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Farm-level indicators for resilience to climate change stressors

For assessing mixed and agroforestry farms as well as mono-activity farms

16 July 2021

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Deliverable 1.3	Indicators of resilience on farm level
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Photo on front page: *Photo of poplar silvoarable experiment at Cranfield University, Bedfordshire, UK; photo by Paul Burgess.*

[1] **R**=Document, report; **DEM**=Demonstrator, pilot, prototype; **DEC**=website, patent fillings, videos, etc.; **OTHER**=other

[2] **PU**=Public, **CO**=Confidential, only for members of the consortium (including the Commission Services), **CI**=Classified

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1 Introduction

1.1 Context

In the AGROMIX project, the concept of resilience of farms and farming systems is applied specifically to farming systems categorized as mixed farming (MF) and agroforestry (AF) systems. Figure 1 shows three separate farming practices (forestry, arable farming and livestock rearing) and their potential combinations that are seen as MF or AF systems. Mono-activity systems are positioned in the three corners of figure 1 (Püttsepp et al 2021).

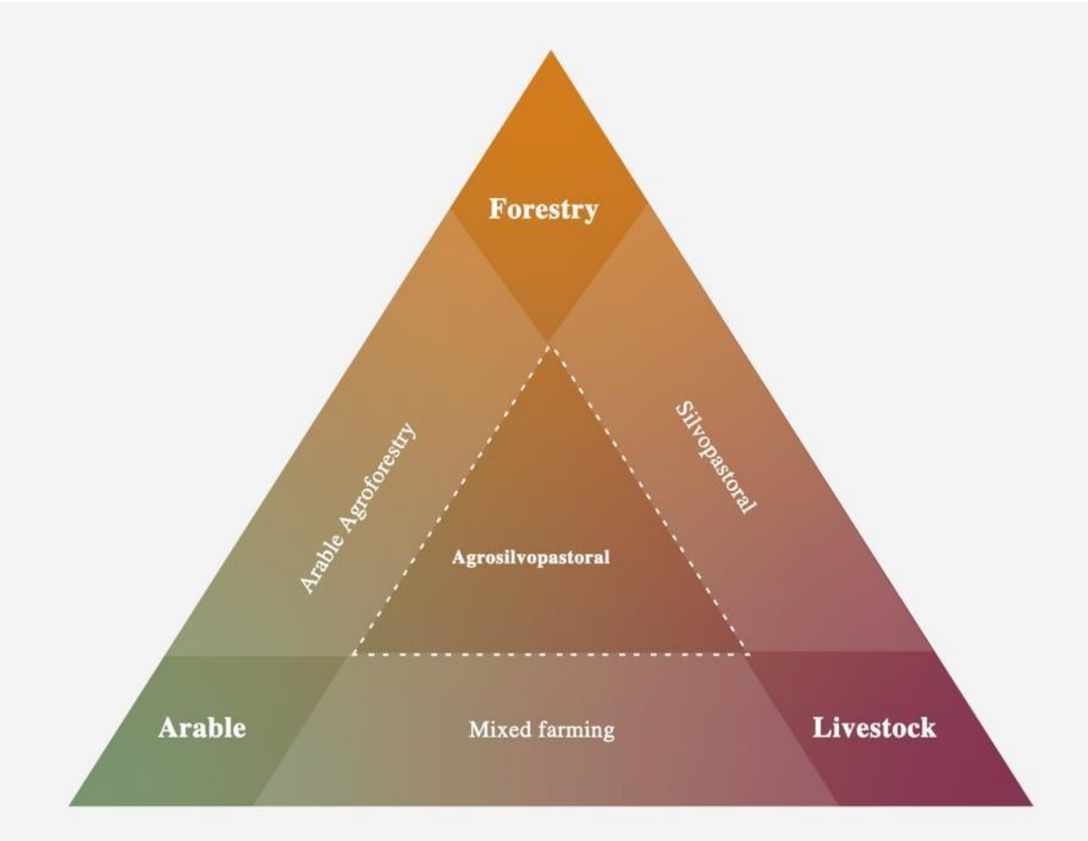

Figure 1. Adapted conceptual representation of agroforestry and mixed farming systems.

Work package 1 of AGROMIX creates the conceptual framework of resilience in the context of MF and AF systems, identifies benefits from these systems and develops a methodology on how resilience can be identified by using indicators. Deliverable 1.1 (Püttsepp et al 2021) of this work package presents the conceptual framework of resilience and working definitions for the project. Here it is stated that a resilience system has multiple capacities: robustness, adaptability and transformability. Based on these insights, this report was compiled which is focused on indicators of resilience. The indicators proposed in this report can determine the resilience of a farm to climate change-induced shocks and stresses. The hypothesis that can be tested with this set of indicators is as following: “Mixed farming systems or agroforestry farming systems

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are more resilient to climate change related shocks and stresses compared to their respective mono-activity agricultural systems".

1.2 Need for indicators

To quantify and evaluate the level of resilience of a specific farm, a set of indicators that covers a sufficient range of resilience aspects is needed. Resilience is a broad concept which needs to be defined specifically, since it may include ecological, economic but also social aspects. These three dimensions are included in the indicator set with equal importance. Sufficient performances on all three dimensions are important in order to be resilient. In the AGROMIX project, we want to explore the potential of MF and AF systems regarding their potential to offer resilience to climate change in Europe. In order to do this, a tailor-made set of indicators is required.

1.3 Objective and principles

The objective of this specific task (Task 1.3) is to provide the AGROMIX project with a coherent set of indicators that combined can quantify and evaluate the level of resilience of a farm to climate change in Europe. This set is able to test the project's hypothesis that a mixed farming system or an agroforestry farming system is more resilient to climate change related shocks and stresses compared to their respective mono-activity agricultural system.

The result of this task is a framework of general non-site-specific indicators and farm-specific indicators, following the definitions and resilience framework of Task 1.1. The created indicator set can be used in other AGROMIX work packages or other projects that want to make a coherent assessment of resilience that can be used to compare the resilience of various farm-types. The set of indicators will cover all relevant components of resilience (ecological, economic, social), as identified in Püttsepp et al (2021).

Before we started with the collection of indicators, several principles were agreed upon that set the scope of the task and its outcome. These principles are listed and explained as:

- When studying resilience, two questions arise: Resilience of what, and resilience to what? For this study, a farm is the unit of analysis for which its resilience will be determined when applying the indicator set. Furthermore, we focus on resilience of the farm against climate change induced shocks and stresses, in the current situation and in the future. The major shocks and stresses considered are droughts, extreme precipitations, heatwaves, followed by pest and diseases, but also policy and market/economic responses because of these events and climate change in general.
- Based on the conceptual framework presented in Püttsepp et al (2021), this report attempts to apply the resilience concept in a practical manner to farm level properties and performances. To do so, we translated the theory into a convenient and concise set of indicators that can identify the level of resilience. In concept, many indicators have a clear link with resilience. However, for the resilience assessment, we tried to quantify these indicator scores and standardise the outcomes so that they can be easily compared and applied.

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- Finally, applying the proposed indicator-set to a farm will provide an ex-ante evaluation of the farm's level of resilience. This means the shock or stress has not yet occurred. We try to give an indication to what extent we expect the farm to be able to cope with and adapt or transform practices after the shocks or stresses occurred (see Püttsepp et al 2021), based on the farm characteristics, current management and the farmer's competences. The indicators are suitable for any farm that uses land for food and feed production, but footloose farms (farms without fields, like intensive livestock farms) are excluded.

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2 Methodology and process

To get to a purposeful and concise set of indicators, the following steps have been taken:

1. Setting the scene, identifying system boundaries, principles and concepts to analyse resilience. Here we aligned with task 1.1.
2. Compiling a longlist of indicators, based on input from project partners, literature, and experts. During discussions with the AGROMIX WP1 team, the set was improved and expanded. Indicators that focus on assessing the resilience of individual farms to climate changed were collected.
3. Categorizing types of indicators to make sure the indicators cover the full scope of resilience, including ecological, economic and social dimensions. Where necessary, the longlist was expanded to fulfil this requirement.
4. Indicator selection criteria were developed and agreed upon with the Work package 1 AGROMIX partners, to which the indicators had to comply. These criteria are as follows:
    - The indicator has a strong link / rationale with resilience. This means that a change in the indicator score, means a change in resilience (in one of the three resilience dimensions: ecological, economic, social).
    - The indicators score needs to be changeable by management choices on the farm itself within 5 to 10 years.
    - The indicator must be suitable to be translated into an AMOEBA diagram-model. This requires a categorisation of the indicator's score on ordinal scale of 1 – 5., where 5 mean the highest score, and thus a higher resilience on this aspect.
    - The indicator needs to have a target value, to be able to link the score to the level of resilience. If no target value was available for relevant, it was drafted together with experts.
5. Application of the criteria on all the indicators in the longlist to develop a concise draft set with general and farm specific indicators. Expert judgement scores were assigned to what extend an indicator complies with the criteria. The indicators that complied with the criteria, were selected.
6. For the selected indicators, a detailed assessment was done. We used literature and expert-knowledge to identify and agree upon target values, scoring of the indicators on an ordinal scale, underpin the links/rationale with resilience, procedures on how to collect data and application possibilities of the indicators. The selected indicators have a relationship with resilience supported by science and are understandable for farmers, policy makers and scientists.
7. Collect feedback from colleagues throughout the AGROMIX project on the draft report and its content and applicability in other work packages.
8. Final set and finalizing the report, including advice and discussion about how to apply the set of indicators.

By following these steps, this report has been created as a deliverable for the AGROMIX project.

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3 Results

3.1 Indicator longlist

The inventory of indicators resulted in 54 possible indicators that might be suitable to measure resilience over the three dimensions of resilience. Hereunder they are presented per dimension, including a description of the link between the indicator and resilience.

3.1.1 Ecological indicators

Dimension	Indicator	Link with resilience
Ecological	Crop species richness in time	A more diverse cropping system in time (crop rotation with a variety of crops that help to maintain soil quality, e.g., cover crops) and space (intercropping, agroforestry, landscape elements) leads to a more resilient system due to better soil health, slower pest outbreaks, spreading risks across a larger area and over more different crops.
	Crop-cultivar diversity	A more diverse cropping system making use of more varieties gives risk spreading due to the different degrees of vulnerability to pests and extreme weather events.
	Crop functional diversity in time and space	Crop diversity expressed not only in terms of species richness but also of functionality. Resilient systems are not only based on high number of crops but also of different kinds of crops and genotypes delivering a range of ecosystem services or tolerating the stresses in different ways.
	Vigorous crop species/varieties	Crop species and varieties have different vulnerabilities to pests and weather extremes. Choosing species and varieties that are vigorous, with resistances or high tolerance levels decreases the risks of large losses due to pests and extreme weather.
	Crop health (depending on management)	Managing your crops (and growth conditions) in such a way that they are healthy makes them better capable in dealing with stresses.
	Stability of production (based on variability of production)	The stability of production on a farm over time indicates that the system can adapt to yearly differences in conditions. If a crop or animal is under stress, their productivity reduces. Vice versa, if your system maintains productivity under stresses, it means that the crops/animals are resilient.
	Herd fertility	If an animal is under stress due to changing conditions and weather extremes, their fertility could be negatively influenced, which makes fertility an indicator for resilience.
	Morbidity	A morbidity rate above a certain threshold indicates that some property of the system might be less resilient or that management is poor. Morbidity is an early indicator for mortality.
	Use of preventive antibiotics	Not needing to use antibiotics preventative to maintain acceptable levels of morbidity and productivity could mean that the husbandry system is resilient.
	Multipurpose breeds of animals	A specialized breed is less able to adapt/transform to changing conditions and changing market demands and therefore less resilient to changes.
	Vigorous/robust breeds	Animal breeds have a different vulnerability to weather extremes. Choosing breeds that are vigorous and with high tolerance levels

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		decreases the risk for decreased production or mobility due to extreme weather.
	Animal diversity	Growing more than one breed or types of animals or with different husbandry management can result in stabilization of animal performances, diversification and robustness.
	Soil cover	Erosion, drought and excess water caused by extreme weather events can be countered by increased soil cover by plants or organic residue, and by doing so, maintaining soil quality and production capacity.
	Access to irrigation systems	Ability to adapt to drought makes the farm more resilient, because the crops are less dependent on rainfall during dry periods.
	Water storage	If enough water can be stored and buffered, the farm can better cope with droughts and by that, improving its resilience.
	Digital support systems	A digital support system (DSS, forecasting) for irrigation and pesticide application helps to act and adapt timely and accurately to events.
	Nutrient cycling	A strong internal and circular nutrient cycling improves resilience, because fewer external nutrients are needed and by that reducing the dependency on external markets. A good nutrient cycling will also benefit soil quality.
	Soil organic matter content	Soil organic matter content is a good indicator for soil quality. In general, soil quality can buffer climate stressors, but also makes it easier to transition to a new production system, for example with new crops.
	Soil compaction	Soil permeability determines whether the system is resilient to excess water and water erosion due to its influence of water infiltration and drainage. It is reduced by soil compaction.
	Soil crusting and cracking	Soil crusting reduces water infiltration thereby increasing runoff and erosion, which leads to poorer soil quality and water holding capacity. Without soil crusting, the system will be more resilient for extreme precipitation events and droughts.
	Soil moisture	If the soil can store more water, it makes the system more resilient to drought since the crops have more water available to stay alive.
	Soil biological quality	A good soil biological quality helps to cope with shocks and stresses by increasing the ability with which the soil can help against pest and diseases and provide nutrients and water.
	Inclusion of banker plants within the parcel (or other forms of habitat provision to natural enemies and/or pollinators)	The system is less vulnerable to pests and diseases; higher functional diversity increases chances of some species being able to counter impacts.
	Plantings to improve the microclimate and waterflows	Landscape elements can mitigate the effects of extreme weather events. For example, windbreaks reduce evaporation due to shade and wind-breaking which helps against drought, contour-planting of beetle banks or tree rows (e.g., agroforestry) can be used for improved infiltration and less runoff.
	Biodiversity (pollinators, natural enemies)	A biodiverse system is less vulnerable to pests and diseases; consequently, a higher functional diversity increases chances of some species being able to counter impacts.
	(Semi-) natural landscape structures	Providing habitat for biodiversity supports natural enemies and reduce the dependency on crop protection products.
	Connectivity of (semi-) natural landscape elements	Agroecosystems with high patchiness and connectedness results in more resilience due to functional diversity and providing a habitat for functional agro-biodiversity.

Sources: GIZ 2014, Seybold 1991, Brock 2017, WRI 2008, Lehman et al 2015, Altieri 2015, Darnhofer 2010, Oppermann 2003; Uthes et al., 2020; Oppermann et al., 2005, Experts WUR.

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3.1.2 Economic indicators

Dimension	Indicator	Link with resilience
Economic	Variability/stability of income/profit	A stable, predictable production and income is an indicator of resilience. Stability of performances over years is linked to management optimized for resource use efficiency and low exposure to risks.
	Market diversification /number of income sources	If more markets are served, the farm is less vulnerable if one of these markets collapse due to a shock or stress.
	% Direct sale to customer	Being less dependent on offtake from whole buyers, gives the farm more space to manoeuvre and find multiple markets for its products. Especially a mix of market channels is a risk mitigation strategy, which can be achieved by partially sell products directly to consumers.
	Contract with retailers	Having a contract to agree offtake of the production for an in advance agreed price assures income, even if the quality is less due to e.g., drought.
	Gross value added from crops	The gross value addition in monetary terms from various crop enterprises measure the performance of the farm. Calculated per ha/year. If this is more, the farm can earn income that can be used as a buffer in bad years.
	Gross value added from livestock	The gross value addition in monetary terms from livestock enterprises measure the performance of the farm. Calculated per ha/year. If this increases, the farm can earn income that can be used as a buffer in bad years.
	Non-farm income	Non-farm income is a measure of the existence of alternative avenues for income and livelihood in rural areas. If there is non-farm income, the enterprise is less vulnerable to highly variable production and income from the farm.
	Machine availability	Having own machinery, farmers can quickly respond to e.g., weather events and by that making sure most produce can be harvested on time.
	Resource use efficiency (productivity)	Being efficient with resources while maintaining productivity, makes the system relatively less dependent on external inputs and availability and prices of these inputs.
	Reliance on subsidies	Dependency on subsidies makes the farm vulnerable in case policies change. Being reliant on subsidies, it might be hard to recover if the subsidy decreases and be a profitable, future proof business.
	Debt and Loan	Being dependent on external capital makes the farm more vulnerable to the shocks or stresses as well as limit the capacity to adapt.
	Preventive investments	Investment on preventive technology (i.e., irrigation) makes the farm less exposed to the climate change.
	Reliance/dependency on external inputs	Self-sufficiency, reliance on natural resources internal to the agroecosystems make it more resilient / If inputs drop out (availability, prices, policies) and the farm is very dependent on them, it will be harder to achieve good production. This is also the case for feed for livestock: Being less dependent on feed from elsewhere, and by that reducing the reliance on external feed. If more own feed is produced, the farm is less vulnerable to markets stresses or crop failures.
	Fair pay for on-farm labour	Dependence on cheap labour can make you vulnerable because this labour is more likely to leave for more profitable opportunities and by that losing good employees.
	Land ownership	Owning the land as opposed to renting it may improve one's willingness to take care of it in the long term, e.g., improve soil quality. A better soil quality improves resilience of the farm, since shocks and stresses can be overcome by crops.

Sources: Gaudin et al 2015, Darnhofer, 2010, Rao 2018, Milestad & Darnhofer 2003, Jacobi et al 2015, experts WUR.

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3.1.3 Social indicators

Dimension	Indicator	Link with resilience
Social	Frequency and quality of training	The more training, the better the farmer is aware of threats and the better (s)he can prepare for future changes because the farmer has more knowledge on how to cope with that
	Cooperation/collaboration with other producers / sale organizations	Through cooperation, difficulties can be compensated by a partner, or a group of farmers can be better organized, making them more resilient to changing situations
	Farmer competences	Knowledge, skills and attitude of the farmer determines his/her adaptive capacity and ways to handle difficult periods with shocks and stresses.
	Access to extension service	Good access and use of advisory services indicate that the farmer will be better able to cope with climate change. The advisor can help a farmer prepare to shocks.
	% of area under agriculture insurance	Reflects the back-up support for falling back in case of risk exposure. The insurance can help the farm business to survive a year with difficulties and makes it possible that the farm can adapt to climate changes.
	Level of social organization	The better organized, the more power the farmers have in negotiations with other value chain parties and policy makers. They can gain from good deals and invest in getting ready for the future.
	Farmer/social networks	More networks stimulate more knowledge/ideas/capacities and improves more resilient. Openness/quality op networks is also important. The more open, the more experiences and knowledge will be shared.
	Inclusion of diverse knowledges and voices in decision making	Diverse knowledge makes the farmer better able to make suitable decisions in the face of climate change, like adapt practices or smart investments.
	Agency of farmer	The extend a farmer can make its own decision, determines if the farmer can adapt to changes or is within a lock-in. The higher the agency, the more adaptive the farmer can behave, the more resilient it will become.

Sources: Cabel & Oelofse, 2012, Milestad & Darnhofer, Jacobi 2015, WRI 2008, Altieri 2015, Personal consultation experts WUR.

Any overlap between indicators is not yet considered in this longlist, nor their suitability to be an actual indicator for our final concise set. Therefore, the criteria presented in 2.1 were applied, of which the results are presented in 3.2.

3.2 Final indicator set

We applied the criteria to the indicators of the longlist, resulting in a selection of indicators that are presented in detail below. After the collection of indicators for the longlist, one new indicator was added, based on the input and reviewing of experts. The indicator "*Greenhouse gas emissions"* was added and evaluated on the set of criteria. Also, the names of several indicators were improved to match the literature and the definitions were expanded and improved.

For each indicator, a table is developed, including the definition, the link with resilience is elaborated, measurement possibilities and costs are mentioned, a target value and an ordinal scale to assess the performance is given. This score on this scale is input for the general resilience assessment in an AMOEBA

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diagram, that makes comparison between indicators possible. A score of 1 is the lowest, a score of 5 refers to the highest level of resilience on this indicator.

The indicators are aligned with the three dimensions of resilience; ecological, economic and social. Within the ecological dimension, two types of indicators can be found: farm specific indicators and general indicators. The general indicators can be applied on any farm that will be assessed. Farm specific indicators will be applied only in case the farm has these kinds of activities, like grassland production, arable farming, or livestock. For example, if a farm cultivates grassland and arable crops, the indicators arable crop diversity and grassland species richness will be assessed. Livestock indicators (herd fertility, animal diversity) will not be evaluated in that case since no livestock is present on the farm. First the farm-specific indicators are listed, thereafter, the ecological, economic, and social indicators.

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3.2.1 Ecological – farm specific indicators

Indicator 1	**Arable crop diversity**
Definition	This indicator is defined as the diversity of crops grown in one year. The definition of 'crops' includes annual cash crops, cover crops, green manures and temporary perennial crops (<4 years) but excludes permanent crops such as permanent pastures, trees and shrubs. Permanent pastures, trees and shrubs contribute to resilience, but this is covered by other indicators. Within arable cropping, a high diversity in different crop groups with a large share of crops with soil improving properties maintains the ability of the soil to deal with excessive rain and droughts (covered by indicator 7 and 8) but also spreads risks of crop failure (e.g., due to an extreme weather event).
Link with resilience	• Rotational diversity of crops reduces yield loss and risk of failure under stress conditions (Bowles et al., 2020). A high diversity in crops usually creates a larger crop diversity each year as well as in the spatial dimension. • "Increasing crop diversity can mitigate the effect of abiotic stress on wheat. Higher diversity resulted in higher yields under stress. Crop diversity improved stress resistance resulting in more resilient systems" (Degani et al., 2019). • "Diversified systems increased resistance and resilience from abiotic stresses and improved the constancy in crop productivity across rotation cycles, compared to the less diversified systems. Quantitative assessments show that the most diversified systems had a 14% advantage in system robustness." (Li et al., 2019). • Observations of agricultural performance after extreme climatic events (e.g., hurricanes, droughts) showed that resilience to climate disasters is closely related to farms with increased levels of biodiversity (Altieri et al., 2015). • Perennialism and crop diversity increases resilience to drought (Sanford et al., 2021).
How to measure and unit	The number of crops cultivated in the same year, but proportional to the farm size (land surface). Because this indicator is mainly focussed on risk spreading, the higher the number of crops, the higher the AMOEBA score.
Cost and timeframe	The assessment is free of costs and takes less than 1 hour to complete, anytime in the year.
Target value	Count the number of crops grown at farm level in one year. The number of crops in a study on European landscapes (each 16 km^2) was between 1 and 8 crops (Billeter et al., 2008). This can be seen as what is reasonably possible in the current socio-economic environment. From Uthes et al., (2020) an optimal of 9 crops can be extracted and a minimum requirement of 4 crops (assuming equal ratios in the Shannon Index). Each perennial (<4 years) counts as 1 point extra with a maximum total score of 5.
AMOEBA scale	1: 1 crop 2: 2-3 crops 3: 4-5 crops 4: 6-8 crops 5: > 8 crops

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Indicator 2	Grassland species richness
Definition	Grassland (in pastures and orchards) with a high diversity of plant species
Link with resilience	There is a positive relationship between species richness in grassland and productivity, as well the temporal variability in productivity is lower in species-rich communities than in species-poor communities (Vogel et al., 2012). The positive relationship between species richness and resilience could be explained by the ability of species-rich grass communities to maintain ecosystem functions under perturbed conditions. There are several underlying mechanisms, e.g. synergistic interactions, selection of species that have improved performances and asynchronous responses among species to the perturbed environment (Haughey et al., 2018). Ruijver et al. (2010) found species richness to be a stronger predictor for recovery than productivity (recovery and proportional recovery increased with species richness). Although the relative importance of certain biological drivers varies substantially across studies, a diversity-stability relationship is mediated by multiple facets of biodiversity (Craven et al., 2018). In the study of Craven et al. (2018) on 39 experiments it was found that species richness was the strongest and most consistent driver of production stability in grassland (through species asynchrony).
How to measure and unit	Number of plant species per 1x1 m plot at and averaged for sufficient repetitions within the field, depending on the surface. Measure it once a year in the growing season when all species have well established (e.g. summer). Points of attention: - When considering a larger or smaller plot size, make sure that the test plot is large enough to include much as possible of the plant species present at the field; - Make sure that the spot where you measure is relatively homogeneous (representative for the vegetation of the entire field); - Grasses can look very similar. Be aware of the differences between species. You can use a field guide to recognize the differences.
Cost and timeframe	The assessment is free of charge. It takes about 0,5 to 1 hour to count species in one PQ-plot (depending on species-richness).
Target value	> 6 plant species is considered species-rich for an agricultural (managed) pasture, however, natural grasslands or semi-natural grasslands can count much more species. There is no general quantified value for species-rich grassland applicable for agricultural managed pastures, semi-natural grassland and other levels across Europe. The field guide from Schippers et al., (2012) is used in the Netherlands and Belgium for development of species-rich pastures for dairy and describes the different levels of species-richness of pastures. Here a pasture is considered species-rich when it contains 40 species per 25m2. Translating that to a reasonable surface to do the measurements for various grassland types across Europe brings us to >10 plant species for a species-rich grassland.
AMOEBA scale	1: 1 plant species per m2 2: 2-3 plant species per m2 3: 4-6 plant species per m2 4: 7-10 plant species per m2 5: > 10 plant species per m2

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Indicator 3	Herd fertility
Definition	Average number of new-borns per year per productive female.
Link with resilience	If an animal is under stress due to changing conditions and weather extremes, their fertility could be negatively influenced, which makes fertility an indicator for resilience.

How to measure and unit	The productive female is a female in age of reproduction and not intended to be culled. The value needs to be compared within the breed or species itself (ITAVI experts 2019, 3trois3 2019).
	Some numbers as a reference:
	• France 2017: 30 weaned piglet per productive sow
	• France 2020: 165 to 180 hatching eggs per hen per 41 weeks of production (depends on density and ambiance conditions) so 144 and 155 chick per hen per 41 weeks of production.
	• France 2020:
	    ○ 5 or 6 calves per productive cow (meat breed).
	    ○ 2.4 to 2.8 calves (average) per productive cow (milk breed) (Minimum from 2 to 2.4 and maximum 2.8 to 3.4 calves per cow)
	    ○ Depends on breeding systems: maize mountain, pasture mountain, plain with more or less maize.

Cost and timeframe	Measure it once a year by asking to the farmer and look at the farm files.
Target value	Just higher than the average value of the species. The average needs to be assessed on national level.
AMOEBA scale	1: lower than 50% of the average 2: between 50 and 70 % of the average (per species) 3: between 70 and 85 % of the average (per species) 4: between 85 and 100 % of the average (per species) 5: better than average (per species)

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Indicator 4	Livestock - Animal diversity
Definition	Number of species and breeds in a year at farm level
Link with resilience	Several links with resilience can be identified. Having several species and or breeds on a farm (Magne et al., 2019): 1. allows more resistance to diseases propagation or permit different responses of each breed or species to a stressor. 2. if the different species are complementary it allows for more autonomy and resilience to the farm activity. 3. allows more adaptation possibilities for a farmer to recover and adapt after a shock.
How to measure and unit	Two different variables need to be counted to calculate the final score: - Number of different animal species on a farm in a year - Number of different breeds (for each species) on a farm in a year 1 species: 1 point 2 species: 2 points 3 or more species: 4 points 1 species with at least 2 breeds: + 1 points with a maximum total score of 5 2 species (or more) with at least 2 breeds: +2 points with a maximum total score of 5
Cost and timeframe	Measure it once a year by asking the farmer or visiting and assess the farm.
Target value	Several types of species and in each species several breeds.
AMOEBA scale	Calculated the number of points based on the numbers of species and breeds. Calculated the number of points based on the numbers of species and breeds. 1: Only 1 species and 1 breed. 2: 2 species, or 1 species with at least 2 breeds. 3: 2 species with at least in 1 species 2 breeds. 4: 4 or more species or at least 2 species with at least 2 breeds. 5: 3 species or more with least in 2 species 2 different breeds.

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3.2.2 Ecological – general indicators

Indicator 5	Stability of production (base on variability)
Definition	The stability of production is defined as how variable the production is over the years, on farm level.
Link with resilience	A lower variability means a higher stability (Raseduzzaman & Jensen, 2017). The stability of production over time indicates that the system can adapt to yearly differences in conditions. If a crop or animal is under climate stress, their productivity goes down. Vice versa, if your system maintains productivity under stress, it means that the crops and animals are resilient.
How to measure and unit	The coefficient of variation (CV) is widely used to compare the stability of yield or the variability of a crop over time (Raseduzzaman & Jensen, 2017; Smith & Robertson, 2007; Rao & Willey, 1980). It is calculated by dividing the standard deviation of the mean by the mean production (e.g., dry weight biomass of a crop/ha, milk/X number of cows) at a farm: $\%CV = \frac{SD}{B} \cdot 100$ where B is the mean production of a treatment/crop/mixture/animal species and where SD is the standard deviation of that treatment/crop/mixture/animal species. After calculating the %CV of production for each crop or animal species in multiple years the average of all %CV's can be taken to see the overall performance in terms of variability of production. The %CV is likely to also be influenced by inherent characteristics of the species.
Cost and timeframe	To measure production variability, the production should be known for at least 5 years. Making the calculation requires some time but can quickly be done in case the data is available.
Target value	The lower the CV% of production is, the higher the stability. There will however always be some variability. Less than 5% CV is identified as the target value, meaning a very stable production over time.
AMOEBA scale	1: %CV of >50 2: %CV of 26-50 3: %CV of 11-25 4: %CV of 5-10 5: %CV of <5

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Indicator 6	Herbaceous soil cover
Definition	Soil cover is defined as an herbaceous growing crop (including natural pasture), cover crop, weeds, or plant residues (mulch) and is fulfilled when the bare soil is not visible when observing from above. The formula to calculate soil cover with visual data is as follows: $$\frac{\sum_{n=26}^{n=1} \%visual\ \ cover}{26}$$ Where *n* = moment of observation
Link with resilience	Soil cover of living plants or plant residues slows down the velocity of the rainfall before it reaches the soil and improves the water infiltration and thereby protect the soil against water erosion, runoff and crusting. It also protects the soil against climatic influences such as drought and wind (erosion) (Montenegro et al., 2013; Zuazo et al., 2009). Prevention of soil loss in the situation of heavy rainfall or strong wind is crucial for agricultural production in the long term. The protection of the soil from drying out from heat and wind is also beneficial in the case of drought. These aspects make soil cover an indicator for resilience.

How to measure and unit	• Land without agricultural production activities is not included in the assessment.
	• All measurements should be done outside the headlands and driving tracks.
	• % Visual soil cover can be estimated every two weeks with a precision of at least ± 25% by determining the cover in a 0.5x0.5 m square in sufficient repetitions to get an average of an area or field. If the row distance of the crop is larger than 0.5 m, a larger area may need to be used for the assessment (consider the area in between the middle of the two inter-rows on both sides of the crop row).
	  ○ A soil cover estimation smartphone app may also be used. For example: the SoilCover app by Josephinium research.
	  ○ Estimation can also be done by making pictures using a frame and analysing the picture with software such as MatLab.
	• To retrieve a value for one year of the whole farm, an average for all the measured areas or fields is calculated.
	• Soil cover can also be identified via the Normalized Difference Vegetation Index (NDVI). The NDVI is a good way to estimate soil cover (personal contact J. Booij, 2021). Via remote sensing observation, it identifies living green vegetation. The higher the index, the more vegetation cover is present, and it can construct an image through time of for example a cropping season. Mulch and other plant residues are seen as soil cover, but it is unknown if this can be trustworthy measured with the NDVI. Therefore, having mulch or plant residue as soil cover; use the visual observation method.
	The graph below shows the NDVI for a maize field where also a green manure is grown. A maximum of 0.9 is measured and a minimum of 0.2-0.3. The NDVI data is publicly available, via the Sentinel satellite data (Copernicus, n.d.). To calculate a yearly average, add up the scores of NDVI per year and divide them by the number of observations. The minimum observation is 12 per year, of which in every month of the year an observation.

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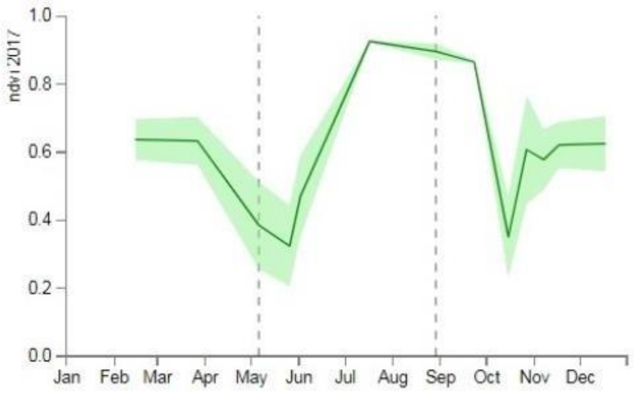
<table>
<tr><td></td><td colspan="2">
</td></tr>
<tr><td>Cost and timeframe</td><td colspan="2">The determination is free of costs. Assuming bi-weekly estimation is only required during four months in a year with a 20 minute of time requirement per week, the yearly time requirement is 20 x 8 weeks = 2.7 hours per year per field.
The indicator is calculated after collecting data on soil cover for at least one year. Due to the influence of weather on soil cover in pastures, it is recommended make the determination in several years with varying weather.
The NDVI analysis requires some data analysis, and therefore time.</td></tr>
<tr><td>Target value</td><td colspan="2">The desired soil cover is 100%. We assume a minimum soil cover of 50%, representing systems with at least a 6-month cover of one annual crop with no cover crop following it.</td></tr>
<tr><td>AMOEBA scale</td><td>For manual observations:
1: < 50%
2: 51 - 60%
3: 61-70%
4: 71 - 80%
5: > 81%</td><td>For NDVI estimation of yearly average scores:
1: NDVI <0.4
2: NDVI 0.4-0.5
3: NDVI 0.51-0.6
4: NDVI 0.61-0.79
5: NDVI > 0.8</td></tr>
</table>

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Indicator 7	Soil organic matter
Definition	% Soil organic matter (SOM) in the 0-30 cm soil layer. Determined in fields with regular or permanent herbaceous cover such as an arable field or pasture.
Link with resilience	Soil organic matter is an indicator for general soil quality since it positively influences many soil properties, such as fertility, moisture retention and infiltration, soil organisms and structure (aggregation) (Seybold et al., 1999). These soil properties can help buffer against climate stressors such as drought, wind and excess water (Altieri et al., 2015), but also makes it easier for the farm to transition into a new production system, for example with new crops, if that is required. The SOM is improved by the addition of organic matter by (solid) organic manure, compost, (cover) crop and tree residues and by less disturbance of the soil, for example by reduced tillage or the use of more perennial vegetation (pasture, trees and shrubs). Generally speaking, stable SOM contributes more to the soil structure-related soil attributes, while labile SOM is important for soil fertility and as food for soil organisms.
How to measure and unit	• The SOM should be determined by the loss on ignition method (Schulte & Hopkins, 1996) with the temperature that been used to establish the target values. • Alternative method: SOC can be determined by an elemental analyser. SOM can thereafter be calculated from SOC and minor changes are easier to measure with this method than with the loss on ignition method. • Land outside agricultural production activities is not included in the sampling. • All measurements should be done outside the headlands and driving tracks. • The sampling is done within an area or field with an herbaceous cover. Trees nearby the sampling spot is allowed. • Sampling should be done in sufficient intensity so that a reliable average can be established for an area or field over the whole depth (30 cm). • To retrieve a value for the entire farm, an average for all the production areas or fields should be calculated. • If not possible to measure in all areas or fields, randomly select sampling points across the farm or manually select sampling points with expected varying SOM levels. If groups of fields with similar characteristics/management, the random sampling should be divided among those groups.
Target value	The SOM has a large variation depending on type of land use (annual crops, pasture or wooded) and soil type (texture, history, climate). The range of SOM on a mainly mineral soil usually ranges between 1-10%. A higher % of SOM gives a higher resilience score, however, the efficiency with which a certain % of SOM provides benefits for resilience is dependent on additional properties such as soil type, which makes it not possible to define an overall target value for all locations. Because of this, soil-type specific target or reference values that are already established by (regional) government, agricultural advisors or research institutes should be used for evaluation. The target values should

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	not be distinguished based on agricultural land use type but should be distinguished per soil type/location (region).
Cost and timeframe	• The costs are around €15 per (mixed) sample for the material and analysis by external parties and requires 2 labour hours for sampling. At least one (mixed) sample per two hectares is recommended, consisting of 20 subsamples per ha, taken in W-form. • To follow the development of the SOM in time, the same points should be sampled each year. • If applicable, the moment in the crop rotation should be considered since it may influence the level SOM measured. For more reliable results, measure in at least two years, following different crops. • It is also important to select the proper moment of time to do the sampling. Due to the seasonal peaks of SOM mineralization, especially in Mediterranean climates, it is advisable to sample for SOM assessment in mild seasons, preferably in early fall, before main tillage operations. • Repeat over years the sampling with the same methodology and at the same time.
AMOEBA scale	A score of 1 should be awarded for the lowest historical % SOM of the soil type/location, which stands for a state where the production function of the soil is threatened. A score of 5 should be awarded for values that match the highest historical % SOM of the soil type/location, or, if known, when the SOM percentage is stable and doesn't improve any further, considering the soil type. The % SOM for scores 2 - 4 should be evenly distributed between the value for the scores 1 and 5. If no minimum reference values are available, ROTHC modelling can be used.

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Indicator 8	Soil compaction
Definition	This indicator measures the hydraulic conductivity in soil layers that are suspected to be compacted to such a degree that water flow is inhibited. The saturated hydraulic conductivity K_{Sat} in cm/h is a measure for how easily water can pass through the soil profile when the soil is saturated with water. The K_{Sat} is determined by the pore size distribution and tortuosity of flow paths which in turn are determined by soil texture and structure (see figure). To influence the K_{Sat} of compacted layers the structure of the soil can be improved by organic matter management, reducing stocking rate, different soil tillage and wise machine use (avoiding driving with heavy machines, especially in wet weather conditions).
Link with resilience	The field saturated hydraulic conductivity tells how well the soil can transmit water through the profile and cope with excessive rainfall (Vogel, 2000). It is an indicator that is complementary to soil cover. The soil cover is a proxy indicator for infiltration capacity through the soil surface, due to decreased risk of soil crusting and erosion. If the soil structure is poor due to lack of macropores or compacted in the layers below the surface of deeper, the drainage of water and subsequently the infiltration as well may become insufficient. The soil will then risk waterlogging, water erosion and runoff in the situation of excessive rainfall. Compaction also limits potential for capillary rise of moisture from deeper soil levels which makes the system less resilient to drought.
How to measure and unit	The method entails three components: 1) The mapping of a field with a penetrologger to identify % area with suspected compaction (Eijkelkamp, n.d., a). a) A standard cone of 1 cm^3 with a tip angle of 60 degrees is recommended. b) Suspected compaction is at resistances from 2.5 MPa and above. At this resistance, root growth is impeded, however, this is not the same as compaction that impedes water flow. This is investigated in step 2. and 3. c) At least 20 measurements are needed per hectare. 2) Measuring the bulk density of the possibly compacted layers using soil sampling rings (Eijkelkamp, n.d., b). a) The soil is possibly compacted when the bulk density is more than 1.7 g/cm^3. b) Example protocol by USDA (n.d.) 3) Measuring the K_{Sat} in the possibly compacted layers soil water permeameter (Eijkelkamp, n.d., c). a) The same rings used for the bulk density measurements can be used. • Based on the % of the field or area with suspected compaction, together with the bulk density (to confirm compaction) and K_{Sat} measured in those compacted layers, a weighted average K_{Sat} for the whole field is calculated to fill in the AMOEBA scale as permeability in cm water per hour. • All measurements should be done outside the headlands and driving tracks. • To retrieve a value for one year of the whole farm, an average for all the measured areas or fields is calculated.

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<table>
<tr><td>Cost and timeframe</td><td>

The tools to use for the measurement are commonly available at research institutes. The penetrologger costs around €3500 with around 20 measurements per 1.5 hour. Measuring bulk density has low costs and takes in total 1 hour for 6 samples including sampling and weighing, excluding drying. The apparatus for the K_{Sat} apparatus costs around €5000 and takes 4 hours for one run excluding waiting time to reach saturation which can take several days depending on soil type.
These soil characteristics only change slowly due to management. To measure a change after application of a measure to improve soil structure, the measurement can be repeated once 3-5 years.
The penetrologger measurement can only be done when the soil is at field capacity, usually in early spring.

</td></tr>
<tr><td>Target value</td><td>
A very high speed of permeability is not desired as moisture retention will be poor. Similarly, a low speed of permeability is not desired as it increases the risk for waterlogging and erosion in the case of heavy rainfall. Because of this, the target value is an intermediate permeability speed. The target values for the AMOEBA scale are formulated based on the seven permeability classes in the table.
Table: Soil permeability classes and estimates of permeability rates by textural class. (Nature, n.d.)
<table>
<tr><th>Permeability class</th><th>Permeability (cm/h)</th><th>Textural class</th></tr>
<tr><td>Very slow</td><td>< 0.13</td><td>clay</td></tr>
<tr><td>Slow</td><td>0.13 – 0.5</td><td>sandy clay, silty clay</td></tr>
<tr><td>Moderately slow</td><td>0.5 – 2.0</td><td>clay loam, sandy clay loam, silty clay loam</td></tr>
<tr><td>Moderate</td><td>2.0 – 6.3</td><td>very fine sandy loam, loam, silt loam, silty clay loam, silt</td></tr>
<tr><td>Moderately rapid</td><td>6.3 – 12.7</td><td>sandy loam, fine sandy loam</td></tr>
<tr><td>Rapid</td><td>12.7 – 25.4</td><td>sand, loamy sand</td></tr>
<tr><td>Very Rapid</td><td>> 25.4</td><td>coarse sand</td></tr>
</table>
</td></tr>
<tr><td>AMOEBA scale</td><td>
For soil permeability, the scale is made up of two parts. A very low infiltration is not desired due to risk of waterlogging in case of heavy rainfall, as well as a very high rate due to risk for low moisture retention. The optimal situation (score of 5) is in the range of 2.0-6.3 cm/h.
1: < 0.13 cm/h or > 25.4 cm/h
2: 0.13 - 0.5 cm/h or > 12.7 - 25.4 cm/h
3: > 0.5 - 1.5 cm/h or > 9.5 - 12.7 cm/h
4: > 1.5 - 2.0 cm/h or > 6.3 - 9.5 cm/h
5: > 2.0 - 6.3 cm/h
</td></tr>
</table>

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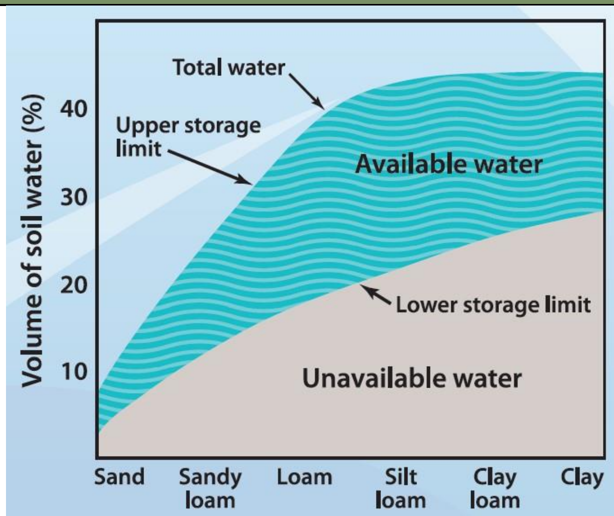
Indicator 9	Plant available water
Definition	The plant available water is defined as the difference in water content of the soil at the field capacity (upper storage limit) and the permanent wilting point (lower storage limit) (see figure, the blue area). The plant available water is mainly determined by soil texture and the soil organic matter (SOM) and partly by soil structure (Reynolds et al., 2018).  *Figure: The relative amounts of water available for plant growth for different soil textures. (http://soilquality.org.au/factsheets/water-availability).*
Link with resilience	If the soil can store more water, it makes the growing system more resilient to a dryer climate. The farmer can influence this soil property by management that increases the soil organic matter and improves the soil structure. An increase of 1% in SOM can increase the water holding capacity by several millimetres (De Lijster et al., 2016). These extra millimetres can make a difference during a drought and make it possible to delay irrigation and save water.
How to measure and unit	The plant available water is here expressed as mm of water available in the upper 30 cm of the soil. It is measured by, for example, the sand/kaolin box method (an example of this equipment: Eijkelkamp, n.d., d) at 10 and 25 cm soil depth. If equipment for these measurements is not available, there is an alternative approach to calculate Plant available water, explained in Behrman et al. (2016), making use of texture, soil organic matter and measurements of bulk density.
Cost and timeframe	• The Sand/kaolin box that can be used for the measurement is commonly available at research institutes and takes approximately 1 hour to use per soil ring. An indication for the number of rings per field is 8, which gives 4 rings per layer. • To retrieve a value for one year of the whole farm, an average for all the measured areas or fields is calculated. • The samples should not be taken after tillage or soil disturbance but preferably in spring about 6 weeks after sowing and a crop has "settled" in the soil. Soil moisture should not be too low. • Since this soil property changes slowly due to improved management, measurements do not have to be repeated until 2-5 years, dependent on the type of new management.

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Target value	Clay and loam soils can reach plant available water amount of 62.5 mm over 30 cm soil depth. A very coarse sand can have a low plant available water amount of 30 mm (Schwankl & Prichard, 2009).
AMOEBA scale	1: < 30 mm 2: ≥ 30 mm < 40 mm 3: ≥ 40 mm < 50 mm 4: ≥ 50 mm < 62.5 mm 5: ≥ 62.5 mm

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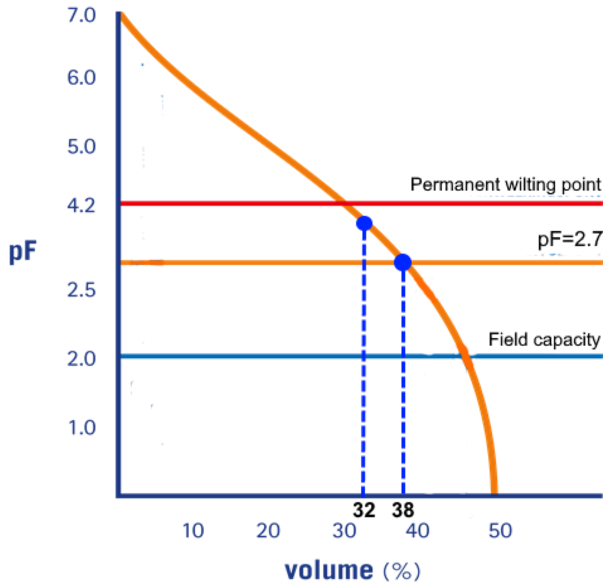
Indicator 10	Sufficient irrigation
Definition	% Irrigation demand being met by a suitable irrigation water supply
Link with resilience	The possibility to irrigate is linked with the resilience and stability of food production to climate change and droughts (Ngoma et al., 2019; Zou et al., 2012). Some farms are completely rain-fed while others have the possibility to fully irrigate, or to some degree. The need for irrigation is dependent on the local climate, soil type species of crop and its stage of development. The extent to which a farm can irrigate depends on size of farm, size and efficiency of irrigation equipment, volumes of water storage, allowed quantities water to extract and the salinity of the irrigation water. Having sufficient possibilities for irrigation makes the farm able to withstand droughts with less yield loss.
How to measure and unit	For the indicator *Plant available water,* the pF curve of the soil has to be determined. The irrigation need can be determined by measuring the moisture volume in the soil (%) with a moisture meter (several types available) and by using the already-established pF curve. The focus of this indicator is on drought that causes irreversible damage to the crop. This occurs at a certain pF level that is different per  crop and lies around pF=2.7. A list of the pF level from which crop damage occurs in different crops is available in the appendix 1. For the number of days that the pF is higher than this value, the deficit moisture to reach pF=2,7 is calculated in millimetres. This is done by calculating the % difference in moisture volume between the pF from which crop damage occurs and the current % volume of moisture, multiplied by the rooting depth of that crop. For example, with damage from pF= 2.7, the minimum soil moisture of a particular field is 38%. The measured soil moisture is 32% and the rooting depth is 25 cm. The moisture is measured as an average over the rooting depth. An estimated irrigation demand for that day is then (also see figure): $(0.38 - 0.32) \times 250 = 15\, mm$ The total need for irrigation to reach above the pF of crop damage for the whole drought period is thereafter compared with the available irrigation water resources. A percentage is calculated for the ratio of irrigation demand that is met by irrigation water supply. The method to calculate the number of mm of irrigation water available for use depends on the type of sources and local conditions and restrains as mentioned in “Link with resilience.”

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Cost and timeframe	This indicator measures the current performance of the farm in case of drought and cannot be evaluated until drought occurs and is therefore not predictive for resilience. Soil moisture measurements should only start when there is risk for water stress and crop loss. This indicator is determined per year, hence, to get a good estimation, at least two years should be evaluated, but preferably more. It must be evaluated for the whole farm and not per field if the water availability is the same across the whole farm. A moisture meter is readily available in agricultural research facilities as well as on farms. The time it takes to determine this indicator depends on the length of droughts and the ease of determining the available water. An estimation of the time requirement is 8 hours.
Target value	The highest resilience against drought based on this indicator is achieved when 100% or more of the irrigation demand can be met by readily available irrigation water sources. Since droughts are expected to become more severe, a 5 is given when there is large margin to be able to deal with such droughts. Note that systems that are completely rain fed, will score 0 in case of a drought that causes crop damage. Even though some grazing systems are based on surviving droughts in the long term, their score will be low for this indicator. If no irrigation is required because the precipitation is always sufficient, a score of 5 is always given. It is also important to note that not all irrigation water is effectively taken up by soil and plant, therefore an estimation can be made for the effectiveness and thereafter include the losses as extra mm's required for irrigation.
AMOEBA scale	1: 0 % of demand met by irrigation 2: 25 % of demand met by irrigation 3: 50 % of demand met by irrigation 4: 100 % of demand met by irrigation 5: >150 % of demand met by irrigation

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Indicator 11	Trees and shrubs
Definition	This indicator is defined as: The edge (m) between trees or shrubs and fields for agricultural production divided by the field size (ha). A field for agricultural production is defined by regular or permanent use for an herbaceous crop, an outdoor run or pasture. Under the definition of trees and shrubs falls non-productive trees, but also trees and shrubs for fruit and nut production.
Link with resilience	Trees provide multiple regulating ecosystem services that can be beneficial in a changing climate with more extremes (See also AGROMIX D1.2). These services include microclimate modification (lowered temperature, reduced windspeed and evapotranspiration), shelter against heat for livestock and water quality and regulation by reduced runoff, improved infiltration and water holding capacity (Smith et al., 2013; Keersmeacker et al., 2015). For optimal use of these effects the placement and spatial spread of the trees and shrubs in the landscape plays a key role. For example, in the case of contour line plantings to reduce erosion or microclimate gradients next to a hedgerow. Looking at the landscape scale, heterogeneity plays an important role in resilience (Vos et al., 2013; Oliver et al., 2015)

How to measure and unit	• The assessment can be done manually (measuring in field) or by assistance from digital maps and tools. Per field, the total interface between the crop/pasture and tree/shrubs is estimated or measured in m per hectare.
	  o In the case of highly uneven and rounded edges (due to canopy shape etc.), rationalize the length of the edge using straight lines.
	  o If the field has trees outside the field that border onto the field border, this edge between field and tree/shrubs is also included.
	  o The edge of a solitary tree or shrub is calculated by using the circumference of a circle. Since measuring the canopy diameter of every tree is not workable, pragmatic choices can be made.
	• In case of a large natural area or pasture, several areas of 1 ha should be sampled randomly across the whole area to get a reliable average. The centre point of the sampled 1 ha should lie at least 50 m from any field edge.
	• To retrieve a value for one year of the whole farm, an average for all the measured areas or fields is calculated.

Cost and timeframe	The assessment can be done in any year and can be repeated after around 5 years if changes in tree and shrub cover is expected. The assessment is free of charge and costs approximately 1 hour per field. It is recommended to evaluate this indicator for the whole farm unless it can be done for a number of representative fields.
Target value	Microclimate effects from hedgerows are strong, up till around 5 times the hedge height, at further distance it decreases gradually (Leuschner & Ellenberg, 2017). With an average tree height of 10 m this gives microclimate effects at least to a distance of 50 m away from the hedgerow. On 1 ha of 100x100 m, fitting on average two such hedgerows, this gives a total length of 400 m of hedgerow edge. As a comparison, for edge density of

	fields, an environmental landscape metric, an optimal value of ≥400 m per ha has been proposed an optimal for sustainability (Uthes et al., 2020).
AMOEBA scale	1: ≤ 100 m ha^{-1} 2: > 100 m ha^{-1} - 200 m ha^{-1} 3: > 200 m ha^{-1} - 300 m ha^{-1} 4: > 300 m ha^{-1} - 400 m ha^{-1} 5: > 400 m ha^{-1}

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3.2.3 Economic indicators

Indicator 12	Number of income sources
Definition	This indicator is defined as the summation of the income sources from different activities on and off farm. A type of product that is sold is defined as an income source. This means that feed production for own animal-consumption is not considered. Each source should at least contribute 10% or more to the yearly income of the farm to be considered. The different income sources we consider are (based on Jacobi 2015, Choptiany 2015): • crops • livestock • trees for timber and/or biomass • trees for fruits and/ or nuts • food processing • non-farm activities (like day-care camping or off farm employment)
Link with resilience	There are multiple reasons why a diversification of income sources leads to a higher resilience of the farm to shock and stresses. • A diverse farm with multiple activities will have more stable incomes and reduced environmental pressures (de Roest et al., 2017). It spreads the risk of farm activities. If the production of one activity is severely hit by a drought for example, there are still other that can deliver income and function as an insurance (Jacobi 2015). • A diversified farming strategies allows the farmer to experiment and innovate while holding a strong fallback position by other sources of income (Herens 2017).
How to measure and unit	Sum up the number of income sources mentioned in the definition of this indicator. If 4 or more crops are cultivated, this can be counted as 2 incomes sources in the scoring. So, if you cultivate 4 or more crops per main season, this can be seen as two income sources. The required information can be collected once a year, through a semi structured interview or a form that can be filled in by the farmer. In this interview or form, multiple indicators can be discussed. An interview will take approximately 1 hour.
Cost and timeframe	An interview and some data processing on a yearly basis.
Target value	The higher the number of income sources from different activities, the higher the AMOEBA score. The target value is to have more than 4 income sources (based on Choptiany et al 2015).
AMOEBA scale	1: 1 type of income source or activity 2: 2 types of income source or activity 3: 3 types of income source or activity 4: 4 types of income source or activity 5: 5 or more types of income source or activity

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Indicator 13	Dependencies on external inputs
Definition	The dependency on external input is defined as the degree of being reliant on inputs like seeds, crop protection products, feed, energy and fertilizers that are not available on the farm itself and need to be imported onto the farm. Local inputs are seen as better than external inputs (Jacobi 2018). Here local inputs are defined as products and inputs from closer than 20 km to the farm (derived from LTO-NZO 2017). Internal inputs are inputs that come from the farm itself.
Link with resilience	A lower dependency on external inputs leads to a higher resilience of the farm: - A farm is expected to be more resilient to market uncertainties for inputs, if they have a lower dependency on external inputs. By optimising the links between crops and livestock, the level of inputs can be decreased and with that the dependencies on external inputs (Bonaudo 2014). - A more diverse farm system at all levels is regarded as a promising strategy to safeguard food production with only limited dependence on agrochemicals for example (Ten Napel 2006). - Regarding feed production, the more a farm produces themselves, the less vulnerable it is to market uncertainties. A variety of types of feed produced on the farm makes the farm less vulnerable (see also crop diversity and grassland diversity indicators) (Personal communication Chiron, Pechenart 2021).
How to measure and unit	The required information can be collected once a year, through a semi structured interview or a form that can be filled in by the farmer. In this interview or form, multiple indicators can be discussed. An interview will take approximately 1 hour.
Cost and timeframe	An interview and some data processing on a yearly basis.
Target value	Mainly/only internal products used to minimize dependencies on external markets and products (see AMOEBA scale).
AMOEBA scale	1: All to most inputs are external; mainly dependent on external actors, no local markets. 2: Inputs are partly external and partly local. 3: Only parts of the inputs (e.g., some seeds or some special inputs) comes from non-local sources. 4: All inputs are from local markets or internal 5: Only internal inputs used.

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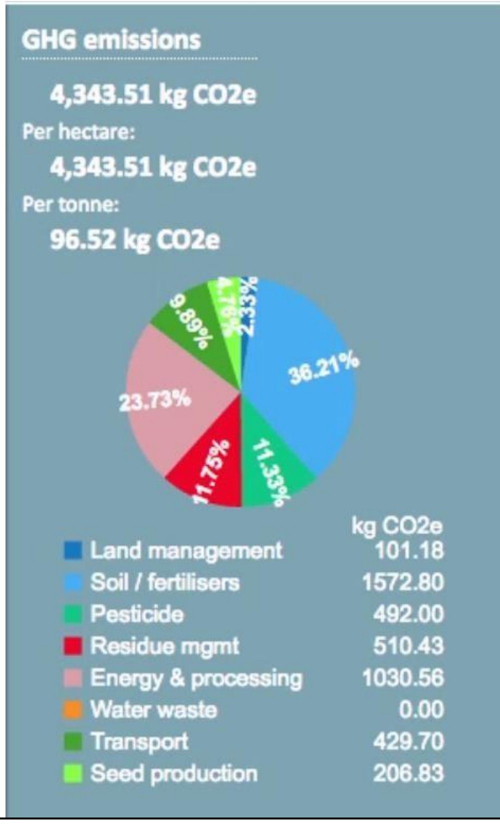
Indicator 14	Greenhouse gas emissions
Definition	Greenhouse gas (GHG) emission intensity per quantity product is the definition of this indicator (Meeuwissen et al., 2019).
Link with resilience	The lower the GHG emission, the more resilient a farm is to future carbon public or private policies and taxes the farm will be. The objectives for GHG emissions reductions are set from for instance the Paris Climate Agreement, the EU Green deal, (EC 2021), but also, private sectors in farming like Unilever (2021), and a farmer organization in the UK (NFU 2019). It can be expected that policies regarding emissions reduction will be in place, meaning that business must cut their emissions. If a farm is moving towards zero emission, it will be more resilient to these policy changes (P. Burgess, personal communication 2021).
How to measure and unit	The Cool Farm tool can calculate the GHG emissions, in CO2 equivalents, per hectare, or per tonne product of a specific crop or livestock. The farm level emission per ton product can be obtained by calculating the weighted average of GHG emissions per tonne over all products. Carbon sequestration by land management can also be incorporated (also via biomass from trees). The tool considers the entire production, including transport, machinery and inputs, see graph below (for potato). 
Cost and timeframe	Make a yearly calculation using for example the Cool farm tool (CFA 2021).
Target value	Net zero emissions, or net sequestration if possible.
AMOEBA scale	The CO2 equivalents emission is assessed per tonne product. 1: > 25 t CO2 eq. per ton product (see Smith et al 2016). 2: 25 - >10 t CO2 eq. per ton product 3: 10 - >1 ton t CO2 eq. per ton product 4: 1 – 0 t CO2 eq. per ton product 5: net sequestration per ton product (more sequestration than emission)

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3.2.4 Social indicators

Garibaldi (2017) found that socio-economic indicators are often not, or too little, considered in the assessment of farming systems. There are not many sources that report on socio-economic indicators. This means that for our task AGROMIX it is also hard to come up with proper estimates and target values on social indicators. For the following indicators, we tried.

Indicator 15	Memberships of farmer networks, cooperatives and projects
Definition	The number of memberships to farmer networks, cooperatives or project is an indicator for the number of connections the farmer has to exchange ideas and experiences, to arrange collective deals and negotiations with suppliers/buyers, and to collect information.
Link with resilience	- Encouraging horizontal sharing of knowledge, cooperation and networking are important to establish the self-organizing capacity of farmers, and by that improving resilience (Jacobi et al., 2015) - The Social-impact toolkit (2021) presented the relevance from relationships and networks and information exchange for a good social system, since it influences the social capital of a farmer.
How to measure and unit	The assessment is made by counting the number of networks to which the farmer is linked to (study groups, colleague networks). It is defined as the # of groups in which the farmer has at least a 'quite active' participation level (Choptiany et al., 2015).
Cost and timeframe	The required information can be collected once a year, through a semi structured interview or a form that can be filled in by the farmer. In this interview or form, multiple indicators can be discussed. An interview will take approximately 1 hour.
Target value	Here we propose that more than 3 separate networks are the target value of this indicator.
AMOEBA scale	1: 1 or less networks 2: 2 networks 3: 3 networks 4: 4 networks 5: > 4 networks The AMOEBA values are based on Choptiany 2015.

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Indicator 16	**Frequency of training**
Definition	Active participation in courses, education, workshops, or training by farmers, focused on knowledge and skills defines the frequency of training per year. A training is under supervision of an expert. It is defined here as the time spent on training related to farming practices (in hours).
Link with resilience	- Education and courses are part of social and human capital and to improve adaptive capacity (and by that resilience) (Jacobi 2015) - The social impact tool showed that training is of great importance for the positive social impact of farming (Social Impact Tool 2021).
How to measure and unit	Identify how much time the farmer has spent on courses, workshops, education and/or training per year through in interview.
Cost and timeframe	The required information can be collected once a year, through a semi structured interview or a form that can be filled in by the farmer. In this interview or form, multiple indicators can be discussed. An interview will take approximately 1 hour.
Target value	Here we propose that two full days (16 hours) per year of training is a good target value, based on discussion with WUR colleagues.
AMOEBA scale	1: < 4 hour per year 2: 4-8 hours 3: 8-12 hours 4: 12-16 hours 5: >16 hours.

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Indicator 17	Short-supply chain
Definition	Short-supply chains provides the farmer a local market and gives communities affordable access to regional food and allows for re-connecting the consumer with the grower and processor. Regional food is here defined as production and consumptions of food within 50 km (following the definition from Oregional 2021, a Dutch enterprise that stimulates regional food chains).
Link with resilience	- Small, direct supply chains are often more resilient in the face of shocks, ensuring food supply in times of crisis, because farmers and consumers are flexible (Michel-Villarreal 2021). - Nearby production and consumption of food can improve confidence between farmer and client and stimulates fair prices and incomes that enables the farmer to produce more sustainable, making the farm ready for shocks and stresses (IPES 2021, Oregional 2021). Community supported agriculture is also a possibility where consumer and producer work together and stimulate the local economic resilience. - Space for manoeuvre for the farmer, since (s)he is less dependent on value chain requirements and claims. The farmer can make quickly make changes in his strategy, and by that being able to handle a shock (Michel-Villarreal 2021)
How to measure and unit	Identify how many short-supply chain activities the farmer undertakes. For every activity or characteristics, 1 point can be counted for the AMOEBA scale: - Direct sale to consumers = +1 point - Direct sale to end-user (e.g., restaurant, hospital) = +1 point - Produce delivered to local food processor = +1 point - Produce mainly regionally consumed (within 50km) = +1 point - Direct contact between farmer and consumers about farm management and strategy = +1 point Count to number of points.
Cost and timeframe	The required information can be collected once a year, through a semi structured interview or a form that can be filled in by the farmer. In this interview or form, multiple indicators can be discussed. An interview will take approximately 1 hour.
Target value	Here we propose five activities of the farm or characteristics of the supply chain. If the farm incorporates all, a score of 5 will be assigned.
AMOEBA scale	1: zero or 1 activity/characteristic present 2: 2 activities/characteristics present 3: 3 activities/characteristics present 4: 4 activities/characteristics present 5: 5 activities/characteristics present

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4 Discussion & Conclusion

4.1 Discussion of findings

During the selection procedure when the criteria were applied on the longlist, the majority of the indicators excluded were lacking a strong proven link with resilience in the literature. Two other common obstacles for the exclusion of indicators were the establishing a definition of what is to be included in the indicator and the availability of target values suitable across Europe from scientific sources. This caused many indicators that logically have a relation with resilience inoperable. Even in the shortlist of indicators, arbitrary choices were made when establishing target values. The selection process for this indicator set shows many similarities to Rao et al., (2018) who followed similar steps to identify agricultural resilience to climate change. Also, our results and indicators are to a certain extent in line with their findings.

An example of excluded indicators is those related to resilience against pests and diseases of plants. These were discarded because there is a large uncertainty in which new pests and diseases will occur due to climate change and whether general natural enemies will help against this. Another example of an excluded indicator is *soil biology*. Literature research and expert opinion from partners show that soil biological quality can be an important indicator to deal with climate stressors such as drought (Lehman et al., 2015). However, it was not directly included due to the lack of affordable and measurable indicators that show this relationship, availability of global target values and the temporal influence of weather conditions and crops on the community of soil organisms. Soil biology is partly covered by the indicators *soil cover*, *soil organic matter* and soil structure related indicators, to mention a few examples. The livestock *heat stress* was discarded as farm specific indicator, mainly because no thresholds could be found in literature for animal-related indicators as signs of heat stress (Hoffmann et al., 2020). The indicators for animal heat stress *respiration rate* and *core temperature* seem to be suitable parameters to assess individual heat loads but were excluded since they are either time-consuming or there may be interference in data transmission, data variance due to insertion depth, risks of logger losses and effects of drinking (internal temperature measurements) or external factors such as sunshine, shade, wind (external temperature). Also, the consequences of heat stress are partly covered by the indicator *herd fertility*.

Most ecological indicators are evaluated at field (or species/herd) level (except for *crop/animal diversity*, *variability of production*, *sufficient irrigation* and *trees and shrubs*), while the economic and social indicators are evaluated for the whole farm at once. Our initial approach was to select indicators that beforehand can predict the resilience to climate change-induced stressors. However, it was concluded that this was not fully possible when aiming to include all aspects. For example, *herd fertility*, *stability of production* are responses to climate stressors that can only be evaluated during and after the stress. The indicator *sufficient irrigation* is evaluated in the current situation of the system. Since droughts may become more severe, a buffer is included in the target values in the case of a more severe drought. Also here, the evaluation is the most suitable during and after the drought stress.

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In Table 1 we show which climate change related shock each indicator mainly relates to. From this table it is apparent that the resilience to all three shocks is covered by multiple indicators. The selection of indicators was done by looking at complementarity of the indicators but avoiding too much overlap. Indicators that are complementary and possibly interact with each other are for example SOM and *plant available water.* These are possibly positively related because the plant available water is mainly influenced by soil texture and SOM. *Animal diversity* and *crop diversity* both to some degree included in the indicator *number of income sources,* with the addition of other income sources. A final relationship between indicators is between *Memberships to networks and cooperatives* and *Frequency of training* since trainings may be given from the groups of networks and cooperatives. Nevertheless, the first indicator is more focused on evaluating the social and economic safety and resilience, while the second is focused on farmer know-how and flexibility to adapt.

Table 1. The list of indicators and how they relate to the three climate shocks targeted for evaluation. A dark green colour stands for a strong link, while a light green colour stands for a less strong link.

			Climate shock		
Category	**Nr**	**Indicator**	**Drought and heat**	**Heavy precipitation**	**Market and policy responses**
Farm-specific	1	Grass species diversity	dark green	dark green	
	2	Arable crop diversity	light green	light green	dark green
	3	Animal herd fertility	dark green		
	4	Animal diversity			dark green
Ecological	5	Variability of production	dark green	light green	dark green
	6	Herbaceous soil cover	light green	dark green	
	7	Soil organic matter	dark green	light green	
	8	Soil compaction	light green	dark green	
	9	Plant available water	dark green		
	10	Trees and shrubs	dark green	dark green	
	11	Sufficient irrigation	dark green		
Economic	12	Number of income sources	dark green	dark green	dark green
	13	Dependencies on external inputs	light green		dark green
	14	Greenhouse gas emissions			dark green
Social	15	Memberships to networks and cooperatives	light green	light green	light green
	16	Frequency of training	light green	light green	light green
	17	Short supply chain	light green	light green	light green

The very practical approach we followed to produce a quantitative assessment of indicators (via the AMOEBA scale) of resilience, required estimations, assumptions, and expert judgement, since not much literature is

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present about indicator scores and target values. Several sets of indicators were found, including the rationale with resilience, but a translation into numbers and scoring for operationalization was often lacking. Here we did try to provide this scale on farm level to be used for individual farms, applied by researchers or practitioners, to assess their level of resilience.

4.2 Application in practice

The combined set of indicators can be used to give an estimation on the level of resilience a farm has against climate change. It also highlights points for improvements regarding resilience since it shows the indicators that do not perform well. This analysis is mainly done based on ex-ante assessment, where the characteristics of the farm will predict to what extend the farm can cope, adapt and transform its practices to a changing climatic situation.

A suitable way to present and compare farms, is an AMOEBA or spider diagram. The individual scores of the indicators are plotted in one diagram. An example of such a diagram can be found in Figure 2. It shows two fictional farms and their fictional scores on the indicators. This can also be done for all types of farms relevant in AGROMIX or other projects. The farm specific indicators can also be incorporated in the graph. In order to be prepared against the variety of shocks and stresses from climate change, it is important that a farm scores sufficient on all resilient indicators, and with that, the resilience dimensions. A good score on one indicator cannot compensate for a low score on another; it is really about the full and combined assessment and scores. The analysis using these indicators also shows where the farm or farmer must improve his performances.

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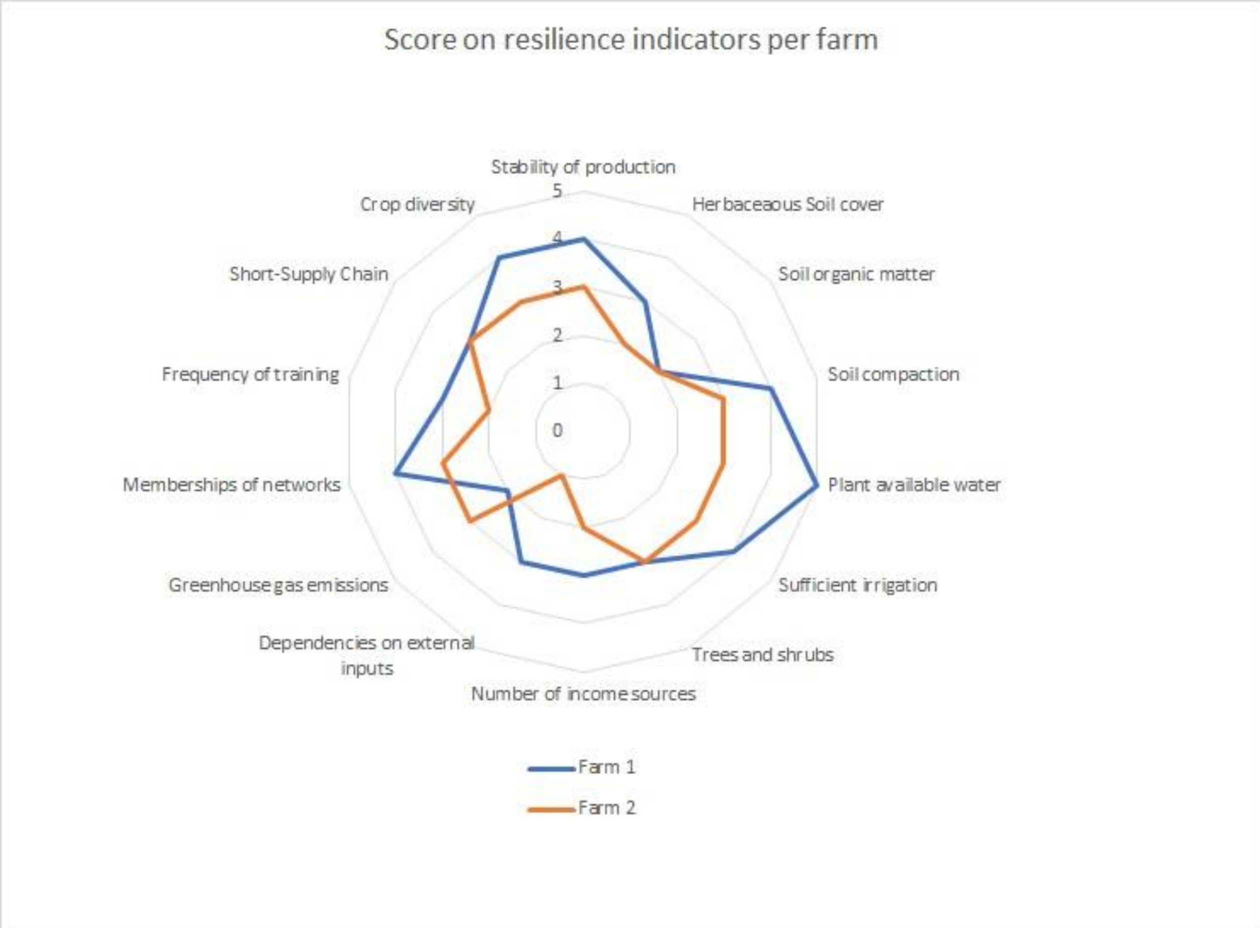
Figure 2: Fictional scores of two fictional farms. The farm 1 (in blue) is more resilient than farm 2 (orange). However, farm 2 also can make improvements on for example soil organic matter and greenhouse gas emissions. The farm specific indicator relevant for these farms are in the top-left corner: crop diversity.



The other work packages of AGROMIX can use this set of indicators in their pilots or experimental sites to grasp the level of resilience of the farms. The indicator set can be applied on any farm in Europe that makes use of land. The assessment requires yearly time investments and measurements, by which also the development over time can be identified after different practices have been implemented.

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Appendices

Table 2. The pF level from which crop damage occurs due to soil moisture deficit, for different vegetables and arable crops (Dekkers et al. 2000).

Crop	pF from which crop damage occurs
Potato	2.8
Strawberry	2.7
Endive	2.8
Asparagus	3.0
Cucumber	2.9
Celery	2.8
Cauliflower	2.9
Beans	2.8
Broccoli	3.0
Chinese cabbage	2.9
Zucchini	3.0
Peas	2.9
Cereals	2.7
Celeriac	2.8
Fennel	2.6
Rapeseed	2.9
Head lettuce	2.8
Red beet	3.0
Corn	3.0
Carrot	3.0
Leek	2.8
Radish	2.7
Lettuce	3.0
Spinach	2.7
Cabbage	2.8
Brussels sprouts	3.0
Sugar beet	3.0
Onion	2.8

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