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Improved crop rotation[1]

1 Measure definition

Crop rotation means cultivating different crops in a temporal sequence on the same land, compared to monocultures continuously growing the same crop (Summer 2001).

Rotating crops is one of the oldest agricultural strategies to control environmental stresses, nutrient and water balances, crop performances and systems' resilience. Nevertheless, in the past fifty years, specialisation of farm production, e.g. the decoupling of mixed crop-livestock farming, combined with an increased availability and usage of plant protection agents were drivers to more simplified cropping systems reducing the length of rotations and diversity of crops (Barbieri et al. 2017). As a result, short cereal-based rotations today dominate many European agricultural landscapes (Peltonen-Sainio and Jauhiainen 2019).

Improved crop rotations benefit from synergies between crops in the temporal sequence and/or in the same space, such as with undersown cover crops. The crops in the rotation should derive from different categories, i.e. primary (wheat, maize) and secondary cereals (e.g. spelt, barley, triticale, oat), grain legumes, and temporary fodders, including forage legumes. Globally, oilseeds, vegetables and root crops have the lowest share of cropland in rotations (Barbieri et al. 2012). Depleting crops such as maize that cause higher loss of mineral nutrients or destruction of organic matter due to intensive management, are combined with or followed by replenishing crops, e.g. cover crops or legumes. Especially the integration of grain and fodder legumes, as well as temporary grassland shows benefits for the subsequent crops (Garrett et al. 2017; Peltonen-Sainio and Jauhiainen 2019).

In organic farming, extended and complex crop rotations with a high diversification of crops, e.g. including more fodder crops and legumes, catch crops and undersown cover crops, are key strategies to support agroecosystem functioning that keeps soils fertile and plants healthy since synthetic pesticides are prohibited (Barbieri et al. 2017). Relying on synergies between crops and resulting ecosystem services in improved crop rotations is not limited to organic agriculture, but any form of agriculture can make use of these benefits.

Geographical and biophysical applicability

- **Suitability to different biophysical conditions:** Crop rotations are used worldwide to manage crop production. Diversified and improved crop rotations relying on the integration of crops from different categories, e.g. grass, higher share of forage or grain legumes, can be applied to any area suitable for cropland.
- **Suitability in EU/German conditions:** The temperate climate and the landscape structure of central Europe allow for improved crop rotations with higher diversity of crops coming from different crop categories, including higher share of legumes and temporary grassland. Further support for diversification of crops in space and time has to be supplied from policy regulations.

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[1] This factsheet was developed as part of the research project "Naturbasierte Lösungen (NbS) im Klimaschutz: Marktanreize zur Förderung klimaschonender Bodennutzung" (FKZ 3721 42 502 0) and is also published as part of the Annex to the UBA report "Role of soils in climate change mitigation", see www.umweltbundesamt.de/publikationen/Role-of-soils-in-climate-change-mitigation.

Fit with NbS definition

Provided that crop rotations are locally adapted and follow the principles of good agronomic practice as outlined above, they contribute to carbon sequestration objectives and fulfil all aspects of nature-based solutions as defined in the working definition for this research project by Reise et al. (2022). Crop rotations have to be locally appropriate and protect soils, and not rely on intensive fertilisation/agro-chemical inputs or unsustainable irrigation.

2 Mitigation Potential

2.1 Carbon sequestration

Cropping sequences play a considerable role in either soil carbon stock loss, maintenance or increase. Integrating legumes, e.g. alfalfa, and fallow periods can increase carbon stocks in the long-term compared to monocultures (Blair and Crocker 2000; Yang and Kay 2001). Crop rotations with legumes show a maintenance of the initial SOC compared to a reduction in rotations without legumes (Pikula and Rutkowska 2014) and the integration of grass ley in a cereal rotation leads net SOC increase (Prade et al. 2017).

A meta-analysis on long-term experiments found a sequestration rate of 0.2 t C/ha/year when enhancing the complexity of crop rotations (West and Post 2001). A simulation across European arable land showed that integrating ley (two consecutive years of alfalfa) in the crop rotation lead to constant C accumulation with median annual SOC sequestration rates of 0.11 t C/ha/year by 2050. A scenario with cover crops (grass mix or rye grass) in the crop rotation resulted in similar sequestration potential magnitude as the integration of ley but with much higher variability related to climate change (Lugato et al. 2014).

2.2 Total climate impact

Agricultural systems are in general net sources of GHG emissions, but improving crop rotations can decrease total GHG emissions. A reduction of 28% CO_2e was shown by the integration of catch crops and spring cereals in typical northern European cereal rotations due to a better use of fertilizer-N, while N-leaching was reduced at the same time (Olesen et al. 2004). Further studies have shown that the integration of legumes in simple crop rotations can reduce N_2O emissions compared to monocropping systems (Behnke et al. 2018; Li et al. 2017), even though the responses are climate related and may change under future climate conditions (Li et al. 2017). The impact on the total GHG emissions can vary across crop rotations, depending on the crops, the sequence of crops and other management factors, e.g., fertilization and tillage, making the evaluation of GHG emissions on crop rotation or yield difficult.

2.3 Limitations on the mitigation potential

The carbon sequestration potential of improved crop rotation depends strongly on implementing co-management factors such as reduced tillage (Shreshta et al. 2015) and how single crops in the rotation are managed, e.g., with high- or low-input of organic matter and crop residue management (Vinther et al. 2004). The positive impact of improved crop rotation (e.g. inclusion of green manure crops) and reduced tillage on soil carbon stocks was shown in a study of nine longterm field trials in Europe (Krauss et al. 2022). However, long-term sequestration gains due to a beneficial cropping sequence can be reversed quickly by tilling/ploughing the soils due to fast mineralization processes of organic compounds. Sequestration continues to occur only until soils reach saturation state.

3 Adaptation and co-benefits

- **Yields:** Crop rotation diversification improves yield of single crops compared with monocultural production, e.g. spring wheat (Jalli et al. 2021) and increases temporal yield stability (Gaudin et al. 2015; Macholdt et al. 2020).
- **Soil and biodiversity:** Rotations with enhanced complexity provide higher microbial abundance and diversity (Tiemann et al., 2015) supporting soil health and fertility.
- **Biodiversity:** A diversification in the crop rotation also improves agrobiodiversity on farm and landscape-level in space and time, increasing habitat niches for wildlife biodiversity.
- **Landscape water management:** Improving crop rotations can help to manage the eco-hydrological regime of landscapes by higher daily discharge, groundwater seepage and lower evapotranspiration compared to simplified cropping patterns (Sietz et al. 2021).
- **Nutrient management:** The usage of N-fertilizers can be reduced when integrating legume crops in the rotation. The nitrogen fixing potential of the previous legume crop increases the N supply to the soil by 36 to 49% (Cox et al. 2010).
- **Climate impacts:** The diversification of crop rotations improves sustainability and resilience to inter-annual weather variability by lowering the risk of crop failure and supporting temporal yield stability (Macholdt et al. 2020). Specifically the integration of permanent grassland, forage or grain legumes improved the resilience of cropping systems to hot and dry conditions by conserving soil moisture and/or improving plant access to water resources (Gaudin et al. 2015).
- **Weed and pest control:** Crop rotations avoiding the sequence of similar crops reduce weed and pest breakthrough due to changes in crops (host to non-host) and crop management. On a landscape scale, the diversification and length of crop rotations and their occurrence at different stages in one year prevent seed dispersal between fields and control short- and long-term weed population densities (González-Díaz et al. 2012). They also enhance natural pest control in agricultural landscapes (Rusch et al. 2013).

4 Trade offs

- **Costs:** Enrichment of farms' agrobiodiversity may increase costs of management and production because of the need for machinery and labour (Firbank et al. 2013).
- **Nutrient management:** Reducing N fertiliser can be achieved with integration of legumes in the crop rotation and reducing the doses of N fertilisation in the subsequent crop. This comes along with reduced gross margins, thus a trade-off between environmental and economic goals (Nemecek et al. 2015).
- **Economic return:** Diversifying crop rotations by integrating perennial polycultures, e.g. legume-grass mixtures or wildflower mixtures, increases regulating ecosystem services such as soil fertility, climate regulation or pollination, but scores lower for biomass production compared with maize (Weißhuhn et al. 2017).

5 Implementation challenges

A diversification of crops can be challenging for farmers used to the production in monocropping systems or very simple crop rotations due to lack of knowledge and local experiences or suitable machinery. Moreover, there are several more systemic barriers that hinder crop diversification, i.e., 1) crop diversification requires market outlets for minor crops which may not be available due to a lack of consumer demand for these crops; 2) uptake of new crops can also lead to higher costs since standards in processing and distribution are often specified for products of dominant species; 3) there is a lack of incentives and conditionality through the Common Agricultural Policy, accompanied with little public R&D on minor crops.; 4) there are few active substances (pesticides) approved on minor crops (Meynard et al. 2018).

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