HELMHOLTZ
Centre for Environmental Research

UFZ Discussion Papers

Department of Environmental and Planning Law

2/2024

Sustainable Cultivated Landscapes in Germany: Comparison of 27 Practical Measures for more Sustainability and their Effectiveness

Stefan Möckel, Marieke Cornelia Baaken, Bartosz Bartkowski, Michael Beckmann, Michael Strauch, Jessica Stubenrauch, Martin Volk, Felix Witing, André Wolf

September 2024

Publisher:
Helmholtz-Zentrum für Umweltforschung GmbH – UFZ
Permoserstr. 15
04318 Leipzig

ISSN 1436-140X

Sustainable Cultivated Landscapes in Germany:

Comparison of 27 Practical Measures for more Sustainability and their Effectiveness

Authors: Stefan Möckel[a], Marieke Cornelia Baaken[b], Bartosz Bartkowski[a], Michael Beckmann[a], Michael Strauch[a], Jessica Stubenrauch[a], Martin Volk[a], Felix Witing[a] and André Wolf[a]

Institutions: [a] Helmholtz Centre for Environmental Research - UFZ, Leipzig, [b] Department of Economics, Institute of Environmental Systems Science, University of Osnabrück

Abstract

With months of drought, hot summers and flooding, global warming has also become increasingly apparent in Germany over recent years. The Climate Protection Act, which was amended in 2021, therefore aims to achieve climate neutrality by 2045. At the same time, a favourable conservation status for habitats, species and water bodies are still the exception in cultivated landscapes, in spite of obligations under European law to achieve this. In this article, we estimate the potential impacts of various landscape designs and integrated land-use measures in terms of climate change mitigation and adaptation, favourable conservation status as well as long-term food security and profitable land use. Based on these impact assessments, we then identify priority measures to be taken. The comparative assessment of effectiveness is intended to help prioritise the most suitable measures in view of limited financial and human resources.

Keywords: design of cultivated landscapes, agriculture, forestry, integrated measures, prioritisation, climate change, climate adaptation, security of food, water and biomass supply, biodiversity

Funding information

This article is part of a UFZ research project on sustainable agricultural landscapes in Germany which is co-funded by the Federal Ministry of Education and Research (BMBF) as part of the funding initiative "Soil as a sustainable resource for the bioeconomy - BonaRes" (funding reference 031B0511A) and the junior research group "AgriScape - Conflicting goals on the way to multifunctional agricultural landscapes" (funding reference 01UU2203) as well as by the projects OPTAIN (Grant Agreement 862756) and BESTMAP (Grant Agreement 817501) funded by the EU's Horizon 2020 Framework Programme for Research and Innovation funded projects OPTAIN (Grant Agreement 862756) and BESTMAP (Grant Agreement 817501).

1 Introduction

In 2022, climate change continued with the same trend as in recent years in Central Europe, once again leading to longer periods of drought throughout large parts of Germany. The lack of precipitation over the last 5 years has worsened overall, exacerbating the problems in forests and water bodies (including tree and fish mortality), while causing considerable yield losses in agriculture in some cases.[1] The weather in Central Europe appears to be changing faster than previously assumed in climate projections[2]. Average temperatures in Europe have already exceeded the global 2°C limit in recent years,[3] increasing the pressure to act, both in terms of climate protection and climate adaptation. Agricultural landscapes are of particular importance in both fields of action, as they are characteristic of large areas of Germany and are under particular pressure to adapt[4], as they have great potential for climate protection. [5]

In our previous discussion paper "Sustainable cultivated landscapes in Germany: Goals and Requirements from an Ecological, Economic and Legal Perspective", we summarised the objectives and requirements for cultivated landscapes in Germany – dominated by agriculture and forestry – from an ecological, economic and legal perspective.[6] According to our understanding of sustainability, cultivated landscapes are sustainable if they can be used for agriculture, forestry and other land uses in the long term, while at the same time maintaining or (in the case of degraded habitats) restoring the performance of the ecosystem functions and the quality of the habitat. The German Advisory Council on the Environment deems this to be sustainable and environmentally sound.[7] To date, economic and social objectives and framework conditions have led to an intensification of anthropogenic land use in most cultivated landscapes in Germany (in particular agricultural production, settlements and transport), at the cost of degraded ecosystems and the loss of wild plants and animals.[8] This contradicts not only the international Sustainable Development Goals as well as the national sustainability goals,[9] but also the existing legal requirements under international and European law and Article 20a of the German Basic Law, which obligate Germany to protect the natural foundations of life and to restore good ecological conditions for habitats, species and water bodies.[10] Of particular note here is the European Nature Restoration Regulation 2024/1991, which was adopted in June 2024 and obliges the member states to restore ecosystems in cultivated land, surface waters and marine areas in a comprehensive and time-bound manner.

Good ecological conditions are a prerequisite for many ecosystem services that our society uses free of charge. In addition, the more disturbed, overused or degraded that soils, water bodies and habitats are, the greater the vulnerability of cultivated landscapes to climate change and extreme weather events.[11] Conversely, the impacts of climate change can be mitigated if existing environmental problems in cultivated landscapes are minimised as much as possible and cultivated landscapes become climate-neutral in the medium term and act as carbon sinks in the long term. [12]

Dynamic changes in cultivated landscapes are not only caused by climate change, but also by species population changes, the introduction of non-native species and societal changes, such as the legal framework, the economic market situation, consumption patterns or the leisure behaviour of the population. Climate-adapted and sustainable cultivated landscapes must therefore be highly resilient, tolerant and flexible in the face of short-term disruptions and long-term changes, the nature, extent and timing of which all remain uncertain, even with state-of-the-art computer modelling. Measures to promote such cultivated landscapes are risk-prevention measures in the sense of the precautionary principle.[13]

In this article, we present a selection of measures to promote climate-adapted, sustainable cultivated landscapes and evaluate them with regard to the following objectives:

- Increasing resilience to extreme weather events intensified by climate change (e.g. heavy rain, floods, storms, heat and drought, late frosts);
- Climate neutrality of cultivated landscapes;
- A good ecological conservation status of water bodies, habitats and species;
- The long-term security of food, drinking water and biomass, and
- Long-term economic profitability and income security.

The above objectives were prioritised by the team of authors using the objectives and obligations identified in the previous paper from ecological, legal and economic perspectives.[14] In our opinion, the objectives reflect the most important societal interests in cultivated landscapes, integrating a large number of more specific objectives, such as the preservation or restoration of the water absorption capacity and water storage capacity of soils, the creation of retention areas or the reduction of nutrient and pollutant loads to protect ecosystems.[15] The 5 objectives are interrelated, which is why there are also overlaps in some cases.

Sections 2 and 3 of this paper are intended to provide policy makers, landowners and land users with an overview of various measures with positive effects on as many of the five objectives as possible, and to identify and discuss possible conflicts with specific objectives.

2 Measures to promote climate-adapted and sustainable cultivated landscapes

Tables 1 to 3 contain a selection of measures which, according to our findings, best promote the establishment of climate-adapted and sustainable cultivated landscapes. To make things more transparent, we have differentiated between landscape design measures and production-integrated agricultural and forestry management measures in the tables. The transition between the two categories is fluid, as landscape design measures change the way in which the land is used for agriculture and forestry and, conversely, the way in which the land is managed shapes the landscape and directly or indirectly influences the ecosystems in a landscape.

We have differentiated between the two groups of measures primarily according to the extent to which they are measures of "everyday management" within a specific agricultural and forestry land use (production-integrated) or whether they measure results in a change in the type of use (landscape-shaping) in accordance with the jurisdiction of the Federal Administrative Court on Section 14 (2) BNatSchG.[16] Non-everyday farming methods also include measures for improvement and changes to the water regime of land (e.g. the creation of terraces and ditches, removal of drainage ditches or drainage systems).

Numerous studies were consulted for the selection of measures and the assessment.[17] Then came the expert knowledge from our team of authors, particularly in the case of economic profitability, where the evidence is largely selective and unsystematic. The economic assessment is based on business economics and not macroeconomics. Existing or future state subsidies (e.g. direct payments or subsidies under the second pillar of the Common Agricultural Policy) were not taken into account for two reasons. Firstly, these distort the economic assessment. Secondly, a possible need for subsidies, e.g. for conversion costs or higher management costs, can only be recognised if they are not taken into account.

The measures that were analysed are not new, but have been scientifically researched for some time and applied in practice to varying degrees. Nevertheless, our assessments are at a higher level of abstraction. Firstly, because existing field studies did not analyse all measures or all landscape types in Germany and only partially investigated the effects with regard to the objectives we selected. Secondly, because the measures analysed can be implemented in different ways and to a different extent and also have different effects on the specific landscapes depending on the local conditions. The assessments are therefore to be understood as trends and development curves for the average effects of the measures, which can be regarded as plausible according to our state of knowledge.

We used the following assessment scale for potential impacts:

- (++) Measure significantly promotes the objective
- (+) Measure has a predominantly positive effect on the objective
- (+/-) Measure is neutral overall, i.e. it has no significant impact on the objective or the positive and negative effects roughly balance each other out
- (-) Measure has a predominantly negative impact on the objective
- (- -) Measure substantially hinders the objective

The assessment is relative, as it is based on the positive or negative deviations from a reference state, with the assumed reference state based on the current predominant state in local cultivated landscapes. In the case of landscape-related measures, this is a landscape with large fields, few landscape elements, improved and drained areas with watercourses that have been extensively altered for rapid, area-saving water runoff. For production-integrated measures, we assumed conventional agriculture with reduced crop rotations without intercropping and mixed crops as well as the use of fertilisers and pesticides geared towards high yields. In forestry, monocultures of spruce, pine or beech are the reference values. The assumption of these highly simplified reference conditions was essential for comparability, even if it does not reflect the diversity of land uses and management forms that already exist in many landscapes today (e.g. small-structured landscapes, mixed forests). Tables 1 to 3 can therefore also be used to assess current landscapes according to the extent to which they already feature the selected landscape-related or production-integrated measures and are therefore already better adapted to climate change and designed to be sustainable and environmentally friendly.

Table 1: Landscape-related measures[18]

Measures / Objectives	Increasing resilience to extreme weather events (climate adaptation)	Climate-neutral cultivated landscapes	Food security, drinking water security and biomass security for energy and materials	Good ecological conservation status of water bodies, habitats and species	Economic profitability and income security
Changes in use					
Establishment of extensive agroforestry systems on permanent grasslands with fruit trees, nut trees, oaks, chestnut trees, willows, etc. (e.g. orchards, hay meadows with individual oaks)	(+ to ++) against droughts and heat due to shading and reduction of wind strength	(+) Short to medium-term carbon sequestration in perennial plants (+) Increase in soil carbon sinks through tree roots	(+ to ++) Increase in food production from fruit trees and better water availability for permanent grasslands (+) Increase in biomass production (+) Timber production	(+ to ++) Increased habitat diversity depending on location and tree species (-) Loss of grassland habitats that depend on minimal shade cover	(-) short-term: investment costs for planting (+/- to +) Higher income due to diversification of use and climate adaptation, despite higher management costs
Establishment of agroforestry systems on arable land with short rotation or rows of trees for timber or rows of fruit, chestnut or nut plantations	(+ to ++) against droughts, frost, heat, heavy rain and erosion events due to shading, reduction of wind strength and greater water and sediment retention in permanently planted rows of trees and shrubs	(+ to ++) Increase in the soil carbon sinks where trees are grown (+ to ++) Medium to long-term carbon sequestration in perennial plants	(+ to ++) Risk reduction in terms of frequency and extent of yield losses due to climate adaptation, land use diversification and increased potential for natural pest control (- to +) Biomass production (+) Timber production (- to +/-) Reduction in food production due to loss of arable land where rows of trees are grown, if no compensation due to fruit and nut production and climate adaptation	(+ to ++) Increased habitat diversity and connected biotopes depending on the type of agroforestry system (+) Lower soil and pollutant loads into neighbouring water bodies and habitats due to water retention and reduction in wind speed	(-) short-term: investment costs for planting and conversion (- to +) long-term: Better yields due to climate adaptation, diversification of use and higher biodiversity, but loss of arable land and higher management costs
Conversion of arable land into forest with mixed stands	(++) against droughts, frost, heavy rainfall and erosion events due to shade, reduction of wind speed, higher water and sediment retention and an overall more balanced microclimate in the forest	(++) carbon sequestration in trees in the medium to long term, with construction use (++) Increase in soil carbon sink (+) Elimination of nitrous oxide emissions from fertilizers	(++) Hardwood production (++) Improvement of water quality (depending on the intensity of previous arable farming) (--) Reduction in food production due to loss of arable land (-- to -/+) Reduction in biomass production, as higher biomass yields per year are possible with arable crops or SRC than with forests	(+ to ++) Greater habitat diversity within areas characterised by agriculture (++) Lower soil and pollutant loads into neighbouring water bodies and habitats	(-) short and medium term: investment costs for planting and extensive loss of income until the trees are ready for felling (- to +/-) long-term: lower profits depending on timber prices and other costs (-) higher potential damage from storms, fires, disease and infestations in forests compared to arable crops

Objectives Measures	Increasing resilience to extreme weather events (climate adaptation)	Climate-neutral cultivated landscapes	Food security, drinking water security and biomass security for energy and materials	Good ecological conservation status of water bodies, habitats and species	Economic profitability and income security
Conversion of arable land into permanent grassland	(++) against storms, heavy rainfall and droughts due to year-round vegetation with deep-rooted plants or drought-resistant grasses	(+ to ++) Increase in the soil carbon sink	(+ to ++) Improvement in water quality (depending on the intensity of previous arable farming and future grassland management) (-) Reduction in food production, as only animal feed production/grazing is possible	(+ to ++) Greater habitat diversity depending on the intensity and type of permanent grassland management (++) Lower soil and pollutant loads into neighbouring water bodies and habitats	(- to --) lower profitability
Conversion of permanent grassland to forest with mixed stands	(+/- to +) against droughts, frost and heavy rainfall due to shade, reduction in wind speed and an overall more balanced microclimate (-) Higher vulnerability with unfavourable groundwater availability for forests	(++) Medium to long-term carbon sequestration in trees (+/- to +) Increase in soil carbon sink	(+/- to +) Increase in biomass production (++) hardwood production (+/- to +) Improvement in water quality (depending on the intensity of previous grassland management) (-) Reduction in food production	(++) Promotion of forest habitats and species (--) Decline in open grassland species due to habitat loss (+/-) Water bodies	(-) short and medium term: investment costs for planting and extensive loss of income until the trees are ready for felling (+/- to +) Long-term: expected higher profits depending on timber prices and costs (- to --) higher potential damage to forests in the event of storms, fires, disease and infestations
Conversion of monoculture forests into agroforestry systems with permanent grassland	(- to +) higher vulnerability to drought and heat, unless not high vulnerability in forest use due to unfavourable groundwater availability	(-) lower soil carbon sink (--) if the removed trees are used as fuel instead of building material	(+) Increase in food production through livestock, fruit, nut and chestnut cultivation (+/- to -) possible deterioration in water quality (depending on intensity) (- to +) Biomass production (- to --) Reduction in hardwood production	(++) Promotion of open land species (--) Decline in forest species	(++) short-term: high income from timber sales (+) long-term: diversification enables higher and, above all, shorter-term yields and reduces economic risks (++) Lower potential damage levels in the event of storms, fires, disease and infestations

Objectives Measures	Increasing resilience to extreme weather events (climate adaptation)	Climate-neutral cultivated landscapes	Food security, drinking water security and biomass security for energy and materials	Good ecological conservation status of water bodies, habitats and species	Economic profitability and income security
Conversion of monoculture forests into agroforestry systems on arable land	(- to --) higher vulnerability to droughts, heat, heavy rainfall events and floods, unless not high vulnerability to forest use due to unfavourable groundwater availability	(--) strong reduction in soil carbon sink (--) if the removed trees are used as fuel instead of building material	(+ to ++) Increase in food production (- to --) Deterioration of water quality in arable forestry systems (+/- to +) Increase in biomass production (- to --) Reduction in **hardwood** production	(+) Promotion of open land species depending on species (--) Decline in forest species	(++) short-term: high income from timber sales (++) long-term: diversification enables higher and, above all, shorter-term yields and reduces economic risks (+) Lower potential damage in the event of storms, fires, disease and infestations
Introduction of landscape elements					
Planting hedges or rows of trees along field edges or in fields	Similar effects to agroforestry systems on arable land or grassland, but the greater the distance between the hedges, the smaller the effect.				
Morphological diversification measures (creation of terraces, embankments, ditches, retention basins, ponds, etc.)	(++) against heavy rainfall, floods, erosion events and droughts due to slowing of surface water runoff and higher water and sediment retention	(+) Humus enrichment in sediment traps (-) Methane gas formation in ponds and retention basins	(+) Long-term security of food production due to reduced soil erosion (+) Risk reduction in terms of frequency and extent of yield losses due to better climate adaptation (+ to ++) Improvement in water quality (- to --) Reduction in food production due to loss or reduction in use of arable land and grassland	(+ to ++) Greater habitat diversity and connected biotopes (+) Lower soil and pollutant loads into neighbouring water bodies and habitats	(- to --) short-term: high investment costs for diversification measures (- to +/-) long-term: certain losses of arable land and grassland, but overall safeguarding of yield through risk minimisation
Water-related measures					
Raising the groundwater level by changing the drainage regime, removal by drainage systems, raising the bed or damming up watercourses (including rewetting moors and floodplains)	(+ to ++) against floods and droughts due to reduced drainage and slower runoff of groundwater and surface water (-) Risk of soil compaction and soil erosion if arable farming continues	(++) Preservation of carbon sequestration in peatlands and alluvial soils (+) Long-term carbon enrichment, especially when restoring peatlands with peat mosses	(+) Risk minimisation with regard to the frequency and extent of yield losses due to climate adaptation (- to --) Reduction in food production due to abandonment or restriction of use of arable land or grassland	(+ to ++) Improvement of habitat characteristics, especially in peatlands and floodplains	(- to --) Yield declines or abandonment of arable land and grassland (+) Risk minimisation against droughts and floods (+) Cultivation alternatives (carbon farming, paludiculture, forest, permanent grassland)

Objectives Measures	Increasing resilience to extreme weather events (climate adaptation)	Climate-neutral cultivated landscapes	Food security, drinking water security and biomass security for energy and materials	Good ecological conservation status of water bodies, habitats and species	Economic profitability and income security
			(+) Increase in biomass production with change of use to paludiculture or forest (+) Improvement in water availability		
Renaturalisation of watercourses (removal of straightening and other degrading alterations, creation of retention areas)	(+) against floods and droughts due to slower groundwater and surface water runoff and retention areas	(+) Long-term carbon storage due to humus accumulation in riparian areas and retention areas	(+) Improving the water quality of watercourses (+) Increase in fish stocks (- to --) Reduction in food production due to loss or reduction in utilisation of arable land and grassland	(++) Improvement of watercourse morphology and habitat characteristics	(- to --) Yield decline or abandonment of arable land and grassland (+) Risk minimisation against flooding
Establishment of permanently green buffers along watercourses	(+) against erosion events (heavy rainfall, flooding) due to slowed surface water runoff	(+) Long-term carbon sink in the soil of the buffers (+) Short to medium-term carbon sequestration in perennial plants	(+) Improved water quality of surface waters (+) Long-term security of food production due to reduced soil erosion (- to --) Reduced in food production due to loss or restricted use of arable land and grassland	(++) Improvement of the chemical status of surface waters (+) Creation of habitats and connected biotopes	(- to --) Yield decline or abandonment of arable land and grassland (+) Risk minimisation against erosion events and environmental liability claims
Technical systems					
Agrivoltaics PV systems with permanent grassland or arable land use	(+) against hail, heavy rain, storms, heat stress and droughts due to shielding, shade cover and reduction of wind speed	(++) Substitution of fossil fuels	(+) Risk reduction in terms of frequency and extent of yield losses due to better climate adaptation (- to +/-) Lower food production due to restrictions on use or loss of arable land and grassland, unless compensated for by climate adaptation and a more balanced microclimate	(+/-) positive and negative changes in habitat characteristics largely balance each other out without fundamentally changing the habitat	(-) short-term: high investment costs (++) long-term: profitable source of income (+) Risk minimisation due to more protection against extreme events and differentiation of use (-) Increase in the potential amount of damage

Table 2: Production-integrated measures for agricultural land[19]

Objectives Measures	Increasing resilience to extreme weather events (climate adaptation)	Climate-neutral cultivated landscapes	Food security, drinking water security and biomass security for energy and materials	Good ecological conservation status of water bodies, habitats and species	Economic profitability and income security
Diversification of crops					
Diversification of the perennial crop rotation including catch crops (e.g. legumes) or greened rotational fallow land	(+/- to ++) against droughts and heavy rainfall events due to improved soil structure and reduced periods without soil cover (-) With catch crops, possible risk of water shortages for main crop	(+/- to +) Short to medium-term C enrichment in the soil due to deep-rooted crops, fallow land and green manure (+) Reduction in the use of fertilisers	(+/- to +) Higher yields per hectare in the long term (both biomass and, depending on crop rotation, food) due to climate adaptation, less disease and pests and better soil structure (+/- to +) Improvement in water quality (e.g. due to reduced nutrient leaching)	(+) Improvement of soils in terms of properties and biodiversity (+) Improvement of arable habitat characteristics (e.g. for beneficial organisms) (+/- to +) with regard to pollutant loads into surface waters and habitats	(+/- to +) higher yields due to risk minimisation, improved crop protection and better soil structure (+/- to +) Cost savings on pesticides and fertilisers (- to +/-) higher labour efforts and costs
Diversification of the field crops grown (mixed crops, main crops and sub-cultures)	(+) generally due to crop diversity and improved soil structure				
Intensity of fertiliser and pesticide use					
Reduced use of mineral and farm fertilisers geared towards maximum yields	(+) against heavy rainfall due to lower risk of nutrient leaching (+) greater robustness of the crops in some cases	(+ to ++) depending on the extent of fertiliser reduction	(+ to ++) Improved quality of food and water (-- to -/+) Lower yields per hectare depending on the extent of fertiliser reduction and cultivation of legumes, but at the same time a reduction in disease and pests	(+ to ++) Improvement in the characteristics of arable habitat and adjacent habitats (e.g. for beneficial organisms) and surface waters, depending on the extent of fertiliser reduction	(+) Risk minimisation of crop failures due to less disease and pests (+) Cost savings for fertilisation and plant protection (-- to +/-) lower yields per hectare
Reduced use of chemical plant protection products and expansion of non-chemical plant protection measures in accordance with the principles of integrated plant protection	(+ to -) Non-chemical plant protection measures can increase resilience to extreme weather events (e.g. with crop diversification), but also reduce it (e.g. ploughing tillage)	(+/- to -) depending on the type and scope of non-chemical plant protection measures and the energy sources used	(+) Improved quality of food and water (+/- to -) lower yields per hectare depending on the extent of pesticide reduction and non-chemical crop protection	(+ to ++) Improvement in the characteristics of arable habitat and neighbouring habitats (e.g. for beneficial organisms) and surface waters, depending on the extent of pesticide reduction	(- to +/-) non-chemical crop protection more expensive than chemical crop protection to date (- to +/-) lower yields per hectare

Type of tillage					
Preservation tillage with permanent ground cover	(++) against flooding and erosion events due to permanent ground cover and higher infiltration capacity of the soil (+) against droughts due to increased water storage and improved soil structure	(+) Increase in soil carbon content due to higher biomass input	(+) Long-term security of food production and biomass production due to reduced erosion (++) Improved water quality (in particular by reducing phosphorus and sediment loads into water bodies) (+/- to +) long-term: higher yields per hectare due to improved soil structure	(++) Increase in soil biodiversity due to greatly reduced disturbance (-) Negative impacts on biodiversity when using total herbicides for seedbed preparation (-) Possible increased use of pesticides in the event of non-compliance with crop rotation rules	(-) short to medium term: higher investment costs for machinery (+) long-term: higher and more stable yields due to climate adaptation
Introduction of pyrolysis charcoal	(+) against droughts due to improved water storage in the soil	(+) for vegetable carbon from residues due to long-term C storage in the soil (+/-) for biochar from fresh wood, as more long-term C sequestration is also possible here with construction use	(+/- to +) higher yields per hectare for some crops (e.g. maize, wheat) (+/- to +) Improvement in water quality due to binding of pollutants to vegetable carbon (activated carbon effect)	(+/-) Unknown effects on soil biodiversity	(-) High costs of vegetable carbon and its incorporation (+) Higher and more stable yields possible due to lower susceptibility to drought
Reduction and elimination of mechanical soil compaction (e.g. by means of soil-conserving machinery, ploughing of compacted soils including deep ploughing of plough soles)	(+) against droughts, floods and erosion events due to increased water storage capacity, infiltration capacity and capillary effects through improved soil structure	(+) due to lower methane and nitrous oxide formation in the soil (+/-) no significant influence on soil carbon with compaction-friendly tillage (-) Higher greenhouse gas emissions from ploughing with fossil fuels	(+) Increase in water availability for agriculture and water supply (+) Long-term security of food production and biomass production due to reduced soil erosion	(+) Increase in soil biodiversity due to improvement in soil structure	(-) short to medium term: higher investment costs for machinery (+) long-term: higher and more stable yields due to lower susceptibility to drought and waterlogging
Special technical measures for extreme events					
Irrigation and sprinkler systems	(+ to ++) against droughts, heat and late frosts	(-) due to energy requirements for pumps and for manufacturing the systems, particularly in the case of fossil fuels	(+ to ++) Yield protection (+/- to --) Competition with drinking water depending on water availability	(-- to +/-) Depending on water availability, water extraction can worsen quantitative and possibly also ecological and chemical conditions in water bodies where water is extracted and neighbouring habitats (e.g. floodplains)	(+ to ++) Yield protection (- to --) Investment and operating costs for irrigation and sprinkler systems and water charges

Fleece crop covers	(+ to ++) Protection against heavy rain, hail, drought and frost	(-) due to energy requirements for the production of fleece and disposal, particularly in the case of fossil fuels	(+) Yield protection during extreme events and minimisation of pests and weeds (+) Increase in food production by extending the cultivation periods	(- to +/-) depending on the surface area and release of microplastics (-) Risk of fleece being swept away during storms and flooding	(+ to ++) Yield protection in the event of extreme events and pests (+) Prolonged cultivation periods (-) Costs for fleece
Heating as frost protection	(+) against frost	(--) due to energy requirements for heating and for the production of heating systems, particularly in the case of fossil fuels	(+) Yield protection during frosts	(- to +/-) depending on the extent of heating	(+) Yield protection (-) Costs for heating

Table 3: Production-integrated measures for grasslands and forests[20]

Objectives Measures	Increasing resilience to extreme weather events (climate adaptation)	Climate-neutral cultivated landscapes	Food security, drinking water security and biomass security for energy and material utilisation	Good ecological conservation status of water bodies, habitats and species	Economic profitability and income security
Grassland areas					
Extensive without fertilisation and with a maximum of 0.5 livestock units or a maximum of 3 mowings	(+) with regard to drought due to lower grazing pressure or less frequent mowing	(+/-) Depending on the location, carbon sequestration in the soil can at least offset greenhouse gas emissions from livestock farming	(+) Improvement of water quality (-) Reduction in food production	(++) Improvement of habitat characteristics as pastures or mown meadows	(-- to +/-) Reduction in income is only partially offset by lower operating costs and higher revenues
Forest areas					
Climate-adapted monocultures	(+) against droughts and heat waves due to higher resilience to drought stress	(+/-)	(+/- to +) Increase in biomass production due to improved climate adaptation	(+/-) no significant improvement in habitat characteristics (-) Negative effects of pesticide use for defence against pests and diseases	(+) higher yields due to climate adaptation (+) Lower costs for cultivation, harvesting and marketing (-) Higher crop failures and market risks
Mixed stands (same age)	(+ to ++) against droughts, heat waves and forest fires due to higher resilience to drought stress and infestations	(+) More secure long-term sequestration of carbon in the soil due to lower risk of large-scale dieback of entire forest areas	(+ to ++) Increase in biomass production due to improved climate adaptation and reduced risk of failure	(+ to ++) Improvement of habitat characteristics	(+ to ++) higher yields due to climate adaptation and reduced crop failures and market risks (+/- to -) higher costs for harvesting and marketing
Mixed stands (mixed ages with natural regeneration)	(++) against droughts, heat waves, forest fires and storms due to higher resilience to drought stress, infestations and wind damage	(++) More secure long-term sequestration of carbon in the soil due to significantly lower risk of large-scale dieback of entire forest areas	(++) Increase in biomass production due to improved climate adaptation, reduced risk of failure and more continuous timber harvesting (+) Lower nutrient loads into water bodies due to more continuous timber harvesting	(++) Improvement of habitat characteristics	(++) higher yields due to climate adaptation and reduced crop failure and market risks (+) more continuous yields (-) higher costs for harvesting and marketing

3 Discussion of the effectiveness assessment

Tables 1 to 3 illustrate that there are major differences between the measures with regard to the five objectives. Measures that contribute to the diversification of cultivated landscapes by expanding crop systems or changing landscape elements and structures increase the resilience of cultivated landscapes to extreme weather events.[21] This has a fundamentally positive effect on food security, biomass security and drinking water security. At the same time, most measures promote climate protection and the achievement of good conservation statuses for water bodies, soils and biodiversity. According to the Commission for the Future of Agriculture and the German Agricultural Industry Association, unused parts of the landscape and structures should also have a minimum percentage of 10 % open land in the landscape to preserve biodiversity.[22]

There are major differences between the various diversification measures in terms of effectiveness, large-scale feasibility and costs (investment, management and opportunity costs). The greatest costs in the form of opportunity costs arise when agricultural or forested land is taken out of productive use (e.g. hedges, buffers, the widening of watercourses). Food security is also often negatively affected in this instance. If the domestic demand for food and animal feed remains the same, this can indirectly worsen the environmental situation in other countries through the resulting increase in imports.[23]

In contrast, diversification measures that expand agricultural crop rotations or cultivated crops or establish polycultures of annual and perennial crops, such as those in agroforestry systems, often have a positive long-term effect on the income security of agricultural and forestry operations.[24] Indeed, profitability will decrease in the short term due to the conversion and investment costs incurred. However, once the conversion phase is over and diversified cultivation systems have been successfully established, the advantages outweigh the disadvantages, as diversification increases resilience to extreme weather events and market fluctuations, while reducing the risks from pests and diseases. Furthermore, new sources of income could for landowners and land users in the area of carbon farming[25] and for certain agricultural and forestry products (e.g. construction and production raw materials, protein crops) that were previously in low demand as part of Germany's goal of achieving climate neutrality by 2045.

In order to accelerate the economically and ecologically beneficial diversification of cultivation systems in the long term, society could - bear some of the costs for the establishment of agroforestry systems and mixed forests (as it did with organic farming) in addition to morphological measures through state investment subsidies. In addition, Germany could promote the diversification of agricultural crops through government consultations or make this a stronger requirement than in the past as part of direct payments. This state cost transfer can be justified by the fact that society will benefit from the reduction of external environmental effects and costs as well as an improvement in the conservation status of water bodies, habitats and species, which has a positive effect on the availability of ecosystem services and the achievement of international and European legal objectives.[26]

The most far-reaching restrictions and effects on agricultural and forestry production and thus on food and energy security are caused by changes to the regional water balance, including raising the groundwater table. Furthermore, the rewetting of drained peatlands and alluvial soils is imperative for achieving climate neutrality, as these areas release considerable amounts of greenhouse gases.[27] Alternative forms of land use (including paludiculture for fens and the reforestation of floodplains) should therefore be promoted for these areas to be rewetted and the establishment of agrivoltaics PV systems should also be legally facilitated due to their contribution to climate protection and income opportunities.

At the same time, large areas of moorland and floodplains with high nature conservation value should be purchased and the swapping of these areas as part of land consolidation procedures should be stepped up for the creation of large conservation and wilderness areas in Germany. To compensate for the associated loss of agricultural and forestry land, the number of very small Natura 2000 sites in local cultivated landscapes could be reduced, where favourable conservation statuses cannot be achieved realistically in the long term due to the impact of surrounding land uses or the genetic isolation of populations, while at the same time harbouring great potential for conflict.[28] Provided that these very small areas are not permanently essential for the coherence of the Natura 2000 network (e.g. as stepping stones), more could probably be achieved for biodiversity in Germany by abandoning them in favour of large protected and wilderness areas. In this respect, the large-scale rewetting of moors and floodplains required for climate protection reasons could also be a key measure for nature conservation.

The introduction of extensive land-use measures for arable land and grasslands could play a considerable role in improving the conservation status of water bodies, soils, habitats and species as well as increasing resilience to extreme weather events (e.g. due to better soil structure and cover, natural plant protection and better water quality). However, extensification in terms of fertilisers, pesticide use and livestock numbers is often accompanied by reduced agricultural yields, unless oversupply is merely reduced or yield reductions can be offset by ecological intensification through diversification and polycultures. Despite lower yields, economic profitability can remain the same or even increase if operating costs fall to the same or a greater extent. At present, however, this is rarely the case, as the actual costs of fertilisation, pesticide use or higher livestock numbers are not yet borne by agricultural and forestry operations due to the externalisation of secondary ecological costs.[29] From an economic perspective, extensification is advantageous as long as the environmental costs of intensive land use exceed the economic added value of food and energy security as well as guaranteed incomes.[30] However, it is important to bear in mind that indirect changes in land use can reduce the economic benefits of extensification and its net environmental impact. This particularly applies to supra-regional environmental goods.

Extensification and the loss of agricultural and forestry land can be accompanied by undesirable displacement effects (sometimes referred to as telecoupling effects). This is the case, for example, if the decline in production in an cultivated landscape or in Germany is offset on the market by the expansion and intensification of agricultural and forestry land use in other regions or countries, resulting in greater damage to the environment, climate or resilience elsewhere.[31] Conversely, local extensification reduces the direct transfer of emissions to other regions and countries by reducing nutrient loads, pesticides and antibiotics for livestock into rivers and oceans as well as greenhouse gas emissions into the atmosphere.

However, the shifting dilemma between intensive and extensive farming can only be reduced to a limited extent through technical progress and the ecological intensification of land use. It should certainly not be a problem that is put off for the future, as Germany is already a significant net importer of agricultural and forestry products in terms of volume, despite high cultivation intensity, using more than 11 million hectares of land in other countries through the markets.[32] The key to resolving this dilemma is to reduce domestic demand for agricultural products, in particular by reducing domestic livestock farming and the demand for animal-based food products.[33] In addition, a more rapid reduction is needed in the ongoing conversion of agricultural and forest land into settlements and transport areas in Germany.

4 Prioritisation of measures

In view of the increasing time pressure, particularly in terms of climate adaptation and climate protection, as well as the limited financial, human and material resources, the regarding a possible prioritisation of measures arises. Criteria for prioritisation usually include, in addition to effectiveness with regard to the desired goals (effectiveness), the business or economic cost-benefit ratio (efficiency), feasibility (in terms of time and space), the long-term nature of the effects and acceptance by those affected and society as a whole. What all criteria have in common is that they involve more or less predictions for the future and depend on many different circumstances and factors in individual cases. The uncertainty of the assessments is correspondingly high.

We therefore limited ourselves to looking at effectiveness in terms of the selected 5 objectives, which were assessed in more detail (albeit at a high level of abstraction) in Tables 1 to 3. Table 4 shows the results of a numerical addition of the effectiveness assessment for the 5 objectives.

Table 4: Prioritisation of measures

Objectives / Measures	Increasing resilience	Climate neutrality	Food, water and energy Security	good condition	Profitability	**Total**
Landscape-related measures						
Agroforestry systems on permanent grasslands	2	1	2	1	1	7
Agroforestry systems on arable land	2	1	1	2	1	7
Conversion of arable land into mixed forests	2	2	-1	2	-1	4
Conversion of arable land into permanent grasslands	2	1	-1	1	-1	2
Conversion of permanent grasslands into mixed forests	1	2	1	0	0	4
Conversion of forests with monoculture into agroforestry systems on grasslands	1	-1	1	0	1	2
Conversion of forests with monoculture into agroforestry systems on arable land	-1	-2	2	-1	2	0
Planting hedges or rows of trees	1	1	0	1	0	3
Morphological diversification measures	2	0	0	1	-1	2
Raising the groundwater level	1	2	-1	1	-1	2
Renaturalisation of watercourses	1	1	0	2	-1	3
Establishment of green buffers along water bodies	1	1	0	2	-1	3
Agrivoltaics PV systems with permanent grassland or arable land use	1	2	0	0	2	5
Production-integrated measures for arable land						
Diversification of perennial crop rotation (incl. catch crops)	1	1	1	1	1	5
Diversification of field crops	1	1	1	1	1	5
Reduced use of mineral and farm fertilisers	1	2	0	2	0	5
Reduced use of chemical pesticides	1	0	0	2	-1	2
Conservation tillage with soil cover	2	1	1	1	1	6
Introduction of pyrolysis charcoal	1	1	1	1	0	4
Reduction of soil compaction	1	0	1	1	1	4
Irrigation and sprinkling	2	-1	1	-1	1	2
Fleece covers	2	-1	1	-1	1	2
Heating as frost protection	1	-2	1	0	1	1
Production-integrated measures for permanent grasslands and forests						
Extensive grassland use without fertilisation and with <0.5 livestock units or <3 mowings	1	0	0	2	-1	2
Climate-adapted monoculture forests	1	0	1	0	1	3
Mixed forest stands (plantations of the same age)	2	1	1	1	1	6
Mixed forest stands (mixed age stands with natural regeneration)	2	2	2	2	1	9

Note: The weighting is based on the authors' assessments, based on the following five-point scale: -2 = clearly negative; -1 = moderately negative; 0 = largely neutral, 1 = moderately positive, 2 = clearly positive. All measures with a total score of 6 or more points are highlighted in dark green and 4-5 points in light green. Measures with a high priority for climate neutrality by 2045 are highlighted in blue.

Even if the assessments contain highly generalised assumptions and individual measures may differ in practice depending on the design and initial situation, there are major differences between the measures that allow them to be prioritised. In terms of landscape design measures, the establishment of agroforestry systems on existing grassland or arable land achieved the highest rating. In addition to good performance in terms of resilience and conservation status, the main reasons for this are the advantages in terms of food and energy security and profitability.

Converting forests into agroforestry systems is not a priority option due to the negative effects on climate protection and good conservation status, even if this option increases food production. Due to the high vulnerability of arable land to extreme weather events and the negative effects of arable farming on the climate and the environment, the conversion of arable land into mixed forest also achieves a high overall rating, although this should only be carried out on poor to moderate arable land due to the negative effects on food production.

Due to their medium to high effectiveness in terms of the five objectives, agrivoltaics PV systems also achieve a high overall rating and are therefore a significant alternative to agroforestry systems for arable land and grasslands, despite their negative impact on the landscape, particularly with regard to achieving climate neutrality.

The low overall score for water-related measures is due to the negative impacts in terms of profitability and the reduction in food production. However, in view of Germany's goal of achieving climate neutrality by 2045, the rewetting of moorland and floodplain soils should nevertheless be given high priority (see section 3). The renaturalisation of watercourses and the establishment of green buffers along watercourses are also of crucial importance for the implementation of the Water Framework Directive 2000/60/EC, even if their contribution to the other objectives is smaller and they reduce economic profitability.

From the production-integrated measures for arable land and grassland, conservation tillage and the reduction of fertilisers have high overall scores. The overall score is similar for the diversification of perennial crop rotations and field crops, although there is a wide range between the different design options. Important production-integrated measures are also the reduction of soil compaction and the introduction of pyrolysis biochar.

The technical measures that are already implemented today as protection against extreme weather events (irrigation, fleeces, heating) only achieve low overall scores due to the negative effects on climate protection and the good conservation statuses to be achieved for water bodies, habitats and species. Although the reduction of pesticides and the extensification of land use practices on permanent grasslands do not achieve high overall ratings, they are important measures for the conservation of biodiversity and are therefore significant for the implementation of the European Habitats Directive 92/43/EEC and the Birds Directive 200/147/EC.

As far as forest management is concerned, the establishment of mixed-age stands should be considered to be much more important than afforestation with climate-adapted monocultures (e.g. Douglas fir), as this is by far the most effective of the five objectives and also offers the best economic cost-benefit ratio with natural regeneration. However, mostly natural forest regeneration is a long-term measure. Particularly in those areas that have been deforested by drought, bark beetle infestations or clear-cutting, the establishment of mixed stands of the same age through planting is likely to achieve the objective more quickly.

5 Conclusion

The last few years of drought in Germany show that climate change is not bypassing Central Europe, but is changing the weather here faster than expected. As a result, weather extremes are becoming much more frequent, posing serious challenges for agriculture and forestry in particular. At the same time, local cultivated landscapes have long exhibited a whole host of environmental problems that urgently need to be solved in order to preserve natural resources and fulfil international and European obligations. The measures listed in Tables 1 to 3 show that there are numerous ways of strengthening resilience to extreme weather events and ensuring domestic food, water and energy security, as well as reducing the negative environmental impacts from agriculture and forestry without unduly restricting profitability.

Overall, prioritisation should be given to diversification in cultivated landscapes and on individual arable, grassland and forest areas in order to promote climate adaptation and to restore good conservation conditions as well as to ensure food, water and energy security and profitability in the medium and long term. The greatest synergies can be achieved from agroforestry on arable land and grasslands as well as from forests with mixed stands. However, additional measures are required to achieve national climate neutrality. In cultivated landscapes, these also include the rewetting of drained moorland and floodplain soils, the expansion of agrivoltaics PV systems in a way that is compatible with nature conservation, and the reduction of mineral fertilisers and livestock numbers. The latter would also have major positive effects on the conservation of biodiversity on land as well as in the North Sea and the Baltic Sea. A change in diet towards less animal-based food products would not only reduce greenhouse gases and the amount of manure produced, but also the amount of land used locally and globally for producing animal feed.

In subsequent articles, we will discuss in more detail the instruments and conditions that the state can best promote to implement the measures considered here.

Notes

---

[1] See UFZ, Dürremonitor Deutschland, https://www.ufz.de/index.php?de=37937 2023; UBA, Niedrigwasser, Dürre und Grundwasserneubildung, Dessau 2021; *Schulte et al*, Fischsterben in der Oder, 2022; BMEL, Erntebericht 2022 - Mengen und Preise, 2022; BMEL, Ergebnisse der Waldzustandserhebung 2021, 2022.

[2] See the overview of the projections and uncertainty factors in *Möckel et al*, Sustainable Cultivated Landscapes in Germany: Goals and Requirements from an Ecological, Economic and Legal Perspective, UFZ Discussion Papers, https://www.ufz.de/index.php?de=14487.

[3] Copernicus Climate Change Service, European State of the Climate 2022, 2023; FAO, Temperature change by region, http://doi.org/10.4060/cb4477en-fig68 2021.

[4] *Renner* et al, Climate Impact and Risk Analysis 2021 for Germany - Partial Report 2: Risks and Adaptation in the Land Cluster, 2021; *Seppelt* et al, in: Wiegandt, 3 Grad mehr, 2022, p. 55 ff.

[5] BMUV, Aktionsprogramm Natürlicher Klimaschutz - Kabinettsbeschluss vom 29. März 2023; Federal Government, Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050, 2019.

[6] *Möckel et al.* 2022 (note 2).

[7] SRU, Environmental Report 1994 of the German Advisory Council on the Environment, Bundestag printed paper 12/6995, p. 45 ff.

[8] Acknowledgement of this e.g. ZKL, Zukunft Landwirtschaft. Eine gesamtgesellschaftliche Aufgabe - Empfehlungen der Zukunftskommission Landwirtschaft, 2021; BMEL, Ackerbaustrategie 2035 - Perspektiven für einen produktiven und vielfältigen Pflanzenbau, 2021; Industrieverband Agrar e.V., Diskussionspapier: Konzept für Biodiversitätsförderung in der ackerbaulich genutzten Agrarlandschaft, 2022.

[9] Cf. UN, Transforming our world: the 2030 Agenda for Sustainable Development - Resolution adopted by the General Assembly on 25 September 2015; Federal Government, German Sustainability Strategy - Further Development 2021.

[10] For details, see Table 2 in *Möckel et al.* 2022 (footnote 2, p. 618 ff.).

[11] See *Kahlenborn et al*, Climate Impact and Risk Analysis 2021 for Germany - Executive Summary, 2021, pp. 42, 47, 50, 69.

[12] Cf. the overview of the challenges of agricultural landscapes in *Möckel et al.* (note 2, p. 612 f.).

[13] Cf. Art. 191 (2) TFEU; *Köck/Hansjürgens*, Das Vorsorgeprinzip - Refine it or replace it?, GAIA 2002, 42.

[14] See Table 2 in *Möckel et al.* 2022, (footnote 2, p. 618 ff.).

[15] Objectives 3g and 6b in Table 2 in *Möckel et al.* 2022, (footnote 2, p. 619).

[16] Cf. BVerwG, decision of 4th June 2003 - 4 BN 27.03; decision of 26th February 1992 - 4 B 38/92, NuR 1992, 328 f.; decision of 14th April 1988 - 4 B 55/88, NuR 1989, 84 f.; decision of 29th November 1985 - 4 B 213.85, NuR 1986, 251-251; judgement of 13th April 1983, - 4 C 76.80, BVerwGE 67, 93, 94. 13. 4. 1983, - 4 C 76.80, BVerwGE 67, 93, 94.

[17] The extensive literature review by *Baaken*, Sustainability of agricultural practices in Germany: a literature review along multiple environmental domains, Regional Environmental Change 2022,

https://doi.org/10.1007/s10113-022-01892-5 and WBAEV/WBW, Klimaschutz in der Land- und Forstwirtschaft sowie den nachgelagerten Bereiche Ernährung und Holzverwendung, 2016; *Leclère et al*, Bending the curve of terrestrial biodiversity needs an integrated strategy, Nature 2020, 1, https://doi.org/10.1038/s41586-020-2705-y; *Hennenberg/Böttcher*, Biomasse und Klimaschutz, 2023; *Wiegandt*, 3 Grad mehr, 2022; Leopoldina, acatech and Akademienunion, Biodiversität und Management von Agrarlandschaften, 2020; *Wirz/Kasperczyk/Thomas*, Kursbuch Agrarwende 2050 - Ökologisierte Landwirtschaft in Deutschland, 2017; *Spiekermann/Franck*, Adaptation to Climate Change in Spatial Planning, 2014; *Palomo-Campesino/González/García-Llorente*, Exploring the Connections between Agroecological Practices and Ecosystem Services: A Systematic Literature Review, Sustainability 2018, 4339, https://doi.org/10.3390/su10124339.

18 Cf. e.g. *Staton et al*, Evaluating the effects of integrating trees into temperate arable systems on pest control and pollination, Agricultural Systems 2019, 102676, https://doi.org/10.1016/j.agsy.2019.102676; *Garibaldi et al*, Working landscapes need at least 20% native habitat, Conservation Letters 2021, e12773, https://doi.org/10.1111/conl.12773; *Veldkamp et al*, Multifunctionality of temperate alley-cropping agroforestry outperforms open cropland and grassland, Communications Earth & Environment 2023, https://doi.org/10.1038/s43247-023-00680-1; *Martin et al*, The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe, Ecology Letters 2019, 1083, https://doi.org/https://doi.org/10.1111/ele.13265; *Pörtner et al*, Overcoming the coupled climate and biodiversity crises and their societal impacts, Science 2023, eabl4881, https://doi.org/10.1126/science.abl4881; *Spiecker/Konold/Mastel*, Multifunktionale Bewertung von Agroforstsystemen, 2010; *Spiecker et al*, Neue Optionen für eine nachhaltige Landnutzung - Schlussbericht des Projekts agroforst, 2009; *Torralba et al*, Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis, Agriculture, Ecosystems & Environment 2016, 150, https://doi.org/10.1016/j.agee.2016.06.002; *Tanneberger et al*, Towards net zero CO2 in 2050: An emission reduction pathway for organic soils in Germany, Mires and Peat 2021, 1, https://doi.org/10.19189/MaP.2020.SNPG.StA.1951; *Beisecker et al*, Changes in water uptake and storage of agricultural soils and effects on the risk of flooding due to increasing heavy and continuous rainfall events, 2020; *Beisecker et al*, 2020 (Fn; *Tscharntke et al.*, Beyond organic farming – harnessing biodiversity-friendly landscapes, Trends in Ecology & Evolution 2021, 919, https://doi.org/10.1016/j.tree.2021.06.010; *Korell et al*, Responses of plant diversity to precipitation change are strongest at local spatial scales and in drylands, Nature Communications 2021, 2489, https://doi.org/10.1038/s41467-021-22766-0; Ökologie&Landbau, Focus on Green Energy, Issue 2/02023.

19 Cf. e.g. *Tilman* et al, Agricultural sustainability and intensive production practices, Nature 2002, 671, https://doi.org/10.1038/nature01014; The State of Carbon Dioxide Removal, The State of Carbon Dioxide Removal, https://www.stateofcdr.org/s/SoCDR-1st-edition.pdf 2023; *Chenu* et al, Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations, Soil and Tillage Research 2019, 41, https://doi.org/10.1016/j.still.2018.04.011; *Kurth* et al, The Case for Regenerative Agriculture in Germany - and Beyond, 2023; *Tanneberger et al*, Saving soil carbon, greenhouse gas emissions, biodiversity and the economy: paludiculture as sustainable land use option in German fen peatlands, Regional Environmental Change 2022, 69,

https://doi.org/10.1007/s10113-022-01900-8; *Finckh et al*, Pflanzengesundheit richtig managen, Ökologie & Landbau 2021, 41; *Finckh et al*, Intra- and interspecific diversity: the cornerstones of agroecological crop health management, Aspects of Applied Biology 2021, 193; *Beillouin/Ben-Ari/Makowski*, Evidence map of crop diversification strategies at the global scale, Evidence map of crop diversification strategies at the global scale 2019, 123001, https://doi.org/10.1088/1748-9326/ab4449; *Lehmann et* al, Biochar in climate change mitigation, Nature Geoscience 2021, 883, https://doi.org/10.1038/s41561-021-00852-8; *Li et al*, Conservation agriculture practices increase soil microbial biomass carbon and nitrogen in agricultural soils: A global meta-analysis, Soil Biology and Biochemistry 2018, 50, https://doi.org/10.1016/j.soilbio.2018.02.024; *Basche/DeLonge*, Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis, PLOS ONE 2019, e0215702, https://doi.org/10.1371/journal.pone.0215702*Li et al*, Residue retention and minimum tillage improve physical environment of the soil in croplands: A global meta-analysis, Soil and Tillage Research 2019, 104292, https://doi.org/10.1016/j.still.2019.06.009; *Razzaghi/Obour/Arthur*, Does biochar improve soil water retention? A systematic review and meta-analysis, Geoderma 2020, 114055, https://doi.org/10.1016/j.geoderma.2019.114055; *Farhangi-Abriz et al*, Biochar effects on yield of cereal and legume crops using meta-analysis, Science of The Total Environment 2021, 154869, https://doi.org/10.1016/j.scitotenv.2021.145869; *Palm et al*, Conservation agriculture and ecosystem services: An overview, Agriculture, Ecosystems & Environment 2014, 87, https://doi.org/10.1016/j.agee.2013.10.010; *Pittelkow et al*, Productivity limits and potentials of the principles of conservation agriculture, Nature 2015, 365, https://doi.org/10.1038/nature13809; *Gentsch et al*, Catch crop diversity increases rhizosphere carbon input and soil microbial biomass, Biology and Fertility of Soils 2020, 943, https://doi.org/10.1007/s00374-020-01475-8; *Glaze-Corcoran et al*, in: Sparks, Advances in Agronomy, 2020, 199; *Altieri/Ponti/Nicholls*, in: Gurr/Wratten/Snyder *et al*, Biodiversity and insect pests: key issues for sustainable management, 2012, 72.

[20] Cf. e.g. BMEL, Klimaangepasstes Waldmanagement - Förderprogramm des Bundesministeriums für Ernährung und Landwirtschaft, https://www.klimaanpassung-wald.de/hintergrund 2023; Wissenschaftlichen Beirates für Waldpolitik, Die Anpassung von Wäldern und Waldwirtschaft an den Klimawandel, 2021; Bode/Kant, Dauerwald - leicht gemacht!, 2021, Natur & Text, 343 p.; *Garnett et al*, Grazed and confused? Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question - and what it all means for greenhouse gas emissions, 2017; *Pretzsch/Biber/Schütze*, Effekt der Mischung auf die Struktur, die Dichte und das Ertragsniveau von Fichtenbeständen, LWF Wissen 2017, 131; *Tretter*, Wege zum Mischwald, LWF aktuell 2017, 6-9; *Henning*, Waldumbau : Gesunden Mischwald bewirtschaften, 2017; *Jentsgen*, Vom Altersklassen-Einheitsforst zum naturgemäßen Dauerwald, 2017; Zerbe, Renaturierung von Ökosystemen im Spannungsfeld von Mensch und Umwelt, 2019, 107; *Wiechmann*, Waldumbau mit Naturverjüngung, LWF aktuell 2009, 36; *Henning*, Erfolgreiche Waldverjüngung, 2015.

[21] Cf. *Frei et al*, A brighter future: Complementary goals of diversity and multifunctionality to build resilient agricultural landscapes, Global Food Security 2020, 100407, https://doi.org/10.1016/j.gfs.2020.100407.

[22] ZKL, 2021 (note 8, p. 102); Industrieverband Agrar e.V., 2022 (note 8, p. 16).

23 See *Smith* et al, The greenhouse gas impacts of converting food production in England and Wales to organic methods, Nature Communications 2019, 4641, https://doi.org/10.1038/s41467-019-12622-7.

24 *Abson/Fraser/Benton*, Landscape diversity and the resilience of agricultural returns: a portfolio analysis of land-use patterns and economic returns from lowland agriculture, Agriculture & Food Security 2013, 2, https://doi.org/10.1186/2048-7010-2-2; *Lin*, Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change, BioScience 2011, 183, https://doi.org/10.1525/bio.2011.61.3.4.

25 See the European Commission's proposal for a regulation establishing a Union framework for the certification of carbon removals, COM (2022) 672 final.$_2$ Critically, *Paul et al*, Carbon farming: Are soil carbon certificates a suitable tool for climate change mitigation?, Journal of Environmental Management 2023, 117142, https://doi.org/10.1016/j.jenvman.2022.117142.

26 On net social benefits, see *Pannell*, Public Benefits, Private Benefits, and Policy Mechanism Choice for Land-Use Change for Environmental Benefits, Land Economics 2008, 225, https://doi.org/10.3368/le.84.2.225.

27 Federal Government, Nationale Moorschutzstrategie, 2022; *Röder/Grützmacher*, Emissions aus landwirtschaftlich genutzten Mooren - Vermeidungskosten und Anpassungsbedarf 2012, 56; BMUV, 2023 (note 5); *Dewitz* et al, MOORATLAS - Daten und Fakten zu nassen Kimaschützern, 2023.

28 In detail: *Möckel*, Natura 2000 areas and agricultural, forestry and fisheries land use, AuR 2021, 2-9.

29 For more detailed information on external environmental costs, see e.g. UBA, Daten zur Umwelt: Umwelt und Landwirtschaft Dessau 2018; FAO, Natural Capital Impacts in Agriculture, 2015.

30 See Natural Capital Germany - TEEB DE, Ecosystem services in rural areas, 2016; *Oelmann* et al, Quantifizierung der landwirtschaftlich verursachten Kosten zur Sicherung der Trinkwasserbereitstellung, 2017; Boston Consulting Group, Die Zukunft der deutschen Landwirtschaft nachhaltig sichern - Denkanstöße und Szenarien für ökologische, ökonomische und soziale Nachhaltigkeit, 2019. According to UBA estimates, the social cost of a tonne of CO_2 in 2020 was at least EUR 195 (UBA, Methodenkonvention 3.1 zur Ermittlung von Umweltkosten - Kostensätze Stand 12/2020, 2020, p. 8).

31 See UBA, Von der Welt auf den Teller - Kurzstudie zur globalen Umweltinanspruchnahme unseres Lebensmittelkonsums, 2021; *Fuchs/Brown/Rounsevell*, Europe's Green Deal offshores environmental damage to other nations, Nature 2020, 671, https://doi.org/10.1038/d41586-020-02991-1; *Smith* et al, The greenhouse gas impacts of converting food production in England and Wales to organic methods, Nature Communications 2019, 4641, https://doi.org/10.1038/s41467-019-12622-7.

32 UBA, From the world to the plate, (note 31, p. 14). See also European Commission, Joint Research Centre, World Atlas of Desertification, Luxembourg 2018, p. 40-41.

33 Cf. Scientific Advisory Council for Agricultural Policy at the Federal Ministry of Food and Agriculture, Wege zu einer gesellschaftlich akzeptierten Nutztierhaltung, Berlin 2015; *Wirz/Kasperczyk/Thomas*, Kursbuch Agrarwende 2050, (note 17); *Breunig/Mergenthaler*,

Besonderheiten des Klimaschutzes im Agrar- und Ernährungssystem - was müssen wir neu denken? Berichte über Landwirtschaft 2022, 1, https://doi.org/10.12767/buel.v100i2.425; *Hayek* et al, The carbon opportunity cost of animal-sourced food production on land, Nature Sustainability 2021, 21, https://doi.org/10.1038/s41893-020-00603-4; Sorg et al, Perspektiven für eine umweltverträgliche Nutztierhaltung in Deutschland, 2021.