestock (FADN)		• Total subsidies on livestock (FADN)	
	ICT use	ICT use frequency / Computer literacy		• Investment in ICT [347] • Use of web and ICT [347]			
	Value chain	Regional product certification		• Regional products sales (% PDO label) [167]	• Regional products sales (% PDO label) [167]	• Nr. of protected designation origin products • Nr. of protected geographical indication products [358]	
		Organic farming		• % Agricultural area under organic farming [356]	• % organic farms [338]	• % organic farmers (EUROSTAT)	
		Voluntary sustainability standards		• Member of certification schemes [347]			
		Supply chain positioning		• Gross value of commodities sold through direct marketing strategy [359] • Gross value of commodities sold to wholesale retailers • Sales of products processed in the farm [360] • Sales of by-products		• Vertical specialisation [361] • Global value chain participation [361] • Global value chain positioning [361]	
		Contract farming		• Contract farming participation [362]			
	Farm size	Farm economic size		• Standard Output EUR (FADN)		• Standard Output (FADN, EUROSTAT)	
		Farm area		• Utilised Agricultural Area (FADN)		• Average Utilised Agricultural Area (FADN, EUROSTAT)	
Landscape structure	Landscape composition	Agricultural land-use composition		• % agricultural land use types [331], [357] • Utilised agricultural area per cropt type (FADN) • Surface proportion of high biological value meadows that are cut late after a specified date [356]	• Share of agricultural land use types [331], [357] • [363] • HNV farmland [364] • Agroforestry [365] • Shannon–Wiener's index of crop diversity [162]	• Utilised agricultural area per cropt type (FADN) • Share of main land types in utilised agricultural area (EUROSTAT) • % specialised cropping (EUROSTAT) • % specialised livestock (EUROSTAT) • Share of HNV farmland (CMEF-CAP) • Shannon–Wiener's index of crop diversity [162]	
		Semi-natural habitat composition		• % semi-natural habitat [331], [357]	• % semi-natural habitat [331], [357]		

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale	Regional scale	Global scale
	Landscape configuration	Density of landscape elements		• Tree density [331], [357] • Density of linear landscape elements m/ha [331], [356], [357]	• Tree density [331], [357] • Density of linear landscape elements m/ha [331], [356], [357] •		
		Agricultural field size		• Average field size ha [350], [357]	• Average field size ha [350], [357][366]		
		Semi-natural habitat patch size		• Average habitat patch size ha [350], [357]	• Average size of habitat patch size ha [350], [357] • Density of small woody features [367]		
Agricultural productivity	Agronomic productivity	Crop yield	• Crop yield ton/ha [331] • Absolute yield gain of species mixtures [368]	• Crop yield ton/ha [331]	• Crop yields ton/ha [369], [370] • Crop yield gaps ton/ha [72][371]	• Crop yields ton (EUROSTAT) • Crop yield gaps ton/ha [72][371]	
		Yield variability	• Yield variability [372]	• Yield variability [372] • Yield consistency index [373]			
		Animal productivity		• Milk yield litre / LU (FADN), [73] • Malmquist–Luenberger (ML) productivity indices [64] • Animal productivity per unit of area [349]		• Milk yield litre / LU (FADN)	
	Resource-use efficiency	Input efficiency		• Cashflow-turnover rate [355] • Total factor productivity [334]		• Productivity of inputs EUR/EUR [374] • Total factor productivity in agriculture EUR/EUR (CMEF-CAP)	
		Nutrient efficiency	• Crop yield per unit of N fertilizer input • Crop yield per unit of P fertilizer input				
		Labour efficiency		• Labour profitability/Return to labour [167] • Net added-value per annual work unit [186] • Return to own labour [167]		• Agriculture added-value per worker (UN-SDG)	
		Energy efficiency		• Energy efficiency MJ inputs / total income [349]			
		Water efficiency	• Crop yield per unit of water	• Gross margin per unit of irrigated area [56]			

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale	Regional scale	Global scale
		Feed efficiency		• Feed efficiency [349] • Feed energy conversion ratio [349] • Feed conversion ratio [83]			
		Input self-sufficiency		• Feed self-sufficiency [349] • Forage self-sufficiency [349] • Degree of self-sufficiency for energy consumption [334]			
	Profitability	Economic output		• Crop output (FADN) • Livestock output (FADN) • Gross profit (FADN)		• Production value at producer price (EUROSTAT) • Crop output (FADN) • Livestock output (FADN) • Gross profit (FADN)	
		Economic added-value		• Net added-value (FADN) [349]		• Net added-value (FADN)	
		Total output		• Total output (FADN)		• Total output EUR/ha (FADN)	
		Total output variability		• Revenue variability [375]			

Table D.4: *Ecosystem service provision* indicator metrics

Theme	Sub-theme	Indicator	Field scale	Landscape scale
Regulating services	Habitat creation and maintenance	Habitat quality		• Habitat quality indicator for common birds [376] • Terrestrial and aquatic habitat quality [377] • Habitat quality [378]
		Habitat availability		• Habitat availability index [379] • Habitat suitability for megafauna [380]
		Habitat connectivity		• Average edge density of semi-natural habitats in study site [381] • Contagion index of woody and herbaceous semi-natural landscape elements [350] • Cohesion index [382] • Interspersion and Juxtaposition Index [382], [383] • Connectivity index (γ-index) [356]
		Habitat fragmentation		• Average euclidean-nearest-neighbour distance between semi-natural landscape elements [350] • Proximity of woody and herbaceous semi-natural elements within a 5000-m radius [382], [384]
		Habitat temporal stability		• Inverse coefficient of inter-annual variability of NPP [161], [385]
		Net primary production		• NPP in agricultural land [386]
	Pollination	Pollination potential	• Pollination value [387]	• Pollination supply [378], [388] • Pollination flows [389] • Pollination potential [390][391]
	Air quality regulation	Air pollution retention capacity		• Pesticide emissions to air [392] • Air quality index [393]
	Climate regulation	Carbon sequestration potential	• Soil carbon balance [356]	• Soil organic carbon [394] • Carbon fluxes [395] • SOC stock of agricultural soils [396] • Topsoil organic carbon content [397] • Carbon storage/sequestration [390][398]
		Albedo		• Near infrared albedo [161], [399] • Albedo stability [161], [399]
		Evapo-transpiration		• Potential evapo-transpiration [400]
		Temperature		• Seasonal mean temperature anomaly [401]
		Humidity		• Surface air relative humidity [401]
	Water quantity regulation	Water flow regulation capacity		• Water retention index [378] • Freshwater resources by river basin district (EUROSTAT) • Groundwater recharge [390]
	Water quality regulation	Water pollution filtration capacity		• Runoff risk [356] • Presence of grass strips/riparian areas [356] • Vegetation cover during nitrate leaching period [356] • Nitrogen retention capacity [402][403]
	Soil regulation	Soil erosion regulation capacity	• Soil compaction [355] • Soil erosion risk [355]	• Erosion prevention [404] • Capacity of ecosystems to avoid soil erosion [378] • Soil loss by water erosion [405] • Soil loss by wind erosion [406] • Natural susceptibility to soil compaction [407]

Theme	Sub-theme	Indicator	Field scale	Landscape scale
				• Soil loss due to crop harvesting [408] • Erosion with sediment transfer and carbon fluxes [395] • Soil salinization risk [407] • Soil erosion [390]
		Soil nutrient fixation capacity		• Phosphorus losses due to soil erosion [409] • Erosion with carbon fluxes [395] • Nutrient retention [390]
Regulating Services (cont.)	Extreme events regulation	Flood regulation capacity		• Flood regulation supply [410] • Change of the mean annual flood discharge per decade [411]
		Wind regulation capacity		• Wind buffering [356] • Wind disturbance risk [412]
		Wildfire risk regulation		• Fire risk index [412]
	Pest regulation	Natural pest control potential		• Pest outbreak potential [171] • Natural Pest Control Potential [413]
Material Services	Energy production	Potential crop yield for bioenergy crops		• Bioenergy crop potential yield [414][415] • Energy output from agricultural biomass [416]
	Food and feed production	Potential crop yield for food crops		• Crop potential yield [72] [414]
		Potential crop yield for feed crops		• Crop potential yield [414]
Non-material Services	Learning and inspiration	Landscape educational value		• Outdoor recreation potential for education recreationist [189]
	Experiences	Landscape aesthetical value		• Visual landscape quality [167], [417]–[419]
		Landscape recreational value		• Supply of assets for tourism supported by ecosystems [109] • Recreation potential index [420][421] • outdoor recreation potential for different archetypical user groups [189]
	Supporting identities	Cultural heritage value		• Heritage Cultural Landscape index in agricultural land [422] • Nr. of cultural events related to agriculture [167] • Nr. of products of denominated origin
		Landscape spiritual value		• Landscape experienced tranquillity [423] • Outdoor recreation potential for spiritual recreationist [189]

Table D.5: *Sustainability outcomes* indicator metrics

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale / Community level	Regional scale	Global scale
SDG 1 – End poverty	Target 1.2	Income level		• Farm income EUR/ha (FADN) • Family farm income / family work unit (FADN) • Farm net added-value/hectare [186] • land productivity [186] • Earned income / family work unit [355]		• Agricultural factor income • Family farm income / family work unit (FADN)	
	Target 1.5	Income stability		• Capitalisation ratio [355] • Investment coverage [355] • Change in net worth (FADN) • Standard deviation in income [424] • Diversity of revenue sources [347]		• Change in net worth (FADN)	
		Farm viability		• Ratio of fixed assets and capital assets [355] • Current ratio [355] • Dynamic Gearing Ratio [355] • Solvency [356] • Viability index [55] • Profitability index [55] • Net present value EUR/ha [343], [425] • Return on invested capital [347] • Rate of return to total capital [225] • Total output/total input (FADN) • Long-term profitability [426]	• Net present value EUR/ha [343], [425]	• Net present value EUR/ha [343], [425] • Total output /total input (FADN)	
		Farm adaptability		• % major agricultural income in relation to total agric. income [349] • Dependence on on-farm income [167] • Operating expenses as proportion of total production value [334] • Safety nets [426]		• Economic damage caused by weather and climate-related extreme events EUR [427]	
		Farm autonomy		• % net income from subsidies [428]		• Short-term loans (FADN)	

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale / Community level	Regional scale	Global scale
				• Indebtedness [349] • Short-term loans (FADN) • Long & medium term loans (FADN) • Reliance on subsidies [91] • Debt-equity ratio [347] • Dependence on the leading supplier [426]		• Long & medium term loans (FADN)	
SDG 2 – Zero hunger	Target 2.1	Nutrition security				• Shannon Diversity of Food Supply • Non-Staple Food Energy • Modified Functional Attribute Diversity • Population Share with Adequate Nutrients • Nutrient Balance Score • Disqualifying Nutrient Score [429], [430]	
		Food security				• Share of population with moderate or severe food insecurity (UN-SDG) • Prevalence of undernourishment (FAO-SDG) • Average Dietary Energy Supply Adequacy (FAO-SDG) • Prevalence of food insecurity (FAO-SDG) • Proteus composite index [431]	• Share of population with moderate or severe food insecurity (UN-SDG) • Percentage of undernourished people (FAO-SDG) • Prevalence of food insecurity (FAO-SDG)
		Food availability				• Food Availability Score (GFSI) • Food Production Diversity [430] • Agricultural trade balance (CMEF-CAP) • Calorie availability • Per capita food available for human consumption (FAOSTAT)	• Per capita food available for human consumption (FAOSTAT)
		Food affordability				• Food consumption as share of total income (FAOSTAT) • Food Affordability (GFSI) • Domestic food price volatility index (UN-SDG)	
		Food safety				• Pesticides residues in food [233] • Food Safety Score (GFSI)	

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale / Community level	Regional scale	Global scale
		Supply stability				• Per capita food supply variability (FAOSTAT) • Per capita food production variability • Food price anomalies (FAO-SDG) • Consumer price evolution of food products • EU commodity price variability (CMEF-CAP)	
		Food self-sufficiency				• Self-sufficiency ratio [197], [216] • cereal import dependency ratio (FAOSTAT)	
SDG 3 – Health and well being	Target 3.4	Farmer and employee's mental health		• Feeling of independence [356] • Subjective well-being • Farmer occupational wellbeing [203] • Farmer's stress [203]		• Suicide mortality rate (SDGs) • Persons reporting exposure to risk factors that can adversely affect mental well-being (EUROSTAT) • Current depressive symptoms (EUROSTAT) • Persons reporting a chronic disease (EUROSTAT)	
		Respiratory illnesses		• Prevalence of respiratory illnesses [432]		• Number of deaths and illnesses from air pollution (GHO) • Death rate attributed to ambient air pollution (UN-SDG) • Share of population with large household expenditures on health (UN-SDG)	
		Physical injuries and fatalities		• Days of working incapacity [356] • Injury rates [347] • Absentee rates / sick leave [347]		Share of population with large household expenditures on health (UN-SDG)	
		Occupational exposure to pesticides		• Availability of protective gear in good condition [355]		Nr. of deaths due to accidental poisoning by and exposure to pesticides (WHO-MD)	
	Target 3.9	Zoonotic diseases and food-borne outbreaks		• Occurrence of resistant bacteria [355]		• Frequency of zoonosis • Food-borne outbreaks [433](GHO) • Foodborne disease burden	

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale / Community level	Regional scale	Global scale
		Environmental exposure to pesticides				• Mortality rate attributed to unintentional poisoning (UN-SDG) • Mortality from non-communicable diseases (UN-SDG)	
		Environmental exposure to nitrates				• Mortality rate attributed to unsafe water (UN-SDG) • Mortality from non-communicable diseases (UN-SDG)	
SDG 5 – Gender equality	Target 5.4	Women employment		• Equality man-women status in the farm [356]		• Inactive population due to caring responsibilities by sex (EUROSTAT) • Long-term unemployment rate by sex (EUROSTAT) • Young people neither in employment nor in education and training by sex (EUROSTAT) • Gender employment gap (EUROSTAT) • Gender equality in employment and economic benefits (UN-SDG) • Average daily time spent by women on domestic work (UN-SDG)	
		Women migration				• Emigration rate by sex (EUROSTAT)	
SDG 6 – Clean Water	Target 6.1	Freshwater availability			• Water stress index [353] • Water scarcity footprint [434]	• Freshwater withdrawal as a proportion of available freshwater resources (FAO-SDG)(UN-SDG) • Water Exploitation Index (EUROSTAT)	• Freshwater withdrawal as a proportion of available freshwater resources (FAO-SDG)
	Target 6.3	Freshwater quality		• Pesticide emissions to surface and groundwater [392] • Freshwater toxicity from pesticides [355]	• Pesticide concentration in surface water [435] • agricultural nitrates hazard index [272]	• Nitrates in groundwater (CMEF-CAP) • Phosphate in rivers (EUROSTAT) • Biochemical oxygen demand (EUROSTAT) • Share of the population using safely managed drinking water (UN-SDG)	

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale / Community level	Regional scale	Global scale
SDG 7 – Clean Energy	Target 7.2	Energy security				• Energy imports dependency • Share of renewable energy in transport fuel consumption (EUROSTAT) • Share of final energy consumption from renewable sources (UN-SDG)	
SDG 8 – Work and economic growth	Target 8.2	Economic output agriculture				• GVA agriculture (EUROSTAT)	
		Regional economic output				• Rural GDP per capita (CMEF-CAP) • Annual growth of GDP per capita (UN-SDG)	
	Target 8.8	Workers labour rights		• Share of workers with employment contract [355] • Forced labour [426]		• Long working hours in main job (EUROSTAT) • Level of national compliance with labour rights (UN-SDG)	
	Target 8.9	Economic output tourism				• GVA tourism (EUROSTAT) • Employment tourism • Bathing sites with excellent water quality by locality (EUROSTAT)	
	Target 8.5	Unemployment				• Unemployment rate (UN-SDG, EUROSTAT) • Long-term unemployment rate (EUROSTAT) • Rural employment rate (EUROSTAT) • Employment in agriculture (EUROSTAT)	
SDG 10 – Reduced inequality	Target 10.3	Income inequality		• Farm Income distribution (FADN)		• Farm Income distribution (FADN) • Inequality of income distribution (EUROSTAT) • Real gross disposable income of households (EUROSTAT)	
		Poverty				• Rural poverty (CMEF-CAP) • Poverty Index (GFSI) • People at risk of poverty or social exclusion by degree of urbanisation (CMEF-CAP) • Share of population living in multidimensional poverty (UN-SDG)	

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale / Community level	Regional scale	Global scale
SDG 11 – Sustainable cities and communities	Target 11.3	Rural population				• Population (EUROSTAT) • Population age distribution shares (EUROSTAT) • Emigration rate (EUROSTAT)	
		Social cohesion		• Support through social networks [355] • Proportion of suppliers locally based [347] • Proportion of employees from the locality [347]	• Ethnic fractionalisation [436]	• Employment rate, by citizenship (EUROSTAT) • Young people neither in employment nor in education and training, by citizenship (EUROSTAT) • People at risk of poverty or social exclusion by degree of urbanisation (EUROSTAT)	
		Workers labour rights (8.8)		• Share of workers with employment contract [355] • Forced labour [426]		• Long working hours in main job (EUROSTAT) • Level of national compliance with labour rights (UN-SDG)	
		Quality of life		• Farmer's sense of self-realisation [167] • Farmer's sense of attachment to land [167] • Farmer's sense of contribution to communication [167] • Share of employees with habitable housing [355] • Average weekly working hours [355] • Farmer and employee annual holidays [355] • Satisfaction with living conditions [355] • Participation in community events [355] • Degree of integration in the community [355] • Share of workload in relation to workforce available in the farm [355] • Quality of life index [355]		• Housing cost overburden rate by degree of urbanisation (EUROSTAT) • Overcrowding rate by degree of urbanisation (EUROSTAT) • Total population living in a dwelling with a leaking roof, damp walls, floors or foundation, or rot in window frames or floor (EUROSTAT) • Average number of usual weekly hours of work in main job (EUROSTAT) • Frequency of getting together with family and relatives or friends (EUROSTAT) • Average rating of satisfaction of leisure quality (EUROSTAT)	
	Target 11.4	Cultural heritage		• Enhancement of buildings and landscape heritage [334] • Farmer's appreciation of cultural heritage values	• Stakeholder appreciation of cultural heritage values [167]		
	Target 11.6	Air quality			• Air quality index [393]	• Air quality index [393]	

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale / Community level	Regional scale	Global scale
						• Air pollutant emissions by agriculture (EUROSTAT) • Exposure to air pollution by particulate matter (EUROSTAT)	
SDG 12 – Sustainable production and consumption	Target 12.2	Animal welfare		• Animal welfare indicator [203] • Animal Welfare index [355] • Absence of prolonged thirst [355] • Absence of prolonged hunger [355] • Comfort when resting [355] • Thermal comfort [355] • Freedom of movement [355] • Absence of injury [355] • Absence of disease [355] • Absence of management-related pain [355] • Expression of social behaviour [355]		• Animal Protection Index (WAP)	
		Water footprint		• Water content in farm products m^3 / tonne [437]		• Water footprint of food consumed m^3 / tonne [429] • Green water footprint [438] • Blue water footprint [438] • Grey water footprint [438] • Net virtual water import [301]	
		Land footprint			• Human appropriation of land for food [439]	• Total land footprint [440] • Land required for cultivation of food consumed [441] • Human appropriation of land for food [439] • Land surface converted to cropland (FAOSTAT)	• Human appropriation of land for food [439] • Land surface converted to cropland (FAOSTAT)
		Nutrient footprint				• Nitrogen footprint [438]	
		Material footprint				• Material footprint (UN-SDG) [438]	
SDG 13 – Climate action	Target 13.2	Carbon storage	• Carbon stock of the above-ground woody biomass [442] • Belowground and aboveground biomass carbon density [443]		• Carbon stock of the above-ground woody biomass [442] • Belowground and aboveground biomass carbon density [443]		
		Soil nitrous oxide emissions	N2O emissions from soil [444]		• N_2O emissions from soil [444]		

Theme	Sub-theme	Indicator	Field scale	Farm level	Landscape scale / Community level	Regional scale	Global scale
		Carbon footprint		• Lifecycle GHG emissions CO2 eq. [445], [446]	Greenhouse gas emissions from agriculture [447]	• CO2 eq./capita of food consumption [448] • CO_2 eq. in agriculture (EUROSTAT) • CO2 eq. of food consumption [448]	• CO2 eq./capita of food consumption [448] • Total GHG gas concentration levels ppm CO_2-eq. (EEA) • CO2 eq. of food consumption [448]
SDG 15 – Sustainable terrestrial ecosystems	Target 15.2	Deforestation			• Deforestation footprint [449]	• Deforestation footprint [449] • forest area as a proportion of total land area (UN-SDG)	
		Ecosystem degradation			• Exceedance of critical nitrogen deposition load [450]	• Exceedance of critical nitrogen deposition load [450]	
	Target 15.3	Land degradation		Net loss / gain of productive land [426]	• Desertification risk [451] • Land degradation [452]	• Proportion of land that is degraded over total land area (UN-SDG)	
	Target 15.5	Functional biodiversity			• Rao's Q [453] • Habitat selection ratio [341] • Ecosystem service richness, abundance and diversity [378] • Diversity of classified NDVI [454] • No. of habitat types unit of area [357] [161], [382]	• Gini-Simpson Diversity Index • Total abundance-based dissimilarities of ecosystem service supply [378] • Biodiversity Habitat Index (BIP) • Species Habitat Index [455]	• Biodiversity Habitat Index (BIP) • Species Habitat Index [455]
		Water biodiversity		• Pesticide Risk Score to water biodiversity [356]	• Fraction of aquatic species affected by pesticides [456]	• Freshwater Living Planet Index (LPI)	• Freshwater Living Planet Index (LPI)
		Soil biodiversity	• Abundance and richness of earthworm species [457] • Earthworm species saturation [356]	• Pesticide Risk Score to Soil Biodiversity [356]	• Microbial soil carbon abundance in soil [458] • Soil macrofauna abundance [407]		
		Above-ground biodiversity	• Species richness for different groups of arthropods [357], [457], [459] • Total number of wild plant species occurring in permanent grassland • Wild flora species saturation • Butterfly species saturation [356]	• Pesticide Risk Score to Biodiversity [356]	• Species richness of farmland vertebrates and plants [460] • Farmland bird species richness [461] • Plant composition-community species richness and evenness [341] • Biodiversity Intactness Index [462]	• Common farmland bird index (CMEF-CAP) • Common bird indices by type of estimate (EUROSTAT) • Species loss embodied in food trade [463] • Proportion of local livestock breeds classified as being at risk of extinction (UN-SDG) • Red List Index (UN-SDG) • Mean Species Abundance Index [464] • Biodiversity Intactness Index [462]	• Species loss embodied in food trade [463] • Red List Index (UN-SDG) • Mean Species Abundance Index [464] • Biodiversity Intactness Index [462]

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