A sustainability assessment of an agroforestry system

The economic, environmental and social sustainability of an agroforestry system compared to a conventional, an organic and a perennial cropping system.

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Swedish University of Agricultural Sciences, SLU
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ABSTRACT

The agricultural sector is facing an increasing number of economic, social and environmental challenges and the development of new sustainable agricultural systems is desired. Agroforestry is an example of a production system that contributes to the transformation of current agricultural systems into more sustainable production systems. The aim of this study is to compare the economic, environmental and social sustainability of an agroforestry system to a conventional, an organic and a perennial cropping system in the south-west of Scania, Sweden. To assess the economic, environmental and social sustainability of the different cropping systems, a selection of indicators from the DiverIMPACTS sustainability assessment framework is used. This study shows an increase in environmental sustainability for the agroforestry systems compared to the conventional system, the organic system and the perennial system. The economic and social sustainability could be a challenge for agroforestry systems. However, the increase in diversity of agroforestry systems provides opportunities to increase the economic sustainability as well as the social sustainability.

Keywords: agriculture, agroecology, cropping systems, sustainable agriculture, sustainable agricultural systems, agroecosystems, DiverIMPACTS, Sweden

FOREWORD

Before you lies the master thesis "A sustainability assessment of an agroforestry system: *The economic, environmental and social sustainability of an agroforestry system compared to a conventional, an organic and a perennial cropping system.*" It has been written to fulfil the graduation requirements of the Agroecology master's program at the Swedish University of Agricultural Sciences (SLU), Alnarp.

After having worked for the marketing departments of several big commercial brands, I realised this was not for me. I didn't want to help big brand become bigger, I wanted to make the world a better place. Cliché, but true. I found a new job in the campaigning team at a company fighting against plastic pollution. Definitely a step in the right direction, but I soon realised I was still missing something. It was all about how bad the situation is, and I missed offering a perspective. It can't be all that bad right? There must be positive forces and developments in the world that we can focus on.

Around the same time, my partner and I went on a road trip through Norway. I was reading a book about forest bathing and the power of trees. Being surrounded by so much nature (which is quite rare in the Netherlands, where I'm from) it really resonated with me and everything became so clear. We need nature. We are nature.

I became a forest therapy guide and started to dig into the power of nature and nature-based solutions, which eventually led me to the combination of food production and trees. This was something I wanted to learn more about. After doing some research, I found out about the Agroecology master's program at SLU and here we are. To fulfil the graduation requirements of the program, I wrote my thesis about agroforestry. A subject very close to my heart, since I truly believe this is what we need to make the world a better place.

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ABBREVIATIONS

%SNH	Semi Natural Habitat
ACI	Carbon input during the rotation
BSOleach	Bare soil during drainage periods
CCD	Crop-cultivar diversity
CCM	Number of crops in the rotation with cultivar mixture
CDI	Crop Diversity Index
EY	Energy Yield
LeachAI	Leaching risk of active ingredient
LEG	Legume in rotation
MNUGHG	Mineral Nitrogen Use for GHG balance calculation
MNUNRJ	Mineral Nitrogen Use for fossil energy use calculation
MPU	Mineral Phosphorus use
NU	Nitrogen Use
NWHC	Proportion of crops harvested in wet conditions
PSC	Proportion of short food supply chain and local distribution
QAI	Amount of active ingredients
SAFE	SITES Agroecological Field Experiment
SCCP	Supplier/customer contribution to profitability
SITES	Swedish Infrastructure for Ecosystem Science
SLU	Swedish University of Agricultural Sciences
VolAI	Volatilization risk of active ingredients
WOL	Work overload

1. INTRODUCTION

Agriculture is changing rapidly as the agricultural sector is facing an increasing number of new challenges: the market is globalised, society is concerned with environmental issues, people face food crises, energy crises call for biofuel production and legislative changes are made at global and local scales are threatening the future of agricultural systems in many areas of the world (Sadok et al. 2009; Bergez 2013; Craheix et al. 2015). Since the Second World War, agriculture has gone through an intensification process, resulting in a massive increase in the production of food. The agricultural model for our current food production systems is mainly based on the Green Revolution, which promoted the cultivation of crops in simplified traditional agroecosystems and replaced biological functions, originally provided by diverse communities of organisms, with increased external inputs of energy and agrochemicals (Bommarco et al. 2013; Jankielsohn 2021). Conventional agriculture is productive in producing food, but high productivity comes at a cost. Our current agricultural production system is associated with socio-economic problems, like farmer communities being pushed away from their land, and ecosystem problems like loss of biodiversity, eroded or depleted soils, pollution, climate change and systems that become increasingly dependent on external inputs (Rosenstock et al. 2014; Tittonell 2014; Gassner & Dobie 2022). Climate extremes are becoming more frequent and violent and threaten the modern homogenous agroecosystems covering 80% of the 1,500 million hectares of global arable land. Moreover, industrial agriculture contributes with about 25–30% of the global Greenhouse Gas (GHG) emissions, further altering weather patterns, thus compromising the world's capacity to produce food in the future (Altieri & Nicholls 2012). To address these challenges, stakeholders from the agricultural sector worked actively to implement more efficient production systems at multiple levels, with cropping systems playing an important role (Pelzer et al. 2012; Bergez 2013; Craheix et al. 2015).

Agroforestry has been suggested as a form of a more sustainable land use, compared to conventional agriculture. Agroforestry combines trees and other woody perennials with crops and livestock in ways that increase and diversify farm and forest production while also conserving natural resources (Araujo et al. 2011). Agroforestry systems have the potential to deliver economic, environmental, and social benefits. Environmentally, agroforestry systems can improve biodiversity, increase ecosystem services, support soil conservation by reducing erosion and soil loss, promote carbon sequestration and contribute to mitigate environmental pressures (Jose 2009; García de Jalón et al. 2018; Kay et al. 2019). Agroforestry systems have the potential to improve the soil chemical, physical and biological properties by adding significant amount of above and belowground organic matter and releasing and recycling nutrients into the system (Jose 2009). For example, the inclusion of nitrogen (N) fixing trees in a cropping system contributes to nutrient recycling and higher nutrient use efficiency, increasing the availability of N in cropping systems (Rosenstock et al. 2014). Also, leaching of N and phosphorus (P) to groundwater or surface runoff is potentially reduced because of the uptake of N and P by tree roots, reducing the need for external N and P fertilizers and reducing the negative impact of external fertilizers on the environment (Bergeron et al. 2011; Pavlidis & Tsihrintzis 2017). Furthermore, agroforestry systems increase natural pest control, potentially reducing the need for pesticides that are harmful to the environment (Pumariño et al. 2015; Gassner & Dobie 2022) and promote water availability in cropping systems by taking up water from deep soil layers and recycle it in upper soil layers through water redistribution (Bayala & Prieto 2020). Economically, agroforestry systems could increase the diversity in products and income (García de Jalón et al. 2018). Diversifications on farms is seen as an essential strategy for economic competitiveness in a global market (Jose et al. 2012). Agroforestry systems could reduce the need for external inputs like N fertilizers (Rosenstock et al. 2014; Giannitsopoulos et al. 2020), P fertilizers (Pavlidis & Tsihrintzis 2017; Giannitsopoulos et al. 2020), and pesticides (Pavlidis & Tsihrintzis 2017), hence reducing the costs of these external inputs. Also, because of the water uptake from deep soil layers by tree roots, which makes the water available to nearby shallow rooted associated crops, the need for irrigation could be reduced (Bayala & Prieto 2020). Furthermore, agroforestry systems could provide renewable energy by producing different bioenergy sources within one comprehensive system (Sharma et al. 2016). Social benefits are for example an increase in rural tourism (Rigueiro-Rodríguez et al. 2009; Mosquera-Losada et al. 2012), landscape improvement (Mosquera-Losada et al. 2012; García de Jalón et al. 2018), an increase in job availability (García de Jalón et al. 2018), and improved human well-being by exposing individuals to nature elements (Ulrich 2007). Perceived as challenges of agroforestry systems could be that they are more complex to manage because the farmer needs to consider a wider range of variables, the increase in required labor, the implementation costs and there could be difficulties using the same machinery as before (García de Jalón et al. 2018). Thus, agroforestry provides a broad range of environmental, social and economic opportunities and challenges. However, these can vary by ecological and economic region. It is essential that researchers obtain information that is region-specific in order to create high-quality models that generalize and expand our understanding of agroforestry (Zamora & Udawatta 2016).

Two alternative cropping systems that could contribute to the transformation of current agricultural systems into more sustainable production systems, are organic cropping systems and perennial cropping systems. Organic cropping systems are widely perceived as being more environmentally friendly than conventional farming and receive substantial support from policy for its contribution to ecosystem services, increasing biodiversity and positively influence landscape (Darnhofer et al. 2010). Organic farming practices have the potential to increase soil organic matter and soil fertility, reducing the need for external inputs (Langmeier et al. 2002; Darnhofer et al. 2010). However, organic cropping systems rely on tillage as the primary means to control weeds (Osterholz et al. 2021). Tillage could accelerate soil carbon loss through exposure and oxidation of soil organic carbon, a process generating CO_2 (Al-Kaisi & Yin 2005). Increased tillage in organic cropping systems could therefore contribute to GHG emissions (Mehra et al. 2018). The crops in perennial systems live for more than 2 years. Perennials are either herbaceous crops which survive winter as underground storage or perennating organs, or woody perennials whose tissues persist above ground. Perennial crops have the potential to improve soil quality, enhance nutrient cycling, and sequester carbon, therefore reducing the need for external inputs (Chantigny et al. 1997; Smith 2004; Lemus et al. 2005; Bessou et al. 2012; Agostini et al. 2015). Since perennial crops provide year-round soil coverage, they protect the soil against erosion and nutrient losses throughout the year. Moreover, perennial crops allocate a considerable amount of carbon to their roots, contributing to higher levels of soil organic matter compared to annual crops (Crews & Rumsey 2017; Crews et al. 2018). Additionally, perennial crops are extremely efficient at taking up nutrients from the soil as a result of their extensive root systems, while nutrient losses via leaching or surface runoff are low (Woodmansee 1978; Masarik et al. 2014; Crews et al. 2018).

The aim of this study is to compare the sustainability of an agroforestry system in the south-west of Scania, Sweden, to three different cropping systems: a conventional system, an organic system and a perennial system. The systems will be compared on economic, environmental and social sustainability. To assess the economic, environmental and social sustainability of the different cropping systems, a sustainability assessment framework developed in the DiverIMPACTS project (Iocola et al. 2020), described in the methods, is used. The following research questions are leading in this study:

i) What is the effect of an agroforestry system on the economic, environmental and social sustainability of the cropping system compared to a conventional system, an organic system and a perennial system?

ii) What are the challenges and opportunities of an agroforestry system compared to a conventional system, an organic system and a perennial system?

2. MATERIALS AND METHODS

2.1 Research site

2.1.1 Lönnstorp research station

The cropping systems compared in this study are located at Lönnstorp research station in the south-west of Scania, Sweden. Lönnstorp research station is the southernmost station of the Swedish Infrastructure for Ecosystem Science (SITES). SITES is a national infrastructure for terrestrial and limnological field research funded by the Swedish Research Council, together with the principals of the research stations. The principles of SITES are the University of Gothenburg, Swedish Polar Research, the Secretariat, Swedish University of Agricultural Sciences, and Uppsala University. Lönnstorp research station belongs to the Department of Biosystem and Technology at the Swedish University of Agricultural Science (SLU), in Alnarp. The station consists of a conventionally farmed area of 60 ha at the station, and an area of 18 ha at Alnarp Campus, which was converted to organic farming in 1993 (certified by KRAV). Established in 1969, the station has a subject focus on cropping system dynamics and provides research opportunities in ecology, environmental science and agroecology (Barreiro & Albertsson 2022).

Lönnstorp research station is situated in a temperate maritime climate with a mean annual temperature of 5.5°C. The hardiness zone is 8a, which means the average minimum temperature lays between -12.2°C and -9.4°C. The soil type can be described as sandy loam soil.

2.1.2 SITES Agroecological Field Experiment (SAFE)

The cropping systems compared in this study are part of the SITES Agroecological Field Experiment (SAFE). This infrastructure was established in 2016 in the conventionally farmed areas at Lönnstorp research station and is a long-term field experiment, consisting out of four agricultural cropping systems: a reference (conventionally managed) cropping system, an organic cropping system, an agroecological intensification (agroforestry) cropping system, and a perennial cereal cropping system. Each cropping system is replicated four times (blocks A, B, C and D) and the total area of SAFE is 14.2 hectares (see Figure 1) (Barreiro & Albertsson 2022).

Figure 1. Overview of the four cropping systems of SAFE: reference (conventional) system (REF), organic system (ORG), agroecological intensification (agroforestry) system (AI), and perennial system (PER); repeated in four blocks (A-D) (Barreiro & Albertsson 2022, p. 4).

2.1.3 Reference (conventional) system

The reference system is a four-year conventionally managed crop rotation. Every block of the reference system covers an area of 0.48 ha and is divided into four different plots, each measuring 50 m x 24 m. The rotation includes the following crops: spring barley (*Hordeum vulgare*), winter oilseed rape (*Brassica napus ssp. Napus*), winter wheat (*Triticum aestivum*) and sugar beets (*Beta vulgaris ssp. vulgaris var. altissima*). A grass legume ley cover crop is established after winter wheat. The grass legume ley is a mixture of 15% tall fescue (*Festuca arundinacea*), 10% red clover (*Trifolium pratense*), 5% white clover (*Trifolium repens*), 20% lucerne (*Medicago sativa*), 30% timothy (*Phleum pratense*) and 20% ryegrass (*Lolium perenne*). All crops are grown every year (see Figure 2) (Barreiro & Albertsson 2022).

All spring crops are followed by a winter crop and the cover crop is established after winter wheat to avoid bare soil as much as possible. No crops or cover crops are established after the harvest of sugar beet due to the late harvest of this crop. The crop rotation used in this system is common in conventional farming in south Sweden. This system is fertilized solely with inorganic fertilizers. Herbicides are usually applied every year to all the crops for weed control. Additionally, fungicides and insecticides are applied when needed. (Barreiro & Albertsson 2022).

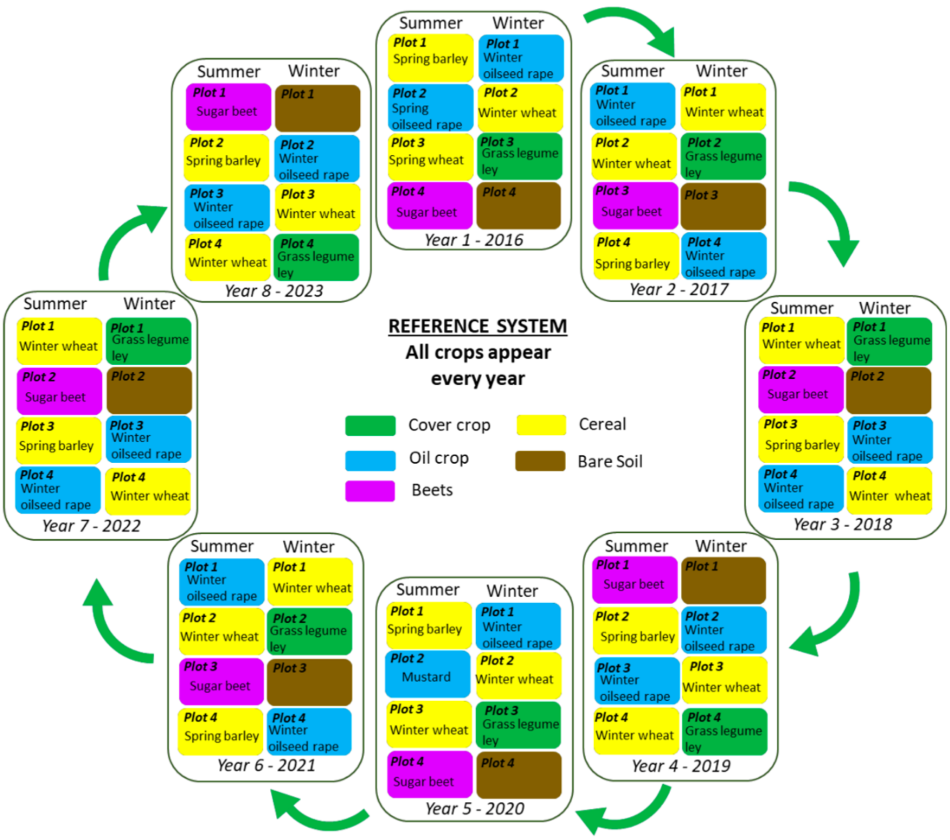


Figure 2. Overview of the crop rotation in the different plots in the reference (conventional) system (Barreiro & Albertsson 2022, p. 5).

2.1.4 Organic system

The organic system is an eight-year organically managed crop rotation. Every block of the organic system covers an area of 0.48 ha and is divided into four different plots, each measuring 50 m x 24 m. The rotation includes the following crops: intercrop of lupine (*Lupinus albus*) with spring barley, winter rye (*Secale cereale*), grass legume ley mixture, sugar beet, intercrop of faba bean (*Vicia faba*) with spring wheat (*Triticum aestivum*), winter oilseed rape, winter wheat and a second grass legume ley mixture. The grass legume ley is the same mixture as the one grown in the reference (conventional) system. All the crops are present in the rotation every two years (see Figure 3) (Barreiro & Albertsson 2022).

All spring crops (intercrop of lupine with spring barley and intercrop of faba bean with spring wheat) are followed by a winter crop (winter rye and winter oilseed rape), and the winter oil seed rape is followed by winter wheat to avoid bare soil as much as possible. Between the rows of winter cereals (wheat and rye) a ley is sown in in the next year's spring. The two species of each intercrop are sown and harvested at the same time. As shown in Figure 3, the initial design of the rotation included red beet. Due to challenges that could not be solved, red beet is replaced by sugar beet in 2019. Since the harvest time of sugar beet is late, it is not possible to establish anything following this crop. Synthetic pesticides or fertilizers are not used in this system. This system is fertilized solely with organic fertilizers and weeds are managed by harrowing directly after ploughing and before sowing. Additional harrowing and manual weeding is performed if needed (Barreiro & Albertsson 2022).

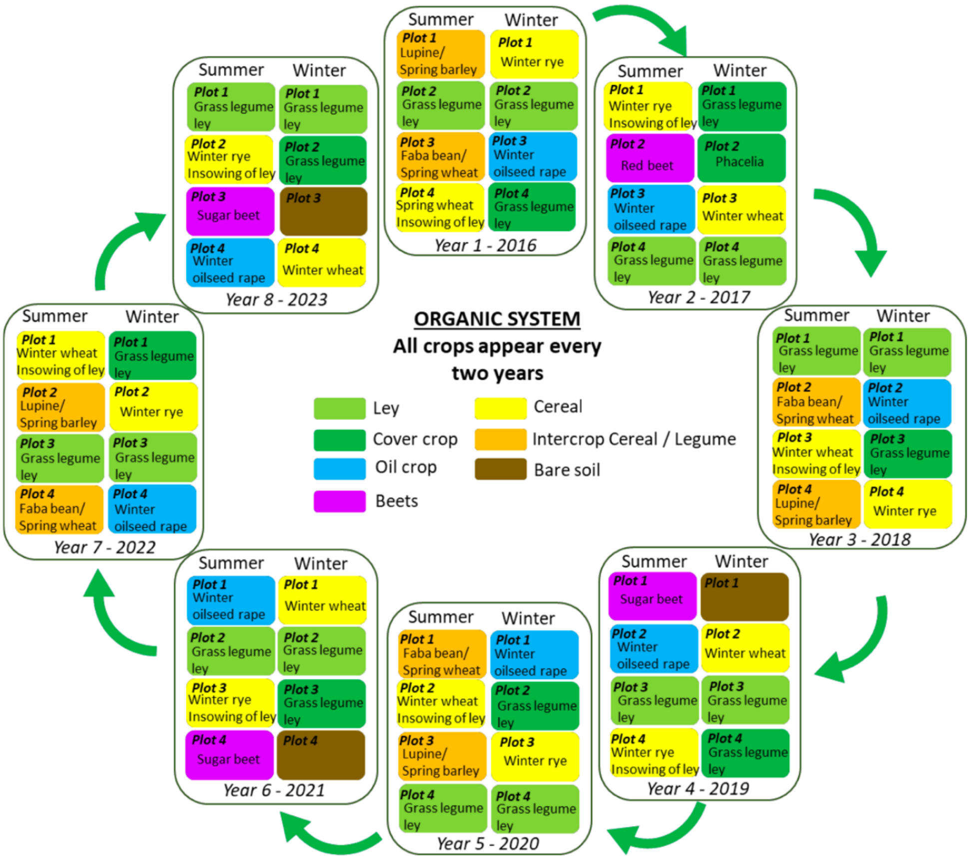


Figure 3. Overview of the crop rotation in the different plots in the organic system (Barreiro & Albertsson 2022, p. 6).

2.1.5 Agroecological intensification (agroforestry) system

The agroecological intensification (agroforestry) system is an eight-year rotation. Every block of the AI system is divided into 15 different plots. Within these 15 plots, four are rows of apple trees (50 m x 2 m), three are rows of hedges (50 m x 2 m) and eight are plots (50 m x 12 m) placed between and outside the rows of apple trees and hedges, where different annual crops are grown. Hence, every block of the AI system covers an area of 0.55 ha. The rotation of the annual crops includes the following crops: intercrop of lupine with spring barley, winter rye, grass legume ley mixture, sugar beet, intercrop of faba bean with spring wheat, winter oilseed rape with alexandrine clover (*Trifolium alexandrinum*), winter wheat and a second grass legume ley mixture (see Figure 4). The grass legume ley is the same mixture as the one grown in the reference (conventional) system. The alexandrine clover is killed by low temperatures in winter. The annual crops are organically managed and per season, the same crop (or crops in case of intercrop) is grown in all the eight annual plots (see Figure 4) (Barreiro & Albertsson 2022).

All spring crops (intercrop of lupine with spring barley and intercrop of faba bean with spring wheat) are followed by a winter crop (winter rye and winter oilseed rape), and the winter oilseed rape is followed by winter wheat to avoid bare soil as much as possible. Between the rows of winter cereals (wheat and rye) a ley is sown in in the next year's spring. The species of each intercrop are sown and harvested at the same time. Since the harvest time of sugar beet is late, it is not possible to establish anything following this crop. Synthetic pesticides or fertilizers are not used in this system. This system is fertilized solely with organic fertilizers and weeds are managed by harrowing directly after ploughing and before sowing. Additional harrowing and manual weeding is performed if needed (Barreiro & Albertsson 2022).

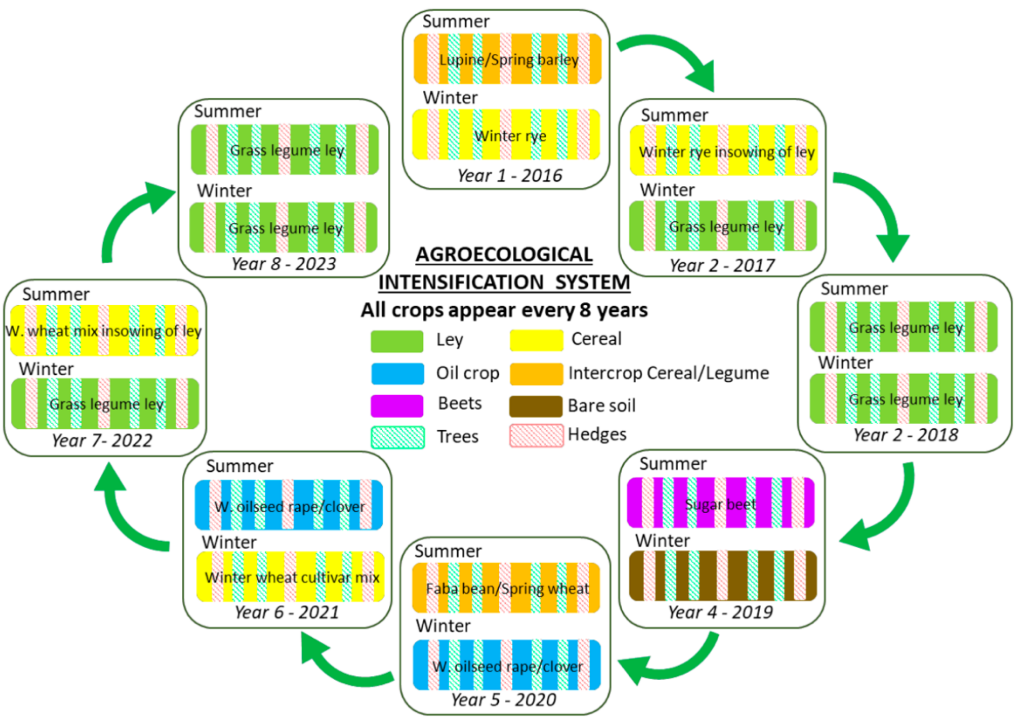


Figure 4. Overview of the crop rotation in the agroecological intensification (agroforestry) system (Barreiro & Albertsson 2022, p. 7).

The hedges in the AI system are planted in 2016, the apple trees are planted in 2017. The apple tree varieties are Topaz (*Malus domestica* 'Topaz'), Aroma (*Malus domestica* 'Aroma') and Santana (*Malus domestica* 'Santana') with rootstock M7. Each one of the rows has a total of 17 apple trees and the distance between the trees is 3 m. In total, each block has 68 apple trees. Some of the apple trees have been damaged by hares, deer and voles after establishment. These trees have been replaced with apple trees of the same variety but with another rootstock (A2). (Barreiro & Albertsson 2022). During the last seasons the apple trees have been replaced continuously due to vole damage.

The species used in the hedge rows are two varieties of blue-berried honeysuckle (*Lonicera caerulea*, cultivars *L. caerulea* 'Ezochi' and *L. caerulea* 'Stubbaröd'), sea buckthorn (*Hippophae rhamnoides*), vosges whitebeam (*Sorbus mougeotii*), black elder (*Sambucus nigra*), goat willow (*Salix caprea*) and two varieties of cherry plum (*Prunus cerasifera* and *P. cerasifera* 'Cecilia'). The trees and the bigger shrubs are placed in the center of each row with a separation on 1.5 m between each other. The smaller shrubs were placed on both sides of the bigger ones in each row, with a separation on 0.5 m between each other. Every hedge row has a different design regarding the distribution of plant varieties (Barreiro & Albertsson 2022).

2.1.6 Perennial system

Every block of the perennial system covers an area of 0.48 ha and is divided into two plots, each measuring 50 m x 48 m. The perennial crops used in this system are intermediate wheatgrass Kernza (*Thinopyrum intermedium*), and an intercrop of Kernza with Lucerne (*Medicago sativa*) (see Figure 5). All crops were planted in 2016 and have been harvested once per year. Synthetic pesticides or fertilizers are not used in this system. This system is fertilized solely with organic fertilizers and no weeding, ploughing or cultivation has been performed since 2016 (Barreiro & Albertsson 2022).

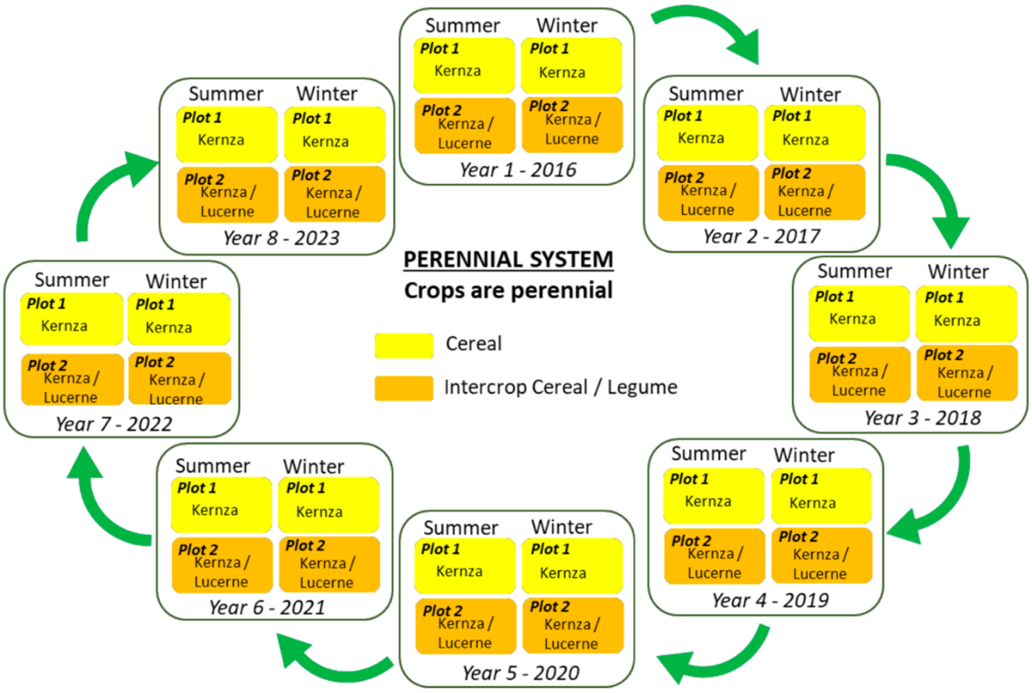


Figure 5. Overview of the crop rotation in the perennial (Barreiro & Albertsson 2022, p. 9).

2.2 Sustainability assessment tool

To assess the economic, environmental and social sustainability of the different cropping systems, a sustainability assessment framework developed in the DiverIMPACTS project (Iocola et al. 2020) is used. Different stakeholders in the agri-food sector, such as farmers, cooperatives, civil society organizations, agri-food industries, interested private companies and researchers, were engaged to co-design a framework of indicators for crop diversification assessment (Iocola et al. 2020). The framework is based on the guidelines of the Sustainability Assessment of Food and Agriculture (SAFA) (FAO 2013). The final framework consists of 19 criteria (six for the economic sustainability, 11 for environmental sustainability, and two for social sustainability) and 32 performance indicators. The criteria are associated with FAO-SAFA themes and sub-themes. The framework of indicators can be used for a critical diagnosis of existing systems (*ex post* assessment) and for the assessment of scenarios (*ex ante* assessment) to identify and design sustainable agricultural systems to be field tested (Iocola et al. 2020). In this study, the framework is used for a critical diagnosis of existing systems (*ex post* evaluation). The complete assessment framework including the criteria and indicators is presented in Table 1.

Table 1. The assessment framework of indicators. The identified criteria are matched with the relative themes/sub-themes (Iocola et al. 2020).

	SAFA Themes/Sub-Themes	Criteria	Indicators
Economic Sustainability	Investment/Profitability	1. Productivity (Prod)	1.1 Energy Yield (EY)*
			1.2 Land Equivalent Ratio (LER)
	Vulnerability/Stability of Production	2. Stability of Production (Stab)	2.1 Yield Coefficient of Variation (YCV)
	Investment/Profitability	3. Profitability (Prof)	3.1 Average gross margin at rotation level (RGM)
	Vulnerability/Risk Management	4. Dependency on external inputs (Dep)	4.1 Total input/turnover (DEI)
	Investment/Profitability; Product Quality and Information/Food Quality	5. Product quality (ProdQ)	5.1 Product standard quality required by the sector/martket (PSQ)
	Investment/Profitability	6. Local valorisation (LocVal)	6.1 Proportion of short food supply chain and local distribution (PSC)*
			6.2 Supplier/customer contribution to profitability (SCCPsuppl and SCCPcust)*
Environmental Sustainability	Biodiversity/Ecosystem Diversity	7. Ecosystem/landscape Diversity (EcosDiv)	7.1 (8.1) Crop Diversity Index (CDI)*
			7.2 Semi Natural Habitat (%SNH)*
	Biodiversity/Species Diversity	8. Crop diversification (CropDiv)	8.1 (7.1) Crop Diversity Index (CDI)*
			8.2 Legume in rotation (LEG)*

Table 1. *Cont.*

Environmental Sustainability	Biodiversity/Genetic Diversity	9. Genetic diversification (GenDiv)	9.1 Crop-cultivar diversity (CCD)*
			9.2 Number of crops in the rotation with cultivar mixture (CCM)*
	Land/Land Degradation	10. Soil degradation (compaction, erosion) (SoilDeg)	10.1 Proportion of crops harvested in wet conditions (NWHC)*
			10.2 Bare soil during erosion risk (intensive rainfall) period (BSOeros)
	Land/Soil Quality	11. Soil Quality (SoilQ)	11.1 (16.4) Carbon input during the rotation (ACI)*
	Fresh water/Water withdrawal	12. Water withdrawal (WatWit)	21.1 Pressure on local water resources (PLWR)
	Fresh water/Water Quality	13. Water quality (nutrient) (WatQualNut)	13.1 Surface nutrient balances (Nitrogen-NBAL and Phosphorus-PBAL)
			13.2 Bare soil during drainage periods (BSOleach)*
	Fresh water/Water Quality	14. Water quality (pesticide) (WatQualPes)	14.1 Leaching risk of active ingredient (LeachAI)*
			14.2 (15.2) Amount of active ingredients (QAI)*
	Atmosphere/Air Quality	15. Air quality (AirQual)	15.1 Volatilization risk of active ingredients (VolAI)*
			15.2 (14.2) Amount of active ingredients (QAI)*

Table 1. *Cont.*

Environmental Sustainability	Atmosphere/Greenhouse gases	16. GHG balance (GHGB)	16.1 Mineral Nitrogen Use for GHG balance calculation (MNUGHG)*
			16.2 Nitrogen Use (NU)*
			16.3 Total fuel consumption for global warming potential calculation (FCFGHG)
			16. 4 (11.1) C input during the rotation (ACI)*
	Materials and Energy/Energy use and Material use	17. Non-renewable resources (NRRes)	17.1 Total fuel consumption for fossil energy use calculation (FCFNRJ)
			17.2 Mineral Nitrogen Use for fossil energy use calculation (MNUNRJ)*
			17.3 Mineral Phosphorus use (MPU)*
Social Sustainability	Human Safety and Health/Public Health	18. Farmer and public health (Health)	18.1 Treatment frequency index (TFI)
	Decent Livelihood/Quality of Life	19. Farmers' quality of life (LifeQual)	19.1 Work overload (WOL)*

* The indicators included in this study.

2.3 Data collection and analyses

For every cropping system in SAFE, a sustainability assessment framework analysis is made. To gather the data needed to calculate the indicators, information regarding the management of the different cropping systems and the knowledge and experience of researchers and field managers involved in SAFE is retained through interviews. The collected data was then organised in an Excel® file prepared by researchers (Iocola et al. 2020). In the Excel® file, formulae are implemented to perform computation of most of the indicators. Seven indicators are supposed to be calculated by SYSTERRE® software, a web-based information system to collect and store farm data, and calculate technical, economic and environmental indicators (Iocola et al. 2020). This study didn't have access to SYSTERRE® software. Therefore, some of these indicators are not included in this study. The indicators that were possible to calculate manually, are calculated as such and are included in this study. The descriptions of how the indicators were calculated can be found in Iocola et al. (2020). More details of how the indicators were calculated can be found in the indicator factsheet (see Appendix 1).

The data available from SAFE is from the year 2016 to the year 2021, in total six years of data. For the agroforestry system, the organic system and the perennial system, the rotation length for the calculations is therefore set to 6 years. For the conventional system, since it is a four-year rotation, the data of the first four years is used for the calculations (2016-2019). Both the conventional and organic system consist out of four plots per year, with different crops grown in every plot, but following the same rotation over the years. Consequently, this means that each plot has a different starting point of the same rotation system. This is due the fact that the cropping systems are set up for research. To be able to give a fair representation of the cropping systems in the comparison, the data used to calculate the indicators consists of the data of one plot in the rotation. Due to resource and time constraint, the data of solely plot 1 (see Figure 2 and Figure 3), is used for this study. For the perennial system, the data of plot 2 (see Figure 5), where the two perennial crops are intercropped, is used for this study.

In the analyses, the agroforestry systems, the organic system, and the perennial system are compared to the reference (conventional) system. Therefore, each indicator of the reference system is set to zero. The results show a percentage change of each cropping system compared to the reference system for each indicator included in this study. In the figures, percentage changes exceeding the value of ±200% were capped to improve visualization. Changes from −5% to +5% are considered a non-relevant change and therefore referred to as neutral (Iocola et al. 2020).

2.3.1 Economic sustainability indicators

Included in this study are Energy yield (EY), Proportion of short food supply chain and local distribution (PSC), and Supplier/customer contribution to profitability (SCCPsuppl and SCCPcust). EY measures the mean energy content of crop yields in a rotation at the cropping system level. To calculate the EY for the conventional and the organic cropping system, the mean of yield t/ha per crop (grown in different plots in different years) is used to give a fair representation of the EY per crop in the cropping systems. PSC measures the capacity of a farm to sell directly to consumers or through short chain mechanisms, and associates the increase in sustainability with a decrease in the percentage of products sold to large-scale distribution (for both export and national market). Lastly, SCCP measures the quality of business relationships of the farmer with his/her suppliers and customers (Iocola et al. 2020).

Not included in this study are Land Equivalent Ratio (LER), Yield Coefficient of Variation (YCV), Average gross margin at rotation level (RGM), Total input/turnover (DEI), and Product standard quality required by the sector/market (PSQ). LER measures the yields of intercropped crops (multiple crops that are grown together) and compares it with yields from growing the same crops in pure stands or in monocultures (Iocola et al. 2020). In the cropping systems compared in this study, the crops that are intercropped are not grown in pure stand or monoculture. Therefore, a comparison between intercropping yields and pure stand or monoculture yields is not possible for the current conditions. YCV assesses the crop yield stability. This indicator requires at least three years of yield data for each crop in the rotation (Iocola et al. 2020). The computation of this indicator is not applicable to the cropping systems that are assessed in current study, since the cropping systems are too young. RGM measures the profitability of crops at the rotation level by calculating a gross margin (Iocola et al. 2020). For current cropping systems there is no data available on work costs, so computation of this indicator is not applicable in these systems. DEI measures the dependency of a system on external inputs (Iocola et al. 2020). For current cropping systems there is no data available on operational costs, so computation of this indicator is not applicable in these systems. PSQ measures the risk of failing to reach the product standard quality required by the sector (Iocola et al. 2020). Quality data of the same crop in multiple years is required to estimate the level of risk. The computation of this indicator is not applicable to the cropping systems that are assessed in current study, since the copping systems are too young.

2.3.2 Environmental sustainability indicators

Included in this study are Crop Diversity Index (CDI), % Semi Natural Habitat (%SNH), % Legume in rotation (LEG), Crop-cultivar diversity (CCD), Number of crop in the rotation with cultivar mixture (CCM), Proportion of crops harvested in wet conditions (NWHC), Bare soil during drainage periods (BSOleach), Carbon input during the rotation (ACI), Leaching risk of activeingredient (LeachAI), Amount of active ingredients (QAI), Volatilization risk of active ingredients (VolAI), Mineral Nitrogen Use for GHG balance calculation (MNUGHG), Nitrogen Use (NU), Mineral Nitrogen Use for fossil energy use calculation (MNUNRJ), and Mineral Phosphorus use (MPU). CDI assesses both the spatial and temporal diversification of a farm, combining species diversity and the proportion of each crop. %SNH measures the share of the agricultural area covered by semi natural agricultural habitats, which contributes to nature conservation and connecting natural areas. Semi-agricultural habitats are considered relatively undisturbed by farming practices. In agricultural ecosystems this could be extensive grassland and pasture, fallow land, extensive margins in cropped land (e.g., hedges, grass buffer strips or flower strips), and low intensity permanent crop areas like fruit orchards and olive groves (OECD 2001). LEG measures the percentage of legumes in the rotation. CCD and CCM assess the genetic diversification in the rotation. NWHC measures the proportion of crops harvested in wet conditions, which affects soil compaction. BSOleach calculates the percentage of bare soil during the nitrate leaching risk period for the rotation. ACI measures the organic carbon input over the course of the rotation. In the DiverIMPACTS sustainability assessment tool, the computation of this indicator is estimated on the basis of values and equations provided by Boiffin et al. (1989) with data commonly available in a farm. This data does not include carbon input by apple trees and the species that are grown in the hedges in the agroforestry system. Due to resource and time constraints, additional data on carbon input by apple trees and the hedge species could not be collected. Therefore, the carbon input by the apple trees and hedges in the agroforestry system are not included in the calculations in this study. LeachAI calculates the active ingredient susceptible to leaching into ground or surface water bodies weighted by a leaching risk factor (Iocola et al. 2020). The leaching risk factor is calculated with the groundwater component of the I-Phy2 indicator for standard conditions

(Lindahl & Bockstaller 2012). QAI assesses the amount of sprayed active ingredient as a causal variable to evaluate the risk for different environmental impacts. VolAI calculates the amount of sprayed active ingredient susceptible to volatility using a volatilization risk factor. MNUGHG assesses the global warming potential associated with the production of synthetic fertilizers applied on the crops in the system. NU assesses the amount of the nitrogen applied on crops through synthetic and organic fertilizers as a proxy of nitrous oxide emissions from the field. MNUNRJ calculates the fossil energy consumption associated with the production of synthetic fertilizers applied on the crops in the system and finally, MPU measures the resource depletion of mineral phosphorus via mineral phosphorus used in the cropping systems (Iocola et al. 2020).

Not included in this study are Bare soil during erosion risk (intensive rainfall) period (BSOeros), Pressure on local water resources (PLWR), Surface nutrient balances (Nitrogen-NBAL and Phosphorus-PBAL), Total fuel consumption for global warming potential calculation (FCFGHG), and Total fuel consumption for fossil energy use calculation (FCFNRJ). BSOeros calculates the percentage of bare soil during the erosion risk period for the rotation. According to the field manager, there has been no soil erosion due to bare soils and heavy rains since he started managing the fields 30 years ago. Therefore, this indicator is set to 0 for all cropping systems. PLWR assesses the relative pressure of water use for irrigation on local water resource in a watershed in the region, taking into account environmental (ecosystem) and human demand (Boulay et al. 2018). Since there was no exact data available on irrigation, this indicator is not included in current study. NBAL and PBAL calculate the surface nutrient balances to assess surpluses or deficits that will impact the environment (Iocola et al. 2020). Both indicators are calculated with SYSTERRE® software and require additional data and computations to be calculated manually. Due to resource and time constraints, these indicators are not included in current study. FCFGHG calculates the global warming potential associated with the consumption and production of fossil fuels used in the system at farm level. FCFNRJ assesses the total fuel consumption for fossil energy use, considering the energy required for producing fossil fuels consumed at farm level (Iocola et al. 2020). Both indicators are calculated on farm level and not on cropping system level. Therefore, both indicators are not included in the current comparison of different cropping systems.

2.3.3 Social sustainability indicators

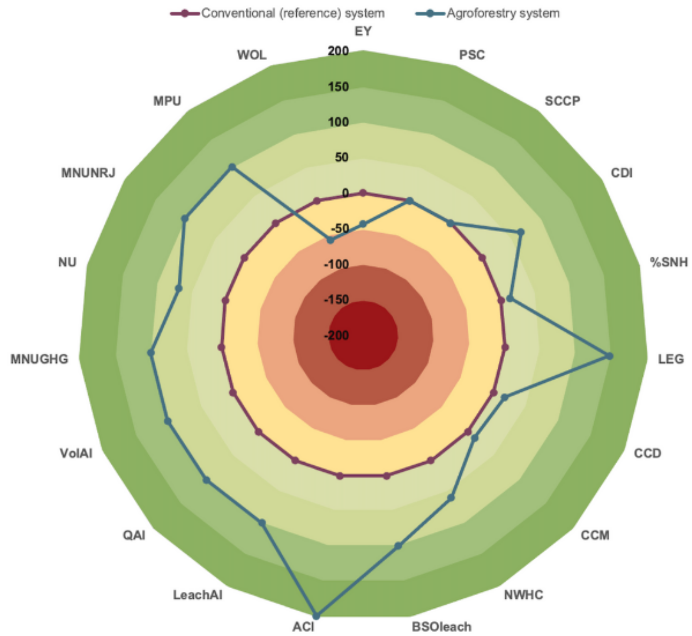
Included in this study is Work overload (WOL), which assesses the potential work overload associated with diversification (Iocola et al. 2020). Not included in this study is Treatment frequency index (TFI), which indirectly assesses the effect of pesticides on health. TFI is calculated with SYSTERRE® software and requires additional data and computations to be calculated manually. Because of resource and time constraints, this indicator is not included in current study.

The assessment framework including the criteria and indicators used in this study is presented in Table 1.

3. RESULTS

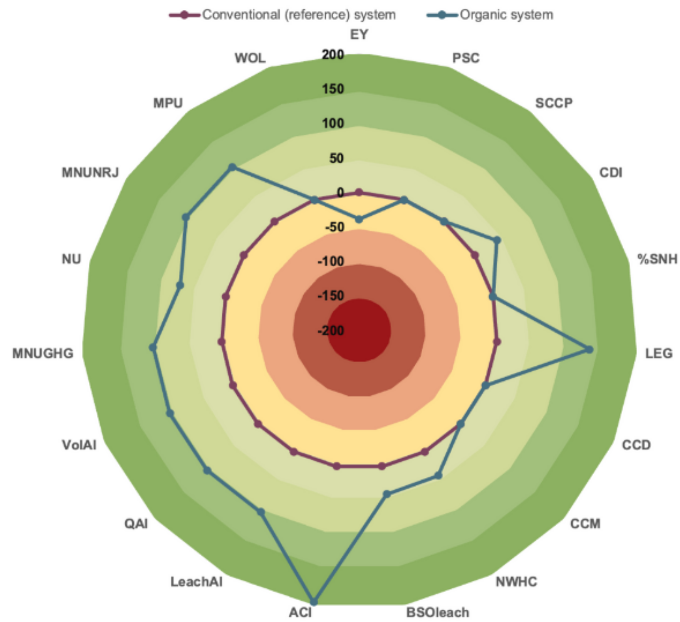
3.1 Overall sustainability of agroforestry compared to a conventional, an organic and a perennial cropping system

The results of the assessment of the agroforestry system compared to the conventional system (see Figure 6) show a decrease in economic sustainability, with one negative change and two neutral indicators. The same applies to for the organic system (see Figure 7) and the perennial system (see Figure 8) compared to the conventional system. The results show an increase in environmental sustainability for all three cropping systems, with 15 positive changes for the agroforestry system (see Figure 6), 12 positive changes and three neutral indicators for the organic system (see Figure 7) and 11 positive changes, three neutral indicators and one negative change for the perennial system (see Figure 8), compared to the conventional system. For the agroforestry system, a decrease in social sustainability is shown in the results (see Figure 6) with one negative change. The social sustainability is neutral for the organic system (see Figure 7) and shows an increase for the perennial system with one positive change (see Figure 8). Overall, the most positive change is seen in the results of the assessment of the agroforestry system.



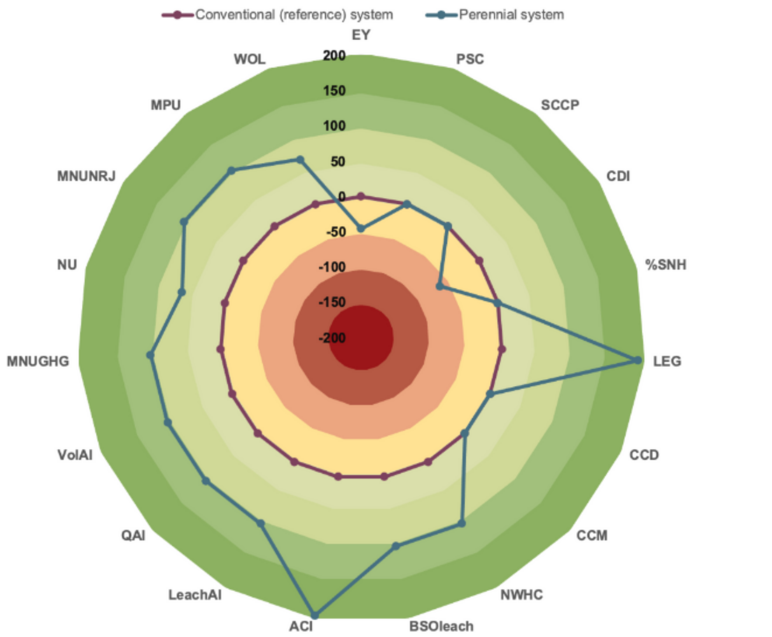
Number of changes	Economic			Environmental			Social		
	positive	neutral	negative	positive	neutral	negative	positive	neutral	negative
Agroforestry system	0	2	1	15	0	0	0	0	1

Figure 6. Radar graph of the sustainability assessment of the agroforestry system.



Number of changes	Economic			Environmental			Social		
	positive	neutral	negative	positive	neutral	negative	positive	neutral	negative
Organic system	0	2	1	12	3	0	0	1	0

Figure 7. Radar graph of the sustainability assessment of the organic system.



Number of changes	Economic			Environmental			Social		
	positive	neutral	negative	positive	neutral	negative	positive	neutral	negative
Perennial system	0	2	1	11	3	1	1	0	0

Figure 8. Radar graph of the sustainability assessment of the perennial system.

3.2 The challenges and opportunities of agroforestry compared to a conventional, an organic and a perennial cropping system.

3.2.1. Economic sustainability

The results of the assessment of the agroforestry system compared to the conventional system (see Figure 6) show a decrease in economic sustainability, due to a decrease in EY (-43.5%). This is a slightly higher decrease in EY than the results shown in Figure 7 of the organic system compared with the conventional system (-38.8%) and a slightly lower decrease in EY than the results shown in Figure 8 of the perennial system compared with the conventional system (-45. 5%). Both local valorisation (proportion of short food supply chain and local distribution) and profitability (supplier/customer contribution to profitability) are neutral for all systems compared to the conventional system (0.00%).

3.2.2 Environmental sustainability

The results of the assessment of the agroforestry system compared to the conventional system (see Figure 6) show an increase in CDI (+65.0%). This is a higher increase in CDI than the results shown in Figure 7 of the organic system compared with the conventional system (+38.3%) The results of the perennial system compared with the conventional system (Figure 8) show a decrease in CDI (-66.7%). %SNH increases with the agroforestry system compared to the conventional system (+13.0%), whereas both the organic system and the perennial system are neutral compared to the conventional system (0.00%). The agroforestry system shows a higher increase in LEG (+147%) than the organic system (+135%) compared to the conventional system. The perennial system shows an even higher increase (+194%). The agroforestry system shows an increase in CCD (+17.0%) and CCM (+13.0), whereas both the organic system and the perennial system are neutral for both indicators (0.00%). The agroforestry system shows a higher increase in sustainability for NWHC (+60.0%) than the organic system (+40.0%) compared to the conventional system. The perennial system shows an even higher increase (+100%). All the systems show an increase in sustainability for BSOleach, with the highest increase for the agroforestry system (+100%) and the perennial system (+100%) and a lower increase for the organic system (+41.2%). All the systems show the same increase in ACI (>+200%). The carbon input in the agroforestry system and in the organic system are 4.01 t C ha^{-1} $year^{-1}$, in the perennial system 4.50 t C ha^{-1} $year^{-1}$ and in the conventional system 0.11 t C ha^{-1} $year^{-1}$. All the systems show the same increase in sustainability for LeachAI (+100%), QAI (+100%), VolAI (+100%), MNUGHG (+100%), MNUNRJ (+100%), and MPU (+100%) compared to the conventional system. The sustainability of NU shows the same increase in the agroforestry system and the organic system (+67.6%) and a slightly lower increase in the perennial system (+62.2%).

3.2.3 Social sustainability

The results of the assessment of the agroforestry system compared to the conventional system (see Figure 6) show a decrease in sustainability for WOL (-58.3%). WOL is neutral in the organic system compared with the conventional system (0.00%), as shown in Figure 7. The results of the perennial system compared with the conventional system (Figure 8) show an increase in sustainability of WOL (+66.7%).

4. DISCUSSION

4.1 Overall sustainability of agroforestry compared to a conventional, an organic and a perennial cropping system

The agroforestry system shows the most positive change towards sustainability compared to the conventional system, the organic system and the perennial system. This is in line with other studies showing that agroforestry systems increase biodiversity conservation (above ground and below ground) (Schroth et al. 2004; Jose 2012), soil enrichment (Jose 2009; Rosenstock et al. 2014), water and air quality (Jose 2009; Bergeron et al. 2011; Pavlidis & Tsihrintzis 2017), and diversity of products and income (García de Jalón et al. 2018). Even though stakeholders identify challenges in implementing agroforestry systems regarding the complexity of work and management costs (Graves et al. 2009; García de Jalón et al. 2018), increased labour (Brownlow et al. 2005; García de Jalón et al. 2018), and administrative burden (García de Jalón et al. 2018; Tsonkova et al. 2018), the advantages are perceived as important benefits, suggesting a net benefit provided by agroforestry systems that is greater than alternative land use options (García de Jalón et al. 2018).

4.2 The challenges and opportunities of agroforestry compared to a conventional, an organic and a perennial cropping system

4.2.1 Economic challenges and opportunities

The economic sustainability of the agroforestry system, the organic system and the perennial system is lower compared to the conventional system due to a decrease in Energetic Yield. Even though Iocola et al. (2020) suggest that a greater diversity in a cropping system should result in a higher Energetic Yield, the yields of the crops grown in the conventional system in current study are higher than the crops grown in the agroforestry system and the organic system which are both more diverse. Garland et al. (2021) found that crop yields were positively correlated with management intensity, implying that yield increases in cropping systems with increasing tillage events and higher fertilizer and pesticides inputs. Therefore, the management of the conventional system with increased tillage events and higher mineral fertilizer and pesticides inputs could be a possible explanation of the differences in yield, even though the agroforestry systems and the organic system have a greater diversity in crops. The greater diversity of the agroforestry system and the organic system could explain the slightly lower decrease in Energetic Yield than the perennial system with a lower crop diversity. As Renard and Tilman (2019) found, using five decades of data on annual yields, a greater diversity of crops increases the year-to-year stability of the total harvest of all crops combined and this effect remains robust after statistically controlling for irrigation, fertilization, precipitation, temperature and other variables. These findings suggest a positive effect of crop diversity on crop yields over time, addressing the importance of crop diversity for stable and resilient agroecosystems for sustainable food production, especially under increasingly unstable climate patterns or extreme weather events (Renard & Tilman 2019; Sanford et al. 2021). In this study, the indicator Yield Coefficient of Variation assessing the crop yield stability is not included since it requires at least three years of yield data for each crop in the rotation (Iocola et al. 2020). The cropping systems that are assessed in current study are too young to calculate this indicator. In line with the findings of Renard and Tilman (2019), an increase in Energetic Yield could be expected for the agroforestry system and the organic system in the future due to greater crop diversity. It is important to note that the agroforestry system hasn't reached its full potential yet at the time of this study. The apple trees in the system haven't reached their full production potential yet, since they have been replaced multiple times during the past few years due to vole damage. Currently, the apple yield is 0.83 t/ha, whereas fruit yield of apple trees could reach up to 140 t/ha (Demestihas et al. 2017). Furthermore, products from the hedges are currently not harvested and the yields not determined. Full productive apple trees and active harvesting and marketing of products coming from the hedges could increase the Energetic Yield and economic value of the agroforestry system. Therefore, the full economic potential of the agroforestry system is not captured by the data of this study.

Since the cropping systems are located on a research site and not on a commercial farm, the focus is not on the economic aspect of the production. Some of the products are sold. These products are sold to large scale distribution (export/national market). Selling the products to large scale distribution is considered an easier solution, due to a transactional cost reduction and lower economic risks (Iocola et al. 2018). However, short chain mechanisms and local markets could result in a premium price for the products and create new sources of income for a farm (Migliorini & Scaltriti 2012). Agroforestry systems provide farmers with the opportunity of generating income from the production of a wide range of conventional and specialty products with a high potential for short chain mechanisms and local markets, providing greater stability through more diversified enterprises with different sources of income and products (Gold et al. 2004, 2015; Jose et al. 2018). Which in turn offers support against yield fluctuations caused by increasingly changeable climate patterns (Hernández-Morcillo et al. 2018). Moreover, short supply chains will improve the business relationship between farmers and supply chain members, including customers, which will contribute to profitability and fair prices for the farmer and the supply chain members (Migliorini & Scaltriti 2012; Hernández-Morcillo et al. 2018). Even though stakeholders involved with agroforestry consider the low profitability of agroforestry systems as one of the most important challenges, the increase in diversity of products, the premium prices the products might provide and new opportunities for income are perceived as major benefits of agroforestry systems (Migliorini & Scaltriti 2012; García de Jalón et al. 2018; Hernández-Morcillo et al. 2018).

4.2.2 Environmental challenges and opportunities

The simplification of cropping systems and a decrease of semi-natural habitat in agriculture have caused a significant decrease of biodiversity in arable land (Bockstaller et al. 2011). Increasing crop species diversity has a positive effect on important ecosystem services and agricultural productivity and stability (Hajjar et al. 2008; Bommarco et al. 2013; Isbell et al. 2017; Renard & Tilman 2019; Sanford et al. 2021). In this study, the highest crop diversity is found in the agroforestry system, compared with the conventional system, the organic system and the perennial system. Also, the share of semi-natural habitat is higher in the agroforestry system compared to the conventional system, the organic system and the perennial system in this study. The share of semi-natural habitat in agroecosystems (e.g., hedges, trees, grass buffer strips or flower strips, wet zones, etc.) is relevant for nature conservation and connectivity among natural areas (Iocola et al. 2020). Studies show that the largest contribution to total biodiversity in agricultural areas comes from natural and semi-natural habitats, which are positively correlated with species richness for vascular plants, birds and arthropods (Bruun 2000; Billeter et al. 2008). The introduction of grain and forage legumes in crop rotations also contributes to diversification of agroecosystems, increasing the diversity of flora, fauna and soil microbes in the systems, hence resulting in more resilient and sustainable agroecosystems (Köpke & Nemecek 2010). Additionally, legumes in crop rotations contribute to nitrogen fixation, soil fertility and productivity (Köpke & Nemecek 2010; Wu et al. 2017; Sánchez-Navarro et al. 2019). In this study, the agroforestry system shows a higher proportion in legumes than the organic system compared to the conventional system, resulting in a higher performance in regard to environmental sustainability. The perennial system shows an even higher proportion, though in this study this is due to the low crop diversity in the perennial system, which results in a higher proportion of the area covered by the intercropped legume in that particular system. The total number of cultivars and/or non-DUS reproductive materials per cropping system and the percentage of crops in the rotation with cultivar mixtures, which are both important for genetic diversity in cropping systems, are highest in the agroforestry system in this study. Increasing crop genetic diversity has a positive effect on pest and disease management, and could increase pollination services and soil processes in specific situations. Especially practices that increase species and genetic diversity, like agroforestry, could improve soil fertility (Hajjar et al. 2008). However, managing ecosystem services could be a challenge since it requires broad knowledge about underlying ecological functions and of the effect of agricultural practices on these functions (Demestihas et al. 2017). Farmers highlighted difficulties in acquiring knowledge about introducing new diversifying agricultural practices in cropping systems. Since advisory services, technologies and markets focus mainly on commodity crops, farmers need to invest their own time to acquire appropriate knowledge about the management of diversified cropping systems (Rodriguez et al. 2021). Therefore, the management of agroforestry systems can be more complex than conventional systems. To promote agroforestry systems and convince farmers that the benefits outweigh the extra costs and work involved in the implementation and management of agroforestry systems, it is important to focus on national demonstration sites and education programs, improved regulation, providing a market for ecosystem services associated with agroforestry, and increasing the opportunities for new profitable businesses (García de Jalón et al. 2018).

To evaluate the impact of crop diversification on the soil, soil degradation and soil quality are evaluated (Iocola et al. 2020). This study included the risk for soil compaction to evaluate soil degradation. The risk for soil compaction in the agroforestry system is lower than in the organic system and the conventional system due to the inclusion and the proportion of sugar beet in the rotations, since sugar beet is frequently harvested in wet soil conditions in areas with moderate climates (Märländer et al. 2003). Due to the total absence of sugar beet in the perennial system, the risk for soil compaction is lowest in that particular system. However, focus on practices to help prevent soil compaction by heavy machinery in these climates could be improved. For example, Ehlers et al. (2000) point out that minimum tillage practices could help prevent soil compaction, but have received little attention thus far. Increased attention for sustainable practices that could help prevent soil compaction could therefore decrease soil degradation and improve the environmental sustainability of cropping systems. Soil quality is related to the presence of soil organic carbon (Iocola et al. 2020). To evaluate soil quality, the current study included carbon input to the soil during the rotation. The amount of organic carbon (e.g., crop and root residues, green manure, organic fertilizers and amendments, etc.) that enters the soil during the course of one rotation is estimated (Iocola et al. 2020). The carbon input in the agroforestry system, the organic systems and the perennial system is significantly higher compared to the carbon input in the conventional system due to the appliance of organic fertilizers (e.g., manure, compost, slurry and digestate) in these systems, resulting in a direct increase in soil organic carbon (Boiffin et al. 1989; Larney & Angers 2012), opposed to the appliance of mineral fertilizers in the conventional system. Research has found that mineral fertilizers can be used to improve soil quality (Geisseler et al. 2017; Singh 2018). However, mineral fertilizers add nutrients to the soil, but not organic matter. Organic amendments add nutrients plus organic matter, offering many more opportunities to improve the physical, chemical and biological properties of the soil (Larney & Angers 2012). As mentioned earlier, the carbon input by the apple trees and hedges in the agroforestry system are not included in the calculations in this study. However, research shows that fruit orchards could sequester 2.4 to 12.5 t C ha^{-1} $year^{-1}$ (Demestihas et al. 2017). For example, Zanotelli et al. (2013) found that the annual organic carbon production of an apple tree can reach up to 8.54 t C ha^{-1} $year^{-1}$ at harvest. 49% of the annual organic carbon production is taken away from the ecosystem through apple production. 5% of the annual organic carbon production is allocated to the increase of the standing biomass, contributing to ecosystem C storage function. 46% of the annual organic carbon production is allocated to organic material (leaves, fine root litter, pruned wood and early fruit falls), contributing to the detritus cycle (Zanotelli et al. 2013). Agricultural management of potentially recyclable materials of trees and hedges such as pruning material or senescent leaves improves carbon input to the soil. Significant amounts of carbon are sequestered via carbon content in organic material and humus production from the decomposition of senescent leaves and pruning material (Sofo et al. 2005; Demestihas et al. 2017).

Regarding water quality with a focus on nutrients, this study shows that the risk of nitrate leaching to surface waters is lowest in the agroforestry system and the perennial system compared to the conventional system. The risk of nitrate leaching to surface waters is marginally higher in the organic system compared to the agroforestry system and the perennial system, but still lower than the risk of nitrate leaching in the conventional system. This is in line with findings suggesting that, even though nitrogen leaching is influenced by soil texture and structure as well as climatic conditions (Demestihas et al. 2017), groundcover management (e.g., cover crops, perennials and trees) significantly reduces nitrogen runoff into surface waters (Kramer et al. 2006; Bergeron et al. 2011; Tribouillois et al. 2016; Demestihas et al. 2017; Pavlidis & Tsihrintzis 2017). The lower impact of pesticides on water quality and air quality in the agroforestry system, the organic system and the perennial system compared to the conventional system, results from the absence of synthetic pesticides in these three systems.

As there is no mineral fertilizer used in the agroforestry system, the organic system and the perennial system, the global warming potential from fertilization is lower in these systems compared to the conventional system. Synthetic fertilizers are the main contributors of greenhouse gas emissions in cropping systems (Van Stappen et al. 2018; Skinner et al. 2019; Rodriguez et al. 2021). Skinner et al. (2019) observed a 40.2% reduction of N_2O emissions per hectare for organic systems compared to non-organic systems. The amount of nitrogen applied on crops through synthetic and organic fertilizers, to estimate the nitrous oxide emissions from the field, is lowest in the agroforestry system and the organic system compared to the conventional system. The amount of nitrogen applied on crops through synthetic and organic fertilizers is slightly higher in the perennial system compared to the agroforestry system and the organic system, but still significantly lower than the amount of nitrogen applied on crops in the conventional system. These results are in line with studies showing that groundcover management, which is applied in the agroforestry system, the organic system and the perennial system in current study, significantly reduces nitrogen runoff, consequently enhancing soil nitrogen availability (Kramer et al. 2006; Bergeron et al. 2011; Tribouillois et al. 2016; Demestihas et al. 2017; Pavlidis & Tsihrintzis 2017). Cover crops can also increase soil nitrogen availability for the next crop once their residues mineralize (Tribouillois et al. 2016). Both the reduction of nitrogen runoff and the increase in soil nitrogen availability, reduce the need of nitrogen fertilizer in cropping systems applying groundcover management. However, cover crops can also cause a decrease in soil nitrogen availability in comparison with bare soil, when competition between non-legume species that mostly take up soil nitrogen is not balanced by nitrogen acquisition and accumulation by legume species that can fix atmospheric nitrogen to increase soil nitrogen availability (Tribouillois et al. 2016). Therefore, non-legume cover crops should be combined with legume cover crops to maximize the benefits of each species. The introduction of trees into the cropping system will also contribute to enhanced soil physical, chemical and biological properties by adding significant amounts of above and belowground organic matter and releasing and recycling nutrients into the system (Jose 2009). Nitrogen fixing trees enrich the soil with carbon and nitrogen via decomposition of plant tissues (e.g., roots and senescent leaves), increasing the availability of nitrogen for other crops in cropping systems (Sitters et al. 2013; Rosenstock et al. 2014), reducing the need for external fertilizer inputs.

As there is no mineral fertilizer used in the agroforestry system, the organic system and the perennial system, the fossil energy consumption due to the production of synthetic fertilizers applied on crops is lower in these systems compared to the conventional system. Mineral fertilizer production is one of the largest contributors to fossil energy consumption by agricultural systems (Van Stappen et al. 2018). Additionally, the lower levels of resource depletion via mineral phosphorus used in cropping systems in the agroforestry system, the organic system and the perennial system compared to the conventional system, results from absence of synthetic fertilizers in these three systems. Therefore, the absence of synthetic fertilizers can be seen as an important measure to improve the environmental sustainability of cropping systems. These findings are in line with research showing that organic farming systems can be a viable measure contributing to a reduction of greenhouse gas emissions in the agricultural sector (Van Stappen et al. 2018; Skinner et al. 2019).

4.2.3 Social challenges and opportunities

The increase in work load in the agroforestry system, results in a lower social sustainability compared to the conventional system, the organic system and the perennial system. The workload of the organic system is perceived neutral compared to the conventional system and the workload of the perennial system is perceived low compared to the conventional system, increasing the social sustainability of the perennial system. These findings are in line with research suggesting that diversification of cropping systems is positively correlated with an increase in labour and complexity of work (Brownlow et al. 2005; García de Jalón et al. 2018). In contrast, in a commercial setting, diversification of cropping systems also provides opportunities for the social sustainability of a farm. For example, diversified cropping systems increase opportunities for short chain mechanisms like local markets and community supported agriculture and could create new farm job opportunities (Migliorini & Scaltriti 2012; García de Jalón et al. 2018; Hernández-Morcillo et al. 2018). As mentioned before, to promote diversified cropping systems like agroforestry and convince farmers and landowners of the benefits of these systems, it is important to focus on national demonstration sites and education programs, improved regulation, providing a market for ecosystem services associated with diversified cropping systems like agroforestry, and increasing the opportunities for new profitable businesses (García de Jalón et al. 2018).

4.3 Limitations of this study and suggestions for future research

Since SAFE is set up for research and the cropping systems are not located on a commercial farm, economic data is missing or does not give a fair representation of what the economics would be for a commercial farm. To calculate the indicators for economic sustainability and make it interesting for commercial farms, assessment should be done on commercial farms with similar cropping systems. Additionally, some of the indicators calculating environmental sustainability automatically score more sustainable for the organically managed systems due to the absence of synthetic fertilizers and pesticides. It would be interesting to assess the sustainability of an agroforestry system including conventionally managed annual crops compared to a conventional system without agroforestry to get a clear picture of the advantages of including agroforestry in cropping systems.

In the sustainability assessment tool used for this study, there is little attention for the advantages of trees and other (woody) perennials. It would be helpful to develop the tool allowing for calculations based on data from trees and other (woody) perennials in cropping systems. Also, in the sustainability assessment tool used for this study, a limited number of indictors measuring social sustainability is included. For a clear representation of the advantages of cropping systems on social sustainability, additional social indicators should be assessed.

To translate the results of this sustainability assessment to agroecological practices adaptable for farmers and managers of commercial farms, additional assessments should be done according the suggestions above. To get insight in the sustainability over time of the cropping systems assessed in this study, it is advisable to repeat the sustainability assessment when cropping systems are older and more developed. Additionally, calculating the indicators for all four plots in the conventional system and the organic system, instead of solely for one plot, is recommended to obtain more representative results regarding the sustainability of these systems.

5. CONCLUSION

This study shows higher environmental sustainability in the agroforestry system compared to the conventional system, the organic system and the perennial system. The economic and social sustainability could be a challenge for agroforestry systems. However, the increase in diversity of agroforestry systems provides opportunities to increase the economic sustainability as well as the social sustainability. A focus on national demonstration sites and education programs, improved regulation, providing a market for ecosystem services associated with diversified cropping systems like agroforestry, and increasing the opportunities for new profitable businesses could help promote the adaptation of agroforestry systems by farmers and landowners.

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SUMMARY

How sustainable is our current food production system? Since the Second World War, agriculture has changed rapidly to feed the growing world population. The focus has been on a high production of food, which resulted in the homogenous agricultural fields you see often around you. These are fields where mostly one crop grows at a time, that are dependent on fertilizers and pesticides to reach the intended productivity. This food production system is successful in producing food, but this high productivity comes at a cost. Our current agricultural production system is associated with social, economic and environmental problems. For example, loss of biodiversity and contribution to climate change. Did you know that agriculture is responsible for about 25-30% of the Greenhouse Gas emissions? To tackle these challenges, stakeholders from the agricultural sector have worked actively on different ways to improve our current agricultural production system. Cropping systems play an important role in these developments. Cropping systems refer to the order in which crops are grown and the management techniques used on a particular field over a period of years. Examples of cropping systems are conventional crop rotations (common in our current agricultural production system), and organic crop rotations.

This study compares four different cropping systems on their performance in relation to sustainability. A conventional system, an organic system, an agroforestry system and a perennial cereal grain system. Organic cropping systems are widely perceived as being more environmentally friendly than conventional farming and are known to increase biodiversity and positively influence landscape. Agroforestry systems combine trees and shrubs with crops and/or livestock to increase and diversify farm and forest production while also conserving both cultivated and wild biodiversity. In perennial cereal grain systems, the crops live for more than 2 years. Since perennial crops cover the soil year-round, they protect and improve the soil, possibly contributing to enhanced soil quality and systems with higher resilience. The four cropping systems are compared on social, economic and environmental sustainability.

When we look at social sustainability, this study shows that the perennial system scores best when work overload is considered. The conventional system and the organic system are neutral and the agroforestry system scores lower on social sustainability. Economically, the conventional systems scores best because of the highest energy yields. Environmentally, taking into account indicators like crop diversity, nitrate leaching risk, and carbon input, the agroforestry system is the winner. Summing up the scores of all the indicators studied in this research, the agroforestry system shows the most sustainable indicators compared to the

conventional system, the organic system and the perennial system, making it overall the most sustainable production system.

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Dear dear Tove, please don't ever change.

APPENDIX 1. INDICATOR FACTSHEET

1. Energetic yield (EY)

Dimension: Economic
Indicator type: Effect
SAFA Theme and Sub-Theme: Investment / Profitability
DiverIMPACTS WP4 internal reference: Productivity (1.1)

Short description
Mean energy content of crop yields in a rotation

Object:
Energy content is an important property of the crop yields. It is also considered a proxy of the efficiency of the system. The indicator is a measure of the mean amount of energy contained in the yields of a rotation at the cropping system level. In this indicator the mean values are used in order to compare the different cropping systems.

Spatial scale: cropping system
Temporal scale: the length of the rotation

Formula

$$EY = (Yield_1 * K_1 + Yield_2 * K_2 + ... + Yield_n * K_n)/n$$

$Yield_n$= Yield (kg/ha DM) of a crop in the cropping system
K_n= energy content (MJ/kg) in a crop
n = length of the cropping system (years)

Energy content in some agricultural products and residues (Villalobos et al., 2016):

Crop	Use	Energy content (MJ/kg D M)	
		Harvested product	Residues
Cereals	Grain	18-19	15.5-18.5
	Forage	18-19	
Legumes	Seed	19-20	18-19
	Forage	18-19	
Soybean	Seed	23.6	19
Cotton	Fiber+ seed	23.8	19
Oil crops	Seed	26-29	18.3-18.8
Sugar beet	Root without crown	17	16.7
Tuber and root crops	Tubers, roots	17	18-20

Grain cereals (wheat, barley, rye, maize, millets, sorghum, rice, triticale); Forage cereals (maize, sorghum); Seed legumes (bean, cowpea, faba bean, lentil, pea, peanut, chickpea); Forage legumes (clover, alfalfa); Oil crops (safflower, sunflowers, rapeseed, flax); Tuber and root crops (potato, cassava, yam, sweet potato). The energy contents of the crops not reported in the table will be provided accordingly to the needs of the CSs

Reference value
The diversified rotations with intercropping and multiple cropping should be characterized by greater EY values than the non-diversified rotations.

Recommendations: No recommendation

Alternative indicator: No suggestion

Reference

Villalobos F.J., Testi L., Mateos L., Fereres E., 2016. The Energy Balance. In: Villalobos F., Fereres E. (eds) Principles of Agronomy for Sustainable Agriculture. Springer, Cham

Agabriel, J., 2010. Alimentation des bovins, ovins et caprins. Besoins des animaux-Valeurs des aliments: Tables Inra 2010. Édition remaniée. Quae éditions.

2. Land Equivalent Ratio (LER)

Dimension: Economic
Indicator type: Effect
SAFA Theme and Sub-Theme: Investment / Profitability
DiverIMPACTS WP4 internal reference: Productivity (1.2)

Short description
LER compares the yields from growing more crops together (intercropping) with yields from growing the same crops in pure stands or in monocultures.

Object:
This indicator measures the effect of the interactions between crops quantifying and evaluating yield advantage of intercrops compared to the pure crops. The resulting number is a ratio that expresses the land area needed in pure cropping to obtain the same yields as in intercrops.

Spatial scale: field level
Temporal scale: crop cycle

Formula

$$LER = (intercrop_1/pure\_crop_1 + intercrop_2)/(pure\_crop_2 + ... + intercrop_n/pure\_crop_n)$$

intercrop = the intercrop yield of one crop (t/ha)
pure crop = the yield of the crop in pure stand (t/ha)

Reference value
An LER greater than 1.0 usually shows that intercropping is an advantage compared to pure cropping, while values that are less than 1.0 shows a disadvantage

Recommendations
No recommendation

Alternative indicator
No suggestion

Reference
Mead, R.,Willey, R. W, 1980. The concept of a Land Equivalent Ratio and advantages in yield from Inter-cropping. Experimental Agric., 16, 217- 218.

3. Yield Coefficient of Variation (YCV)

Dimension: Economic
Indicator type: Effect
SAFA Theme and Sub-Theme: Investment / Profitability
DiverIMPACTS WP4 internal reference: Stability of production (2.1)

Short description
Assessment of the crop yield stability using the coefficient of variation (CV)
Object:
Stability is generally assessed in terms of fluctuation of the yields on a long term average (Conway, 1987; Marten, 1988). The stability of a system could be therefore evaluated calculating the coefficients of variation (CV) of the crop yields in a rotation considering at least three yield data obtained in different years for each crop. Lower the CV, more stable is the system. This indicator could be used to compare the CVs of the single main crops in different systems or the CVs of different rotations.

Spatial scale: single main crop/cropping system
Temporal scale: at least 3 yield measurements (in different years) along the rotation

Formula

$$YCV = \left(\sum_1^y sd_{crop1}/mean_{crop1} + \sum_1^y sd_{crop2}/mean_{crop2} + \sum_1^y sd_{cropn}/mean_{cropn} \right)/n$$

sd_{cropn} = standard deviation of crop yield (t/ha)
$mean_{cropn}$= mean of the crop yield (t/ha)
y = years (at least three different years)
n = number of the crops

Reference value
Lower the YCV, more stable is the system. The diversified rotations should be characterized by < CV of non-diversified rotations.

Recommendations
No recommendation

Alternative indicator
No suggestion

Reference
Conway, G. R., 1987. The properties of agroecosystems. Agricultural systems, 24.2: 95-117.
Marten, G. G., 1988. Productivity, stability, sustainability, equitability and autonomy as properties for agroecosystem assessment. Agricultural systems, 1988, 26.4: 291-316.

4. Average gross or semi net margin at rotation level (RGM or RSNM)

Dimension: Economic
Indicator type: Effect
SAFA Theme and Sub-Theme: Investment - Profitability
DiverIMPACTS WP4 internal reference: Profitability (3.1)

Short description
Assessment of profitability of crops at rotation level by calculating a gross margin, i.e. the difference between products and costs.

Object:
The indicator assesses the profitability of crops or rotation. At this level, profitability can be assessed by the difference between product and direct production cost that can been directly affected to crops like seeds, fertilizer, pesticide, etc.. To evaluate the effect of diversification, the gross margin of a diversified and non-diversified rotation should be compared

Spatial scale: Cropping system
Temporal scale: Length of the rotation

Formula

$$RGM \text{ or } RSNM = [\Sigma_1 (PB_1 - OC_1)])/n$$

RGM = rotation gross margin or RSNM= rotation semi net margin
PB_1 = Gross product (€/ha) = Harvest Yield for each crop in the rotation x market price
OC_1 = Operational charges (€/ha) linked to inputs of seed, fertilizers and pesticides, work, irrigation. Mechanization costs are added to the costs for RSNM.
n = Length of the crop rotation

Reference value
> 100 or more % of non-diversified rotation

Recommendations
It can be calculated at farm level or at cropped surface of the farm (by mean weighted by crop surface). If a crop appears more than once in the rotation, it is better to calculated separately for each crop of the same species along the rotation (see yield indicator) to put in evidence rotational effect.

Alternative indicators
At farm level different farm income indicators are available.

Reference:
Craheix D., Angevin F., Bergez J.-E., Bockstaller C., Colomb B., Guichard L., Reau R., Sadok W., Doré T., 2011. MASC 2.0, Un outil pour l'analyse de la contribution des systèmes de culture au développement durable. Jeu complet de fiches critères de MASC 2.0. INRA - AgroParisTech - GIS GC HP2E, 133 p.

5. Total input/turnover (DEI)

Dimension: Economic
Indicator type: Effect
SAFA Theme and Sub-Theme: Vulnerability / Risk Management
DiverIMPACTS WP4 internal reference: Dependency on external inputs (4.1)

Short description
Economic dependence on external inputs.

Object:
This indicator calculates the fraction of total economic turnover of the cropping system derived from external inputs in the form of operational costs (expressed as a fraction or percentage). A high dependency on external inputs, rather than on-farm resources, heightens economic vulnerability to external shocks and market fluctuations (e.g. in the price of fuel, fertilizer, pesticides). It is calculated using information on yields, crop prices and operational costs of external inputs.

Spatial scale: cropping system
Temporal scale: length of the rotation

Formula

$$DEI = [\Sigma_1 \ (OC_1/PB_1)]/n$$

PB_1 = Gross product (€/ha) = Harvest Yield for each crop in the rotation x selling price
OC_1 = Operational charges (€/ha) linked to inputs of seed, fertilizers and pesticides, fuel, work, irrigation
n = Length of the crop rotation

Reference value
Reference values or benchmarks need to be adapted to the specific rotation, depending on the economic context of the farm. As a general rule, the smaller the DEI, the better, furthermore OC should not exceed PB. In any case the diversified rotations are characterized by < DEI of non-diversified rotations

Recommendations
It is calculated at the level of the rotation for a standardized area (costs expressed in €/ha). Subsidies should be included in the estimate of turnover as an additional source of income. In particular, if subsidies are higher for diversified cropping rotations (e.g. from agri-environmental schemes), then they should be included to reflect a lower dependency for rotation systems compared to monocultures.

Alternative indicator
No suggestion

Reference

Government of France. 2016. Certification Environmentale des Exploitations Agricoles - Plan de Contrôle Niveau 3 - Option B. French Ministry for Agriculture, Nutrition and Forestry, France.

6. Product standard quality required by the sector/market (PSQ)

Dimension: Economic
Indicator type: Effect
SAFA Theme and Sub-Theme: Investment/ Profitability
DiverIMPACTS WP4 internal reference: Product quality (5.1)

Short description
Risk of failing to reach the quality required by the sector
Object:
This indicator aims to assess the risk of not achieving the level of quality requested by the market or by the specific sector on the harvested products (examples: protein content for wheat, absence of visual flaws on vegetables and fruits, etc.). In a cropping system the indicator is calculated as the average of the risk values achieved by each crop along the rotation

Spatial scale: cropping system
Temporal scale: length of the rotation

Formula

$$PSQ = \Sigma i\ Qi / n$$

Qi* = Quality the crop i
n = length of the rotation

Level of Risk	*Values for the coefficient Qi
High: Objective achieved about one year out of three	0
Medium: Objective achieved about one year out of two	1
Low: Objective always achieved	2

Reference value

PSQ	Qualitative classis
PSQ < 1.5	Low
1.5 ≤ PSQ < 2	Medium
PSQ ≥ 2	High

Recommendations: In case of an intercrop or multiple cropping all the crops should be considered for the assessment

Alternative indicator: No suggestion

Reference

MASC 2.0 model
http://wiki.inra.fr/wiki/deximasc/download/package+MASC/WebHome/Jeu%20complet%20de%20fiches%20crit%C3%A8res%20MASC%202.0.pdf
Craheix D., Angevin F., Bergez J.E., Bockstaller C., Colomb B., Guichard L., Reau R., Doré T., 2011. MASC 2.0, un outil d'évaluation multicritère pour estimer la contribution des systèmes de culture au développement durable. Innovations Agronomiques, 20, 35-48.
Craheix D., Angevin F., Bergez J.-E., Bockstaller C.,Colomb B.,Guichard L., Omon B. Reau R., Doré T., 2012. Multicriteria assessment of the sustainability of cropping systems: A case study of farmer involvement using the MASC model. Xth European IFSA Symposium, 1-4 July 2012, Aarhus, Danemark, 8p.

7. Short food supply chain and local distribution (PSC)

Dimension: Economic
Indicator type: Effect
SAFA Theme and Sub-Theme: Investment / Profitability
DiverIMPACTS WP4 internal reference: Local valorisation (6.1)

Short description
To assess the capacity of a farm to sell the production directly to consumers or through short chain mechanisms

Object:
Selling the products to large scale distribution is usually considered an easy solution for farmers because of a lower economic risks, but short chain mechanisms and local markets (i.e., farm shops or collective farmers' shops, solidarity Purchasing Groups, community-supported agriculture, agritourist) could guarantee premium prices and create new opportunities and incomes thus increasing the social-economic sustainability of a farm.

Spatial scale: farm
Temporal scale: the length of the rotation

Formula

$$PSC = 100 - (a + b)$$

a = percentage (%)of products (kg) sold to large scale distribution for export
b = percentage (%)of products (kg) sold to large scale distribution for national market

Reference value
According to Vazzana et al., 2012:

PSC ≥ 50%	high sustainability
PSC < 50%	medium sustainability

Recommendations
No recommendation

Alternative indicator
No suggestion

Reference

Vazzana, C. Moonen, A.C., Bigongiali, F., Bàrberi, P., Lazzerini G., Moschini, V., Colombo, L., 2012. Manuale di DEXI-BIOrt uno strumento per la valutazione agro-ambientale delle aziende orticole biologiche italiane. Progetto SOS-BIO, finanziato dal Ministero delle Politiche Agricole, Alimentari e Forestali. *In Italian*

8. Supplier/customer contribution to profitability (SCCP)

Dimension: Economic
Indicator type: Effect
SAFA Theme and Sub-Theme: Investment / Profitability
DiverIMPACTS WP4 internal reference: Local valorisation (6.2)

Short description
A relationship measure used as indicator of the chain performance
Object:
Being part of a well-performing chain is crucial for a farm. Strong and close relationships with supply chain members, including customers, are needed to reach chain success. Qualitative and successfully relationships are usually obtained in the short supply chains that endorse new behaviours in which the ethical and social components are valorised. In these economic systems, the diversified farms promoting ecosystem services and positive externalities become competitive.
To measure the quality of the business relationships of a farmer with suppliers and customers and quantify their contribution to the farmer economic satisfaction, this indicator (Gellynck et al., 2008) is based on some statements to be answered using a seven-point response scale.

Spatial scale: supply chain
Temporal scale: the length of the rotation

Formula

$SCCP = (SC_{\text{obtained for I Statement}} + SC_{\text{obtained for II Statement}})/2$

SC = Seven-point Likert scale: 1 = completely disagree; 2 = moderately disagree; 3 = slightly unimportant; 4 = neither agree nor disagree; 5 = slightly agree; 6 = moderately agree; 7= completely agree

I Statement: "Our business relationship with our supplier/customer significantly contributes to our profitability"

II Statement: "Our business relationship with our supplier/customer is very attractive because of getting fair prices"

Reference value

SCCP≥ 5.5	high sustainability
2.5 ≤ SCCP < 5.5	medium sustainability
SCCP < 2.5	low sustainability

Recommendations: No recommendation

Alternative indicator: No suggestion

Reference
Gellynck, X., Molnár, A., & Aramyan, L., 2008. Supply chain performance measurement: the case of the traditional food sector in the EU. Journal on Chain and Network science, 8(1), 47-58.

9. Crop Diversity Index (CDI)

Dimension: Environment
Indicator type: Causal
SAFA Theme and Sub-Theme: Biodiversisty- species diversity, ecosystem/landscape Diversity
DiverIMPACTS WP4 internal reference: Ecosystem/landscape (7.1); Crop diversification (8.1)

Short description:
Assessment of crop diversity combining species diversity and proportion of each crop

Object:
Crop species diversity improve important ecosystem services and improve agricultural productivity and stability. The Crop diversity indicator (CDI) is based on the reciprocal Simpson indicator and it assesses diversity by means of a diversity index addressing both crop species richness and the “abundance” of each as for biodiversity indices. This is given by the proportion of each crop in the total cropped area. Furthermore, the indicator can be used to assess both spatial and temporal diversification of a farm.

- **Spatial (spatio-temporal) diversification for the Ecosystem/landscape criterion**

Spatial scale: farm
Temporal scale: one year or duration (years) of the rotation with the most length

Formula

$$CDI = \Sigma_n (1/\Sigma_i p_i^2) / n$$

p_i^2: proportion of the crop i in the total cropped area (expressed on a scale between 0 and 1) within a single year
n = 1 or number of the years of the longest rotation

- **Temporal diversification for the Crop diversification criterion**

Spatial scale: cropping system
Temporal scale: length of the rotation

Formula

$$CDI = 1/\Sigma_i p_i^2$$

p_i^2: proportion of the crop in the rotation (expressed on a scale between 0 and 1)

Reference value:
4 (see Boller *et al.*, 1997)

Recommandations :
It can be calculated for the duration of rotation or for a cropped/farm surface

Alternative indicators
No suggestion

Literature reference:

Bockstaller, C., Lassere-Joulin, F., Slezack-Deschaumes, S., Piutti, S., Villerd, J., Amiaud, B., & Plantureux, S., 2011. Assessing biodiversity in arable farmland by means of indicators: an overview. Oléagineux Corps Gras Lipides, 18(3), 137-144. https://doi.org/10.1684/ocl.2011.0381

Boller, E. F., Malavolta, C., & Jörg, E., 1997. Guidelines for integrated production of arable crops in Europe. Technical guidelines III. IOBC/WPRS Bulletin, 20(5), 5-19.

10. % Semi Natural Habitat (%SNH)

Dimension: Environment
Indicator type: Causal
SAFA Theme and Sub-Theme: Biodiversity/ Ecosystem Diversity
DiverIMPACTS WP4 internal reference: Ecosystem/landscape Diversity (7.2)

Short description
Share of the agricultural area covered by semi natural agricultural habitats.

Object:
The maintenance of semi-natural agricultural habitats can contribute to protect natural resources and their associated species enhancing and guaranteeing agro-environmental and social services and functions as the reduction of soil erosion, the increase of natural enemies of crop pests thus allowing a reduction of the use of pesticides, the improvement of aesthetic quality of the landscape augmenting its recreational value, etc.
According to OECD (2001), the semi-natural agricultural habitats are part of agricultural territory but they are areas relatively undisturbed by farming practices, the use of farm chemicals is totally absent or they are applied at very low rates. These habitats derive from the interactions with other ecosystems and they are classified by OECD (2001) as reported in the following table:

Ecosystem interaction	Semi-natural habitats
Forest ecosystems	Forestry and pastoral woodland
Aquatic ecosystems	Grazing in marshes and water meadows
Agricultural ecosystems	Extensive grassland and pasture; Fallow land; Extensive margins in cropped land (e.g. hedges, grass buffer strips or flower strips); Low intensity permanent crop areas, including certain fruit orchards and olive groves
Mountain ecosystems	Alpine pastures and grass patches
Steppe ecosystems	Dry meadows and dry pastureland

Moreover, for the computation of this indicator, the following uncultivated natural habitats located within the agricultural habitats are also considered as they contribute to provide important ecological services:

Ecosystem	Uncultivated natural habitats
Aquatic ecosystems	Unexploited wetlands, bogs, small ponds, lakes, and diverted rivers
Forest ecosystems	Natural woodlands and forests

Spatial scale: farm level /territory
Temporal scale: -

Formula

$$\%SNH = (A_{SNH} / A_{AA})*100$$

A_{SNH}= total area of the semi-natural agricultural habitats (ha);
A_{AA} = total agricultural area (ha)

Reference value

Greater the percentage reached by the indicator, more sustainable is the system as more beneficial effects are obtained. The diversified systems are usually characterized by greater %SNH values than the non-diversified systems.

Recommendations

Its computation requires field work and GIS analysis but it is easily calculated if a map with the semi natural agricultural habitats is available. The results are strongly influenced by the definition of the semi-natural and semi-natural agricultural habitats and by the spatial resolution used for habitat mapping. In order to allow a comparison among different farms or territories, common methods (same spatial resolution and the inclusion of the same semi-natural habitat) or a standardization of the methods is necessary.

Alternative indicator

No suggestion

Reference

OECD, 2001. Environmental Indicators for agriculture. Methods and Results. Volume 3. Agricultural and food series. Paris: OECD Publications.

BioBio project (Biodiversity indicators for organic and low-input farming systems, EU FP7, KBBE-227161, 2009-2012) - http://www.biobio-indicator.org/

11. % Legume in rotation (LEG)

Dimension: Environment
Indicator type: Causal
SAFA Theme and Sub-Theme: Biodiversity / Species Diversity
DiverIMPACTS WP4 internal reference: Crop diversification (8.2)

Short description
Percentage of legume in the rotation

Object:
The introduction of grain and forage legumes in arable cropping systems through rotation, multiple cropping, and intercropping strategies has not only a positive effect in term of nitrogen fixation, increase of soil organic carbon and weed control, but it also contributes to enhance both temporal and spatial diversification of the agroecosystem. This diversification has a strong influence on the associated diversity of the wild flora, fauna, and soil microbes determining more resilient and sustainable agroecosystems (Köpke and Nemecek 2010, Collette et al., 2011). This indicator considers the percentage of the area covered by legume in a rotation.

Spatial scale: cropping system
Temporal scale: the length of the rotation

Formula

$$CV = (A_1+A_2 + ...+ A_n) *100/TotA$$

A_n = area (ha) covered by legume (cash crop, cover crops, intercropping, etc.)
TotA = Total area covered by all the crops in the rotation

Reference value
According to Vazzana et al., 2012:

LEG ≥ 20%	high sustainability
10% ≤ LEG < 20%	medium sustainability
LEG<10%	low sustainability

Recommendations
In case of intercropping you can calculate the areas covered by the various intercrops in relation to their seeding rates or considering the amounts of their biomass in termination or in harvest phase.

Alternative indicator
An alternative indicator could be the percentage of number of the legume crops in the rotation {(number of legume crops /total crops number)*100}.

Reference
Köpke, U., Nemecek, T., 2010. Ecological services of faba bean. Field Crops Research, 115: 217-233.
Collette, L. , Hodgkin, T., Kassam, A., Kenmore, P., Lipper, L., Nolte, C., Stamoulis, K., Steduto, P., 2011. Save and Grow. Rome, Italy: Food and Agriculture Organization of the United Nations.
Vazzana, C. Moonen, A.C., Bigongiali, F., Bàrberi, P., Lazzerini G., Moschini, V., Colombo, L., 2012. Manuale di DEXI-BIOrt uno strumento per la valutazione agro-ambientale delle aziende orticole biologiche italiane. Progetto SOS-BIO, finanziato dal Ministero delle Politiche Agricole, Alimentari e Forestali. *In Italian*

12. Crop-cultivar diversity (CCD)

Dimension: Environment
Indicator type: Causal
SAFA Theme and Sub-Theme: Biodiversity / Genetic Diversity
DiverIMPACTS WP4 internal reference: Genetic diversification (9.1)

Short description
Total number of cultivars and/or non-DUS reproductive materials per cropping system or per farm

Object:
Genetic crop diversity indicators are necessary and required to detect genetic diversity and potential risk of genetic erosion in an area and along the time. A survey-based determination of crop-cultivar diversity present on farm cannot detect genetic variation at the gene level, but it can be used as a feasible proxy to estimate crop accession diversity.

Spatial scale: cropping system /farm
Temporal scale: length of the rotations

Formula

$$CCD = C_n / Cs$$

CCD = Crop-cultivar diversity
C_n = Total number of crop cultivars and/or non-DUS reproductive materials per farm or cropping system
Cs = Total number of crop species per farm or cropping system

Reference value

CCD value	Sustainability
CCD≥ 1.5	High
1<CCD<1.5	Medium
CCD = 1	Low

Recommendations
In a case of no-DUS (Distinguishable, Uniform and Stable) accessions are cultivated the CCD value is high

Alternative indicator
See PhD of Meul (2008)

Reference

Commission Implementing Decision (2014/150/EU) of 18 March 2014 on the organisation of a temporary experiment providing for certain derogations for the marketing of populations of the plant species wheat, barley, oats and maize pursuant to Council Directive 66/402/EEC. Official Journal of the European Union, L 82/29.

Last, L., Arndorfer, M., Balázs, K. et al., 2014.Indicators for the on-farm assessment of crop cultivar and livestock breed diversity: a survey-based participatory approach. Biodivers Conserv , 23: 3051. https://doi.org/10.1007/s10531-014-0763-x

Meul, M., 2008. Concretisation and operationalisation of ecological sustainability of Flemish farms. PdD thesis University of Ghent, Ghent.

13. Number of crop in the rotation with cultivar mixture (CCM)

Dimension: Environment and Economic
Indicator type: Causal
SAFA Theme and Sub-Theme: Biodiversity / Genetic Diversity, Vulnerability / Risk Management
DiverIMPACTS WP4 internal reference: Genetic diversification (9.2)

Short description
The percentage of crops in the rotation with cultivar mixtures.

Object:
Agricultural cultivars represent and importance repository of genetic diversity. The indicator measures the number of crops in the rotation with multiple cultivars (either spatially or temporally separated). This has implications for risk management, as crop diversity may increase resilience to pests, diseases and extreme weather (i.e. through bet hedging). It is easily calculated by simply counting the number of crops in the rotation with cultivar mixtures and dividing by the total number of crops in the rotation. It therefore ranges 0 (no crops in the rotation) to 1 (all crops in the rotation).

Spatial scale: cropping system
Temporal scale: length of the rotation

Formula

$$CCM = C_C / C_N$$

C_C = Number of crops with mixed cultivars
C_N = Number of crops in the rotation

Reference value
Ranges 0 (no cultivar mixtures) to 1 (all crops in the rotation are planted in cultivar mixtures).

Recommendations
For cases where a crop is repeated in a rotation, but the cultivars in each instance are different, this could lead to an underestimation of cultivar diversity. In such cases, temporally separate cultivar mixtures of the same basic crop should be counted as separate crop cultivar mixtures.

Alternative indicator
An alternative would be to express as an absolute number of "crops with cultivar mixtures" weighted by the number of cultivars in the mix of each crop. This would attribute more weight to more cultivars rather than simply counting each crop with cultivars as 1. A possible weight for the cultivation time of the crop could also account for different cultivation times (i.e. accounting for the time the diversity is actually on the field). Crop genetic diversity can also be assessed in a single integrative indicator combining different indices similar to that above.

Reference

Last, L., M. Arndorfer, K. Balázs, P. Dennis, T. Dyman, W. Fjellstad, J. K. Friedel, F. Herzog, P. Jeanneret, G. Lüscher, G. Moreno, N. Kwikiriza, T. Gomiero, M. G. Paoletti, P. Pointereau, J.-P. Sarthou, S. Stoyanova, S. Wolfrum, and R. Kölliker. 2014. Indicators for the on-farm assessment of crop cultivar and livestock breed diversity: a survey-based participatory approach. Biodiversity and Conservation 23:3051-3071.

Bonneuil, C., R. Goffaux, I. Bonnin, P. Montalent, C. Hamon, F. Balfourier, and I. Goldringer. 2012. A new integrative indicator to assess crop genetic diversity. Ecological Indicators 23:280-289

14. Proportion of crops harvested in wet conditions (NWHC)

Dimension: Environment
Indicator type: Causal
SAFA Theme and Sub-Theme: Land Soil Quality / Land Degradation
DiverIMPACTS WP4 internal reference: Soil Degradation (10.1)

Short description:
Proportion of crops harvested in poor conditions (periods during which the soils are wet)

Object:
The soil compaction induced by agricultural equipment is highly dependent on the type of soil and its water status. In the context of a multi-criteria evaluation, it can be evaluated simply from the proportion of crops harvested in poor conditions (periods during which the soils are wet). This evaluation proposal is based on the assumption that farmers, for the rest of the crop cycle, do not make mechanical intervention when the soil is not sufficiently dried. This criterion is assessed by calculating the proportion (in percent) in the rotation of "at risk" crops involving a harvest in likely wet conditions.

Spatial scale: cropping system/farm
Temporal scale: length of the rotation

Formula

$$NWHC = (NWHCi/CN)*100$$

NWHCi: Number of crops harvested in often wet conditions (e.g. maize, sugarbeet, potatoes, sorghum, catch crops, field vegetable crops harvested in spring or autumn...)
CN: Total number of crops in the rotation

Reference value

Proportion of crops harvested in wet conditions	Qualitative class
NWHC = 0%	Very low
0% < NWHC ≤ 20%	Low to medium
20% < NWHC ≤ 40%	Medium to high
NWHC > 40%	Very high

Recommendations
No recommendation
Alternative indicator
No suggestion

Reference
Craheix D., Angevin F., Bergez J.-E., Bockstaller C., Colomb B., Guichard L., Reau R., Sadok W., Doré T., 2011. MASC 2.0, Un outil pour l'analyse de la contribution des systèmes de culture au développement durable. Jeu complet de fiches critères de MASC 2.0. INRA - AgroParisTech - GIS GC HP2E, 133 p. http://wiki.inra.fr/wiki/deximasc/Main/WebHome

15. Bare soil during erosion risk or drainage periods (BSO)

Dimension: Environment
Indicator type: Causal
SAFA Theme and Sub-Theme:
Land Soil Quality / Land Degradation; Fresh water/Water Quality
DiverIMPACTS WP4 internal reference: Soil degradation (10.2); Water quality (nitrate) (13.2)

Short description
Percentage of bare soil for a given surface or for the rotation during the risk period of nitrate leaching or erosion

Object:
The indicator calculates the percentage of bare soil for a given surface or for the rotation during the risk period of nitrate leaching or erosion. Species diversity is in any case affected by bare soil.

Spatial scale: cropping system/farm
Temporal scale: length of the rotation or pluri-annual

Formula

BSO = 100*surface of bare soil during risk period/surface total

For nitrate leaching:
- Bare soil: soil without living crop cover -> Surface of crop with bare soil in winter: crop sown after winter
- Risk period: during drainage period (mainly winter)

For erosion:
- Bare soil: soil without living crop cover or crop residue-> Surface of tilled crop sown during risk period or in juvenile development stage during risk period; Surface in conservation or reduced tillage excluded.
- Risk period: during intensive rainfall (to be defined locally)

Reference value
<50 % for leaching risk, <70 % for erosion

Recommendations
It can be calculated for the duration of rotation or for a cropped/farm surface

Alternative indicators
An indicator taking into account i) N adsorption (see FP7 Flint project) or ii) rainfall interception (see the C factor in USLE - Universal Soil Loss Equation - erosion model - Hudson, 1993).

Reference

Machet, J. M., Laurent, F., Chapot, J. Y., Dore, T., & Dulout, A., 1997. Maîtrise de l'azote dans les intercultures et les jachères. In G. Lemaire & B. Nicolardot (Eds.), Maîtrise de l'azote dans les agrosystèmes (pp. 271-288). Versailles, Paris: INRA.

Bockstaller, C., Guichard, L., Keichinger, O., Girardin, P., Galan, M. B., & Gaillard, G., 2009. Comparison of methods to assess the sustainability of agricultural systems. A review. Agronomy for Sustainable Development, 29, 223-235. https://doi.org/doi:10.1051/agro:2008058

Hudson, N., 1993. Field Measurement of Soil Erosion and Runoff, Issue 68. Food and Agriculture Organization of the United Nations. pp. 121-126. ISBN 9789251034064.

16. C input during the rotation (ACI)

Dimension: Environment
Indicator type: Causal
SAFA Theme and Sub-Theme: Land / Soil Quality, Atmosphere / Greenhouse Gases
DiverIMPACTS WP4 internal reference: Criteria: Soil quality (11.1); GHG balance (16.4)

Short description
Carbon input to the soil during a single rotation

Object:
The long-term stability and presence of soil organic carbon is a key characteristic of healthy soils. Carbon primarily enters soils through the decomposition of plant matter and via organic substances released by living plant roots (extrusion, sloughing). This indicator reflects the amount of organic carbon (crop and root residues, green manure, organic fertlisers and amendments, etc.) that enters the soil over the course of a single rotation.
The amounts of the C inputs (t C/ha, d.m.) can be indirectly estimated on the basis of values and equations provided by Boiffin et al. (1986) starting from data commonly available in a farm.
The amounts of the C input components not reported in the table will be provided accordingly to the needs of the CSs.

Spatial scale: cropping system
Temporal scale: length of the rotation

Formula

$$ACI = \Sigma (C_i * S_i * Isohum_i) / n$$

C_i = Amount of the component i (i.e, crop residues, crop roots and extra roots, manure, slurry, etc.) in the rotation (t/ha)
S_i = Fraction of the carbon of component i in the rotation
$Isohum_i$ = Isohumic coefficient of component i in the rotation
n = Length of the crop rotation (in years)

According to Boiffin et al. (1986):

Crops and organic fertilizers	Input data for the computation of the indicator	Amount (t/ha) of the different components - C_i				Fraction of the carbon of each component - S_i		Isohumic coefficients - $Isohum_i$	
		Options	Crop residues (CR) at harvest	Root biomass at harvest (RB); RB in a ploughed system (RBP)	Coefficient values	For aboveground biomass	For roots	For aboveground biomass	For roots
Cereals	R = Grain yield (t/ha, wet matter)	Incorporated straw	CR = a*R*(1-W)	RB= b*(1+a)*R(1-W) RBP = b1*RB	W= 0.16 a=1 a1=0.3 b=0.2 b1=0.8	0.45	0.40	0.08	0.15
		Removed straw	CR = a*a1*R*(1-W)						
Mais	R = Grain yield (t/ha, wet matter)	Crop residues not removed	CR = a*R*(1-W)	As above	a = 0.9 see above for the other coefficients	0.44	0.40	0.12	0.15
Silage Mais	MS = Yield (t/ha, wet matter) * dry matter content		CR = a2*MS	RB = b(1+a2)*MS RBP = b1*RB	a2=0.06 see above for the other coefficients	0.44	0.40	0.10	0.15
Sugar beet	R = Root yield (t/ha, wet matter, 16% sugar)		CR = a*R(1-W)	Non harvested roots RBP = b1*R(1-W)/(1-b1)	W=0.8 a=0.6 b1=0.06	0.35	0.40	0.08	0.15
Potato	-		negligible	0.5 t/ha		-	0.40	-	0.15
Green manure	-		3 t/ha	0.8 t/ha		0.44	0.40	0.04	0.15
Rape			5-6 t/ha	1 t/ha		0.44	0.40	0.12	0.15
Pea, bean			3.5 t/ha	1-3 t/ha		0.44	0.40	0.08	0.15
Alfalfa			1-3 t/ha	2-4 t/ha/year		0.44	0.40	0.12	0.15
Manure	T = t/ha, wet matter	T(1-W)			W=0.80	0.35		0.30	
Waste Sludge	T = t/ha, wet matter	T(1-W)			W=0.80	0.18		0.20	

Reference value: No value

Recommendations: No recommendations

Alternative indicator

An alternative would be to express the carbon input as a relative value (%) of total primary productivity returning to the soil. In addition, a humus balance could be calculated using established methods (Brock et al. 2013) and available data (from the literature or field). This would extend beyond carbon to overall changes in soil organic matter, which is more relevant for soil quality (but less so for GHG emissions).

Reference

Boiffin, J., Kéli Zagbahi, J., Sebillote, M., 1986. Système de culture et statut organique des sols dans le Noyonnais : application du modèle de Hénin-Dupuis. Agronomie, 6, 437-446.

Brock, C., U. Franko, H.-R. Oberholzer, K. Kuka, G. Leithold, H. Kolbe, and J. Reinhold. 2013. Humus balancing in Central Europe-concepts, state of the art, and further challenges. Journal of Plant Nutrition and Soil Science 176:3-11.

17. Relative available water remaining (RWAR)

Dimension: Environment
Indicator type: Effect
SAFA Theme and Sub-Theme: Fresh water - Water withdrawal
DiverIMPACTS WP4 internal reference: Criterion: Water withdrawal (12.1)

Short description
Relative available water remaining per area in a watershed, after the demand of humans and aquatic ecosystems has been met (Boulay et al., 2018).

Object:
This indicator assesses the potential of water deprivation, to either humans or ecosystems, building on the assumption that the less water remaining available per area, the more likely another user will be deprived. During periods of low water availability (summer or low water flow), water is considered as a limited resource and water withdrawal for e.g. crop irrigation leads to competition between cropping systems and human or ecosystem demands.
It is first calculated as the water Availability Minus the Demand (AMD) of humans and aquatic ecosystems and is relative to the area ($m^3\ m^{-2}\ month^{-1}$). In a second step, the value is normalized with the world average result (AMD = 0.0136 $m^3\ m^{-2}\ month^{-1}$) and inverted, and hence represents the relative value in comparison with the average m^3 consumed in the world (the world average is calculated as a consumption-weighted average). Once inverted, 1/AMD can be interpreted as a surface-time equivalent to generate unused water in this region. The indicator is limited to a range from 0.1 to 100, with a value of 1 corresponding to the world average, and a value of 10, for example, representing a region where there is 10 times less available water remaining per area than the world average. This method ensures comparability between regions.

Spatial scale: cropping system
Temporal scale: length of the rotation

Formula

$$RWAR = (\Sigma_i\ Ic_i * CF_{mi}) / n$$

RWAR = Relative available water remaining (m^3/year)
Ic_i = Water used for irrigation on crop i (m^3)
CFm_i = characterization factor for month i (m^3/m^3)
n = crop rotation duration (years)

Reference values

	CFm - CHARACTERIZATION FACTORS for AGRICULTURAL USES (m³/m³)											
COUNTRY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Belgium	0.00	0.00	0.00	0.00	0.94	1.40	2.02	2.92	3.30	2.12	0.00	0.00
France	0.00	0.00	0.00	0.74	0.95	2.65	9.93	13.95	4.98	3.18	0.52	0.00
Germany	0.00	0.00	0.00	0.49	0.84	1.10	1.50	2.02	2.29	1.83	1.32	0.00
Hungary	0.00	0.00	0.00	0.73	0.76	0.97	1.28	1.61	1.66	1.44	1.32	0.00
Italy	0.00	0.00	35.07	24.97	29.12	45.54	52.47	57.82	43.11	0.47	0.41	0.00
Netherlands	0.00	0.00	0.00	0.00	0.75	1.00	1.41	1.90	1.91	1.32	0.00	0.00
Poland	0.00	0.00	0.00	0.94	1.24	1.64	1.91	2.36	2.90	3.06	0.00	0.00
Romania	0.00	0.00	0.00	1.61	1.83	6.10	9.28	11.76	13.57	6.93	0.00	0.00
Sweden	0.00	0.00	0.00	0.73	2.01	3.11	4.33	6.09	6.38	6.49	0.00	0.00
Switzerland	0.00	0.00	0.00	0.42	0.45	0.62	2.29	2.71	0.95	0.58	0.34	0.00
United Kingdom	0.00	0.34	0.52	0.90	1.68	2.56	4.50	6.04	6.69	5.26	0.37	0.00

Recommendations
No recommendation

Alternative indicator
Irrigation rate in period of low water availability, according to MASC2 (Craheix et al. 2011)

References
Boulay AM, Bare J, Benini L, Berger M, Lathuillière MJ, Manzardo A, Margni M, Motoshita M, Núñez M, Pastor AV, Ridoutt B, Oki T, Worbe S, Pfister S., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). The International Journal of LCA 23(2): 368-378

Craheix D., Angevin F., Bergez J.E., Bockstaller C., Colomb B., Guichard L., Reau R., Doré T., 2011. MASC 2.0, un outil d'évaluation multicritère pour estimer la contribution des systèmes de culture au développement durable. Innovations Agronomiques, 20, 35-48

18. Surface nutrient balances (NBAl and PBAL)

Dimension: Environment
Indicator type: Causal
SAFA Theme and Sub-Theme: Fresh water/Water Quality
DiverIMPACTS WP4 internal reference: Water quality (nitrate) (13.1)

Short description
N and P Nutrient balances

Object:
Calculation of nutrient balances makes possible to assess surplus or deficit that will impact different environmental compartment. N/P surplus is directly involved in nitrate leaching, phosphate leaching/runoff, and to a less extent of in N gaseous emissions. P and to a less extent N deficit impact soil chemical quality.

Spatial scale: cropping system/farm level
Temporal scale: length of the rotation or pluri-annual

Formula

$$N/PBAL = [\Sigma_i \, input_i - \Sigma_j \, output_j] \, / \, surface$$

$input_i$: amount of input i * nutrient content in input
$output_i$: amount of output i * nutrient content in output
surface: field, fields group or farm surface

Nutrient balance calculations are based on a difference between nutrient inputs and outputs. They can are calculated classically at two levels, farm gate and surface levels. The inputs taken into account are not the same between both levels:

- At cropping system (surface) level, mean inputs are mineral and organic fertilizers, animal dejections, and outputs are crop and forage harvested.
- At farm gate, mean inputs are mineral fertilizers/feeds purchased and outputs: sold animal and crop products.

For N balances: N symbiotic fixation and N atmospheric deposition have to be considered as inputs.

Reference value
For water quality: +25 kg N/ha, soil quality < -25 kg N/ha (to be discussed)

Recommendations
Nutrient balance should be calculated for several years to mitigate interannual variation of yield, e.g. for the duration of rotation.
For N leaching, an indicator assessing soil cover in winter should be associated to a nutrient balance indicator.
For P runoff to surface water, an indicator assessing erosion should be associated to a nutrient balance indicator.

Alternative indicators: Calculation of N/P efficiency

Reference

Godinot, O., Carof, M., Vertes, F., & Leterme, P. , 2014. SyNE: An improved indicator to assess nitrogen efficiency of farming systems. Agricultural Systems, 127, 41-52. https://doi.org/10.1016/j.agsy.2014.01.003
Oenema, O., Kros, H., & de Vries, W., 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. European Journal of Agronomy, 20(1-2), 3-16.
Oenema, O., van Liere, L., & Schoumans, O., 2005. Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of groundwater and surface water in the Netherlands. Journal of Hydrology, 304(1-4), 289-301.

19. Amount of leachable active ingredient (LeachAI)

Dimension: Environment
Indicator type: Effect
SAFA Theme and Sub-Theme: Fresh water/Water Quality
DiverIMPACTS WP4 internal reference: Water Quality (pesticide) (14.1)

Short description
Amount of sprayed active ingredient weighted by a leaching risk factor

Object: This indicator assesses the amount of sprayed active ingredient susceptible to be leached vertically and transferred to ground or surface water bodies. It is based on the calculation of leaching risk factor for each active ingredient (a.i.) by means of an pesticide risk indicator.

Spatial scale: field/cropping system
Temporal scale: year or rotation

Formula

$$\mathrm{LeachAI} = \Sigma_{i} (\mathrm{QAI}_{ij} \,.\, \mathrm{LR}_{ij})$$

LeachAI = Amount of leachable active ingredient (g/ha)
$QAI_{i\,j}$= Amount of sprayed active ingredient i (g/ha) on crop j. : **$QAI_{i\,j}$**= VAI_{jk} . CAI_{ijk} with VAI_{jk} = volume of sprayed pesticide k (commercial product) on crop j CAI_{ij} : concentration of active ingredient I in pesticide k sprayed on crop j
LR_{ij} = Risk factor of leaching for the active ingredient I on crop j (between 0 and 1) calculated with help of the groundwater component of the I-Phy2 indicator (Lindahl and Bockstaller, 2012) for standard conditions

Reference value
The reference value of the leaching component of I-Phy2 is = 0.3 for QAI 1000 g/ha so that LEACH AI=300 g/ha. To take into account uncertainty, precautionary principle we propose 100 g/ha

Recommendations
The value of the indicator does not provide the amount of leached a.i.

Alternative indicator
The leaching risk factor LR can be calculated with another indicator or model than I-Phy2.

Reference

Bockstaller, C., Guichard, L., Keichinger, O., Girardin, P., Galan, M.B., Gaillard, G., 2009. Comparison of methods to assess the sustainability of agricultural systems. A review. Agron. Sustain. Dev. 29, 223-235. https://doi.org/doi:10.1051/agro:2008058
Lindahl, A.M.L., Bockstaller, C., 2012. An indicator of pesticide leaching risk to groundwater. Ecol. Indic. 23, 95-108. https://doi.org/doi:10.1016/j.ecolind.2012.03.014

20. Amount of active ingredients (QAI)

Dimension: Environment
Indicator type: Causal
SAFA Theme and Sub-Theme:
Fresh water/Water Quality
Atmosphere/Air Quality
DiverIMPACTS WP4 internal reference: Water quality (pesticide) (14.1); Air quality (15.2)

Short description
Amount of sprayed active ingredient

Object: This indicator assesses the amount of sprayed active ingredient as a causal variable (pressure) for different environmental impacts

Spatial scale: field
Temporal scale: year or rotation

Formula

$QAI = \Sigma_i \; QAI_{ij}$.

QAI = Amount of sprayed active ingredient (g/ha)
$QAI_{i\,j}$= Amount of sprayed active ingredient i (g/ha) on crop j. : $QAI_{i\,j} = VAI_{jk} \; . \; CAI_{ijk}$ with VAI_{jk} = volume of sprayed pesticide k (commercial product) on crop j CAI_{ij} : concentration of active ingredient I in pesticide k sprayed on crop j

Reference value
We propose a value in relation to previous indicator: 200 g/ha

Recommendations
Decrease or increase of the indicator should be analyzed in relation to their recommended rate. It is possible that the substitution of a pesticide by "more modern" one can automatically lead to a decrease of the indicator.

Alternative indicator
Effect indicator like the amount of leachable a.i (14.1) or volatile a.i. (15.1).
TFI (18.1). However the TFI requires to define a reference rate for each pesticide.

Reference
Hossard, L., Guichard, L., Pelosi, C., Makowski, D., 2017. Lack of evidence for a decrease in synthetic pesticide use on the main arable crops in France. Sci. Total Environ. 575, 152-161. https://doi.org/10.1016/J.SCITOTENV.2016.10.008

21. Amount of volatile active ingredients (VolAI)

Dimension: Environment
Indicator type: Effect
SAFA Theme and Sub-Theme: Atmosphere/Air Quality
DiverIMPACTS WP4 internal reference: Air quality (15.1)

Short description
Amount of sprayed active ingredient weighted by a volatilization risk factor

Object: This indicator assesses the amount of sprayed active ingredient susceptible to be volatilized. It is based on the calculation of a volatilization risk factor for each a.i. by means of an pesticide risk indicator.

Spatial scale: field/cropping system
Temporal scale: year or rotation

Formula

$$VolAI = \Sigma_I (QAI_{Ij} . VR_{Ij})$$

VolAI = Amount of volatile active ingredient (g/ha)
$QAI_{I\,j}$= Amount of sprayed active ingredient i (g/ha) on crop j. : **$QAI_{I\,j}$**= VAI_{jk} . CAI_{ijk} with VAI_{jk} = volume of sprayed pesticide k (commercial product) on crop j CAI_{ij} : concentration of active ingredient I in pesticide k sprayed on crop j
VR_{Ij} = Risk factor of volatilisation for the active ingredient I on crop j (between 0 and 1) calculated with help of the volatilization component of the I-Phy2 indicator based on the regression equations of Woodrow et al. (1997) and transformation rules of Lindahl and Bockstaller (2012).

Reference value
The reference value of the volatilisation component of I-Phy2 is = 0.3 for QAI 1000 g/ha so that VolAI=300 g/ha. To take into account uncertainty, precautionary principle we propose 100 g/ha

Recommendations
The value of the indicator does not provide the amount of volatilized a.i.

Alternative indicator
The volatilization risk factor LR can be calculated with another indicator or model than I-Phy2.

References

Bockstaller, C., Guichard, L., Keichinger, O., Girardin, P., Galan, M.B., Gaillard, G., 2009. Comparison of methods to assess the sustainability of agricultural systems. A review. Agron. Sustain. Dev. 29, 223-235. https://doi.org/doi:10.1051/agro:2008058

Lindahl, A.M.L., Bockstaller, C., 2012. An indicator of pesticide leaching risk to groundwater. Ecol. Indic. 23, 95-108. https://doi.org/doi:10.1016/j.ecolind.2012.03.014

Woodrow, J.S.E., Sieber, J.S.N., Baker, L., 1997. Correlation techniques for estimating pesticide volatilization flux and downwind concentrations. Environ. Sci. Technol. 31, 523-529.

22. Mineral Nitrogen Use for GHG balance calculation (MNU_{GHG})

Dimension: Environment
Indicator type: Effect
SAFA Theme and Sub-Theme: Atmosphere - Greenhouse gases
DiverIMPACTS WP4 internal reference: Criterion: GHG balance (16.1)

Short description:
Global warming potential associated with the production of mineral (synthetic) fertilizers applied on crops

Object:
As mineral fertilizer production is one of the biggest contributors to greenhouse gas (GHG) emissions from cropping systems (Van Stappen et al., 2018), this indicator is used as a proxy for assessing impacts on global warming via GHG emissions from mineral fertilizer production.
It takes into account applied nitrogen (kg N) on each crop of the rotation, the type(s) of mineral fertilizer applied and the global warming potential associated with mineral fertilizer production.

Spatial scale: cropping system
Temporal scale: length of the rotation

Formula

$$MNU_{GHG} = (\Sigma_i (Nmin_{Fj} * GWP_{Fj})) / n$$

MNU_{GHG} = Global warming potential *via* synthetic nitrogen use (kg CO_2eq. /year)
$Nmin_{Fi}$ = Total mineral (=synthetic) nitrogen applied on crop i, in the form of fertilizer j (kg N/ha)
GWP_{Fj} = Global warming potential for fertilizer j production (kg CO_2eq./kg N)
n = crop rotation duration (years)

Reference value

GWP_{Fj} : Global warming potential for mineral fertilizer production (kg CO_2eq./kg N) (*)	
Ammonium nitrate	8.16
Ammonium sulfate	1.82
Calcium ammonium nitrate	8.30
Calcium nitrate	3.14
Diammonium phosphate	2.91
Nitrogen fertilizer, undefined	11.37
Urea ammonium nitrate	5.73
Urea	3.33

(*) Ecoinvent v3.3

Recommendations
The nitrogen content of applied fertilizers must be known (kgN/kg fertilizer). If not, standard nitrogen contents can be provided (see Ecoinvent).

Alternative indicator
No suggestion

References
Ecoinvent - life cycle inventory database v3.4 (https://www.ecoinvent.org/home.html)

23. Nitrogen Use (NU)

Dimension: Environment
Indicator type: Causal
SAFA Theme and Sub-Theme: Atmosphere/Greenhouse Gases; Atmosphere/Air Quality
DiverIMPACTS WP4 internal reference: GHG balance (16.2)

Short description
Total nitrogen applied on crops through mineral (synthetic) and organic (e.g. farmyard manure) fertilizers used as a proxy of nitrous oxide emissions

Object:
Nitrous oxide (N2O) is one of the most important of non-CO2 greenhouse gases (GHG) and agriculture represents its largest anthropogenic source. Numerous field studies reported that N2O emissions are well correlated with fertilizer N rate (Dusenbury et al., 2008; Halvorson et al., 2008). In all of these studies, the increase of the amount of N added to soil resulted in an augmentation of N2O emissions. This is also the basis for the IPCC (2006) greenhouse gas inventory calculations. This indicator uses the amount of N fertilizers applied in field along the rotation as a proxy of N2O emissions.

Spatial scale: cropping system
Temporal scale: length of the rotation

Formula

$$NU = (\Sigma_i N_{min}c_i + N_{org}c_i) / n$$

NU = nitrogen use (kg N/ha /year)
$N_{min}c_i$ = mineral nitrogen applied on crop i (kg N/ha)
$N_{org}c_i$ = organic nitrogen applied on crop i (kg N/ha)
n = crop rotation duration (years)

Reference value
-

Recommendations
The nitrogen content of applied fertilizers must be known. If not, standard nitrogen contents can be provided (see ecoinvent).

Alternative indicator
No suggestion

References

Dusenbury MP, Engel RE, Miller PR, Lemke RL, Wallander R , 2008. Nitrous oxide emissions from a Northern Great Plains soil as influenced by nitrogen management and cropping systems. J Environ Qual 37(2):542-550
Halvorson AD, Del Grosso SJ, Reule CA, 2008. Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. J Environ Qual 37(4):1337-1344
IPCC, 2006. IPCC guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme, Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds). Published: IGES, Japan

24. Global warming potential from total fuel consumption at farm level (FCFGHG)

Dimension: Environmental
Indicator type: Effect
SAFA Theme and Sub-Theme: Atmosphere - Greenhouse gases
DiverIMPACTS WP4 internal reference: GHG balance (16.3)

Short description:
Global warming potential associated with the production and use (through fuel combustion in tractor motor) of fuel(s) consumed at farm level, including machinery consumption for field and farm work processes, and fuel consumption for heating/cooling systems

Object:
This indicator can be approximated by referring total fuel purchases (petrol, diesel, natural gas, etc.) by a farmer within one year. It can be then translated into a global warming potential associated with fuel production and GHG emissions from fuel combustion on field.

Spatial scale: farm level
Temporal scale: length of the rotation

Formula

$$FCF_{GHG} = (\Sigma_i (C_{FUj} * (GWPP_{FUj} + GWPE_{FUj})) / n$$

FCF_{GHG} = Global warming potential for producing and combusting fuels used at farm level (kg CO_2eq./year)
C_{FUj} = Total consumption of fuel j, within one year (kg/ha)
$GWPP_{FUj}$ = Global warming potential for fuel j production (kg CO_2eq./kg fuel j)
$GWPE_{FUj}$ = Global warming potential from fuel j combustion (kg CO_2eq./kg fuel j)
n = crop rotation duration (years)

Reference value

	GWP_{FUj} : Global warming potential for fuel production (kg CO_2eq./kg fuel) (*)	$GWPE_{FUj}$: Global warming potential from fuel combustion (kg CO_2eq./kg fuel) (*)
Diesel	0.55	3.16
Petrol, unleaded	0.77	3.12
Light fuel oil	0.55	...
Liquefied petroleum gas	0.69	...
...	...	

(*) Ecoinvent v3.3

Recommendations
Conversions from litres (l) to kg should be provided (e.g. diesel = 0.84 kg/l) because fuel purchase bills will probably be expressed in litres.

Alternative indicator
No suggestion

References
Ecoinvent v3.3 (https://www.ecoinvent.org/home.html)

25. Total fuel consumption at farm level for fossil energy use calculation (FCF_{NRJ})

Dimension: Environmental
Indicator type: Effect
SAFA Theme and Sub-Theme: Materials and Energy - Energy use
DiverIMPACTS WP4 internal reference: Criterion: Fossil energy and mineral P use (17.1)

Short description:
Total fuel consumption at farm level, including machinery consumption for field and farm work processes, fuel consumption for heating/cooling systems

Object:
This indicator can be approximated by referring total fuel purchases (petrol, diesel, natural gas, etc.) by a farmer within one year. It can be then translated into a total energy consumption for fuel production.

Spatial scale: farm level
Temporal scale: length of the rotation

Formula

$$FCF_{NRJ} = (\Sigma_{i} (C_{Fj} * FED_{FUj})) / n$$

FCF_{NRJ} = Fossil energy consumption *via* fuel consumption at farm level (MJ/year)
C_{FUj} = Total consumption of fuel j, within one year (kg/ha)
FED_{FUj} = Fossil energy demand for fuel j production (MJ/kg)
n = crop rotation duration (years)

Reference value

FED_{FUj} : Fossil energy demand for fuel production (MJ/kg) (*)	
Diesel	56.73
Petrol, unleaded	59.51
Light fuel oil	56.59
Liquefied petroleum gas	57.57

(*) Ecoinvent v3.3

Recommendations
Conversions from litres (l) to kg should be provided (e.g. diesel = 0.84 kg/l) because fuel purchase bills will probably be expressed in litres.

Alternative indicator
No suggestion

References
Ecoinvent v3.3 (https://www.ecoinvent.org/home.html)

26. Mineral Nitrogen Use for fossil energy use calculation (MNU_{NRJ})

Dimension: Environmental
Indicator type: Effect
SAFA Theme and Sub-Theme: Materials and Energy - Energy use
DiverIMPACTS WP4 internal reference: Fossil energy and mineral P use (17.2)

Short description:
Fossil energy consumption associated with the production of mineral (synthetic) fertilizers applied on crops

Object:
As mineral fertilizer production is one of the biggest contributors to fossil energy consumption by cropping systems (Van Stappen et al., 2018), this indicator is used as a proxy for assessing fossil energy use via fossil energy consumption by mineral fertilizer production.

Spatial scale: cropping system
Temporal scale: length of the rotation

Formula

$$MNU_{NRJ} = (\Sigma_i (Nmin_{Fj} * FED_{FEj})) / n$$

MNU_{NRJ} = Fossil energy use *via* mineral nitrogen use (MJ/year)
$Nmin_{Fi}$ = Total mineral (=synthetic) nitrogen applied on crop i, in the form of fertilizer j (kgN/ha)
FED_{FEj} = Fossil energy demand for fertilizer j production (MJ/kgN)
n = crop rotation duration (years)

Reference value

FED_{FEj} : Fossil energy demand for mineral fertilizer production (MJ/kg N) (*)	
Ammonium nitrate	57.25
Ammonium sulfate	23.24
Calcium ammonium nitrate	59.08
Calcium nitrate	17.36
Diammonium phosphate	52.83
Nitrogen fertilizer, undefined	71.83
Urea ammonium nitrate	57.09
Urea	59.10

(*) Ecoinvent v3.3

Recommendations
The nitrogen content of applied fertilizers must be known (kg N/kg fertilizer). If not, standard nitrogen contents can be provided (see ecoinvent).

Alternative indicator
No suggestion

References
Ecoinvent v3.3 (https://www.ecoinvent.org/home.html)

27. Mineral Phosphorus use (MPU)

Dimension: Environment
Indicator type: Effect
SAFA Theme and Sub-Theme: Materials and Energy - Material use
DiverIMPACTS WP4 internal reference: Fossil energy and mineral P use (17.3)

Short description:
Total mineral phosphorus applied on crops through mineral (synthetic) fertilizers

Object:
Considering phosphorus rarefaction and intense use by agriculture, this indicator is used to approximate resource depletion *via* mineral phosphorus used by crop rotation.

Spatial scale: cropping system
Temporal scale: length of the rotation

Formula

$$MPU = \Sigma_i P_{min}c_i / n$$

MNU = Mineral phosphorus use (kgN/year)
$P_{min}c_i$ = Total mineral (=synthetic) phosphorus applied on crop i (kg P/ha)
n = crop rotation duration (years)

Reference value
< non-diversified systems

Recommendations
The phosphorus content of applied fertilizers must be known (kg N/kg fertilizer). If not, standard phosphorus contents can be provided (see ecoinvent).

Alternative indicator
No suggestion

References
-

28. Treatment frequency index (TFI)

Dimension: Social, environmental
Indicator type: Causal
SAFA Theme and Sub-Theme:
DiverIMPACTS WP4 internal reference: Farmer and public health (18.1)

Short description
Indirect assessment of pesticides effects on health

Object:
The phytosanitary Treatment Frequency Indicator (TFI) is an indicator for monitoring the use of plant protection products. The TFI records the number of reference doses used per hectare over a rotation. This indicator can be calculated for a field, a set of parcels, a farm or a territory. It can also be broken down by major product categories (herbicides; fungicides; insecticides and acaricides; other products).

Spatial scale: Field, farm, territory
Temporal scale: Rotation

Formula

$$TFI = \sum TFI_i / n$$

TFIi: Annual TFI per field accounting for insecticides, fungicides, herbicides, acaricides and other plant production products.
N: Rotation duration

Calculation of TFI per year:

$$TFI = (AD \times TA) / (DH \times FA)$$

AD: applied dose
TA: treated area
DH: registered dose
FA: field area

Reference value

Total Treatment frequency	Qualitative class
TFI = 0	Null
0 < TFI ≤ 3	Low
3 < TFI ≤ 5	Medium
TFI > 5	High

Recommendations: No recommendation

Alternative indicator: Health risks for the applicator (See MASC factsheets)

Reference

Craheix D., Angevin F., Bergez J.-E., Bockstaller C., Colomb B., Guichard L., Reau R., Sadok W., Doré T., 2011. MASC 2.0, Un outil pour l'analyse de la contribution des systèmes de culture au développement durable. Jeu complet de fiches critères de MASC 2.0. INRA - AgroParisTech - GIS GC HP2E, 133 p. http://wiki.inra.fr/wiki/deximasc/Main/WebHome
Ministère de l'agriculture et de l'alimentation (2018). L'indicateur de fréquence de traitement, 4p. http://agriculture.gouv.fr/indicateur-de-frequence-de-traitements-phytosanitaires-ift

29. Work overload (WOL)

Dimension: Economic
Indicator type: Effect
SAFA Theme and Sub-Theme: Decent Livelihood / Quality of Life
DiverIMPACTS WP4 internal reference: Farmers' quality of life (19.1)

Short description
Work overload for the farmer due to diversification

Object:
Work overload is a key factor affecting farmers' quality of life. The indicator assesses the change in work overload due to diversification. A higher work overload due to diversification will hamper diversification

Spatial scale: cropping system/farm
Temporal scale: length of the rotation

Formula

$$WOL = 100 * [\sum_i (WOL_i)]/12$$

WOL_i: work overload for month i expressed on a scale between 0 (low) and 3 (very high)

Reference value:
< 17 % i.e. 1 month with a work overload = 2 (medium/high)

Recommendations
No recommendations

Alternative indicators
A assessment of change of life quality due to diversification can be run by the farmer directly and can be assessed on a scale between 1 and 3 for example.

Reference
Craheix D., Angevin F., Bergez J.-E., Bockstaller C., Colomb B., Guichard L., Reau R., Sadok W., Doré T., 2011. MASC 2.0, Un outil pour l'analyse de la contribution des systèmes de culture au développement durable. Jeu complet de fiches critères de MASC 2.0. INRA - AgroParisTech - GIS GC HP2E, 133 p.

APPENDIX 2. FACTSHEET FOR FARMERS & GENERAL PUBLIC

HOW SUSTAINABLE ARE AGROFORESTRY SYSTEMS?

The economic, environmental and social sustainability of an agroforestry system compared to a conventional, an organic and a perennial cropping system.

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Alnarp 2023

THE IMPORTANCE

Our current food production system is associated with social, economic and environmental challenges, like loss of biodiversity and contribution to climate change. To tackle these challenges and to improve our current agricultural production system, cropping systems play an important role. This study compares four different cropping systems on sustainability. A conventional system, an organic system, an agroforestry system and a perennial cereal grain system. The four cropping systems are compared on social, economic and environmental sustainability

Apple tree at Tolhurst Organics CIC (AGFORWARD project)

"Cropping systems are at the core of improving agricultural production systems"

To measure the economic, social and environmental sustainability of the four cropping systems, the following indicators are included in this study:

Economic indicators

- Energy yield.
- Proportion of short food supply chain and local distribution.
- Supplier/customer contribution to profitability.

Social indicators

- Work overload

Environmental indicators

- Crop Diversity Index.
- % Semi Natural Habitat.
- % Legume in rotation.
- Crop-cultivar diversity.
- Number of crop in the rotation with cultivar mixture.
- Proportion of crops harvested in wet conditions.
- Bare soil during drainage periods.
- Carbon input during the rotation.
- Leaching risk of active ingredient
- Amount of active ingredients.
- Volatilization risk of active ingredients.
- Mineral Nitrogen Use for GHG balance calculation.
- Nitrogen Use.
- Mineral Nitrogen Use for fossil energy use calculation.
- Mineral Phosphorus use.

Wakelyns Agroforestry, Suffolk UK, Hazel and potatoes (Martin Wolfe, Organic Research Center).

THE RESULTS

When we look at social sustainability, this study shows that the perennial system scores best when work overload is considered. The conventional system and the organic system are neutral and the agroforestry system scores lower on social sustainability. Economically, the conventional systems scores best because of the highest energy yields. Environmentally, taking into account indicators like crop diversity, nitrate leaching risk, and carbon input, the agroforestry system is the winner.

CONCLUSION

This study shows that agroforestry systems are more sustainable when it comes to environmental factors compared to conventional systems, organic systems and perennial systems. The economic and social sustainability could be a challenge for agroforestry systems. However, the increase in diversity of agroforestry systems provides opportunities to increase the economic sustainability as well as the social sustainability.

WHAT'S NEXT?

To promote the adaptation of agroforestry systems by farmers and landowners, the following actions should be considered:

- The development of national demonstration sites and education programs.
- Improved regulation.
- Providing a market for ecosystem services associated with diversified cropping systems like agroforestry.
- Increasing the opportunities for new profitable businesses could help

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