Methodological Annex:
Biodiversity and climate change impact calculation

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Contents

1. Scenarios for assessing change in the provision of soil quality and pollination services 1

1.1. Assessing the current and future state of biodiversity 2

1.1.1. Current state 2

1.1.2. Future state 3

1.2. Implications of state of biodiversity for providing good soil quality and pollination 6

1.2.1. Good soil quality provision 7

1.2.2. Pollination 8

1.2.3. Implications of (future) climate change and extreme climate events 9

1.2.4. Linking biodiversity index, extreme climate events, crop productivity, and pollination loss, and soil quality and pollination used in our macro models. 11

1.3. Summary of the scenario setup 13

1.4. Example preliminary outcomes from soil quality scenario 14

2. Soil biodiversity, its ecosystem services and human impacts 15

2.1. Ecosystem services provided by soil biodiversity 15

References 19

1. Scenarios for assessing change in the provision of soil quality and pollination services

Our analysis highlights the critical relationship between biodiversity, ecosystem services and agricultural productivity. As a first step, we identify indicators that allow us to determine the state of biodiversity, the diversity of genes, species and ecosystems, on the most spatially detailed scale possible for the world. Since there is no complete overview of the extent and status of biodiversity, we focus on high-resolution geoinformation data that indicate the pressure biodiversity receives. We hypothesise that a higher pressure indicates lower biodiversity compared to a pressure-absent state where biodiversity is optimal. With this approach, we provide a globally comparable index to showcase the extent of biodiversity loss each region experiences. Next, we estimate how a change in this pressure, as a proxy for biodiversity level, affects the provision of specific ecosystem services and, thus, productivity levels, assuming that this relationship is the same across different locations.[1] We initially focused on biodiversity's contribution to the provision of good soil quality in agricultural land and to crop pollination to articulate the impacts of biodiversity loss on agricultural productivity. Finally, we calculated how these indicators will change under different socio-economic scenarios and the resulting environmental changes.

1.1. Assessing the current and future state of biodiversity

1.1.1. Current state

As no global geographically detailed information exists on the current state of biodiversity, we constructed an indicator for the pressure that biodiversity is confronted with in a specific area. Thereby assuming that the higher the pressure is, the lower the amount of biodiversity that is remaining compared to a non-human disturbed state. We compared two proxy indicators for pressure on biodiversity: the Human Modification Index (HMI) and the Pesticide Application Rate Index (PARI).

HMI is based on information on 14 different stressors: the presence of built-up area, croplands and pasture lands, grazing, oil and gas production, mining and quarrying, renewable and non-renewable power generation, roads, railways, power lines, electrical infrastructure, logging and wood harvesting, human intrusions, reservoirs, and air pollution. The HMI is available at a resolution of 0.09 km2 for the globe (Theobald et al., 2020)[2], varying from 0 (no human modification) to 1 (complete human modification). In this study, we assume very high biodiversity in areas without human modification and very low biodiversity in areas with complete human modification.

Although the HMI accounts for the presence of agricultural areas and the intensity of agricultural activities, such as cropping and the number of rotations, tilling, and cutting operations, we also introduced the PARI as an indicator for agricultural intensification. In high-intensity agricultural systems, there is likely to be more use of pesticides, fertilisers, heavy machinery that compacts the soil, irrigation water, and modification of the local water flows. Our current study used the total glyphosate application rate, the most widely used herbicide in the world (Giesy et al., 2000), on agricultural land in 2015 to calculate the PARI. We obtained the data from the Global Pesticide Grids (PEST-CHEMGRIDS) Version 1.01 data set (Maggi et al., 2020). The application of glyphosate was available for 6 dominant crops (corn, soybean, wheat, cotton, rice, and alfalfa) and 4 aggregated crop classes ((1) Vegetables and Fruit, (2) Orchards and Grapes, (3) Pastures and Hay, and (4) Others) at 5 arc-minute resolution (about 10 kilometer at the equator).[3] See Figure 1 for the

[1] This is a restrictive assumption. However, for global scenario development, we do not have location specific data to also link the level of productivity loss and ecosystem services loss per biodiversity loss at the regional level.

[2] Explore the online map of the Human Modification Index in the UNBiodiversity Lab website.

[3] Among those crops cotton, soyabeans, fruits and vegetables, orchards are dependent on insect pollination.

application rate of glyphosate on wheat in 2015 as an example. The application rate on each crop is provided in kilogram per hectare per year (kg/ha-year) by scaling the total glyphosate application rates per grid between 0 (no agricultural intensification) and 1 (very high agricultural intensification)[4] whereby 1 is the maximum application rate in kg/ha/year present on the map.

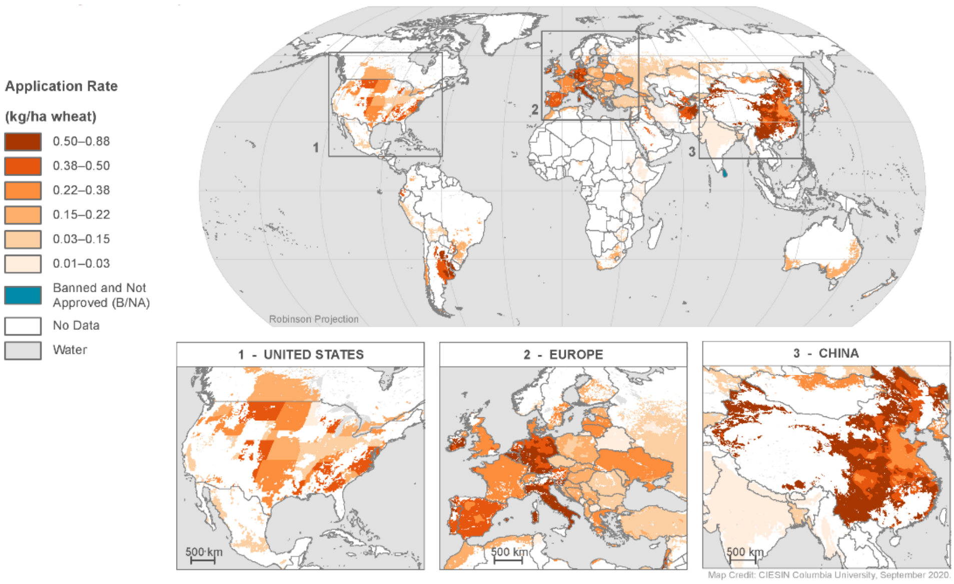

Figure 1: Application rate of glyphosate on wheat in 2015, high estimate (Maggi et al., 2020)

For each grid cell of agricultural land, we assessed the pressure on biodiversity by calculating the average of the Human Modification Index and the Pesticide Application Rate. The Biodiversity Index (BI) for each grid cell is then one minus the average pressure:

$$BI = 1 - \frac{HMI + PARI}{2}$$

1.1.2. Future state

Assessing the current state of biodiversity globally at a detailed geographical scale is already challenging. Assessing the potential future state adds another challenge. Unfortunately, projections for HMI and PARI for the year 2050 are not available. Therefore, this study utilised the GLOBIO model and its projections for Mean Species Abundance (MSA) to estimate future changes in the Biodiversity Index. To assess future changes, we use the output from the GLOBIO model that assesses changes in MSA (Schipper et al., 2020). MSA metric indicates local biodiversity intactness, with values ranging from 0 to 1. A value of 1 means the species assemblage is fully intact, while 0 indicates all original species are locally

[4] The highest application rates are on genetically modified herbicide- tolerant crops and annual crops (especially for desiccant purposes), but not on perennial crops. Therefore, our biodiversity index might be upward biased for the areas where more perennial crops are grown.

extinct.[5] MSA is calculated by comparing the abundance of individual species under specific pressures to their abundance in an undisturbed, natural environment. Only species present in the reference situation are included, and any increases in abundance are ignored to prevent inflation from generalist species thriving in disturbed habitats.

Although MSA suggests that it includes population data, it is also a pressure indicator. However, it uses less pressure than the HMI, and agricultural intensification is not incorporated. GLOBIO combines the pressure–impact relationships with data on MSA's past, present or future pressure levels to make those projections for MSA levels. For our study, we utilise the MSA changes from Schipper et al. (2020) and determine the change in MSA from 2015 to 2050 for each grid cell, and then adjust the Biodiversity Index accordingly.[6]

The current and future average Biodiversity Index for each region considered in our study is presented in Table 1. On average, in this scenario, the Biodiversity Index decreases 5.2% till 2050. The largest decrease (11.8%) is projected for India.

Table 1: Current and future average Biodiversity Index per region.

Region	Current Biodiversity Index	Future Biodiversity Index	% Change BI
LVA	0,63	0,60	-3,6
FRA	0,44	0,39	-10,9
POL	0,49	0,47	-4,3
CAM	0,64	0,60	-5,9
CAN	0,95	0,91	-4,0
ME	0,78	0,75	-4,6
IDN	0,74	0,70	-6,4
KOR	0,50	0,47	-7,1
DEU	0,42	0,40	-4,1
GBR	0,53	0,52	-2,0
ARG	0,75	0,70	-6,3
EAS	0,82	0,77	-6,1
REUR	0,58	0,56	-3,3
ITA	0,41	0,39	-4,8
DNK	0,46	0,45	-1,9
ROU	0,52	0,52	0,2
CHE	0,51	0,48	-5,8
THA	0,60	0,55	-7,7
COCOA	0,65	0,61	-7,2

[5] Please see GLOBIO website for more detailed information on MSA metric and note that MSA does not count for new species in an area, as MSA is calculated for the abundance of species in the reference situation.

[6] For these calculations only data from SSP3 with RCP 6.0 moderate level climate change were available. In the future we also plan to assess changes in pressure factors under different SSP scenarios.

Region	Current Biodiversity Index	Future Biodiversity Index	% Change BI
AUS	0,91	0,87	-5,0
AUT	0,49	0,46	-5,5
AFR	0,86	0,77	-10,6
GRC	0,52	0,48	-7,0
IRL	0,52	0,48	-8,1
STAN	0,87	0,85	-2,2
FIN	0,72	0,69	-4,4
IND	0,58	0,51	-11,8
NLD	0,43	0,41	-4,6
SWE	0,71	0,69	-3,4
PRT	0,45	0,44	-2,6
NZL	0,69	0,64	-8,3
RUS	0,91	0,88	-3,7
NAF	0,89	0,83	-7,5
NOR	0,81	0,77	-4,3
HUN	0,44	0,43	-1,2
USA	0,71	0,68	-4,1
SVK	0,49	0,48	-2,0
BEL	0,44	0,41	-6,3
BGR	0,54	0,52	-3,3
SVN	0,47	0,43	-7,4
RESTEU	0,51	0,48	-5,2
LTU	0,53	0,51	-3,7
JPN	0,51	0,49	-3,4
ESP	0,47	0,45	-3,6
PHL	0,53	0,50	-5,3
MEX	0,70	0,67	-4,4
EST	0,58	0,54	-5,9
CHN	0,71	0,70	-1,6
BRA	0,75	0,72	-4,6
CZE	0,49	0,47	-4,0
ZAF	0,71	0,66	-6,3
TWN	0,54	0,51	-5,0
MYS	0,67	0,61	-7,6
RLAM	0,81	0,77	-5,4
COL	0,79	0,75	-5,0
TUR	0,57	0,51	-9,9

1.2. Implications of state of biodiversity for providing good soil quality and pollination

The study highlights the critical connection between biodiversity, soil quality and pollination ecosystem services. Biodiversity provides various ecosystem services relevant to agricultural production. In this study, we translate a change in biodiversity to an impact on providing two ecosystem services: the provision of a good soil quality and pollination.

Figure 2 and Figure 3 introduce our analysis framework, considering the impact of biodiversity loss on crop productivity via a change in the provision of good soil quality or pollinator presence. In both cases, we determine a situation where we exclude and include the impact of extreme climate events on crop productivity, whereby the resilience of crops to these extremes is determined by the amount of biodiversity present.

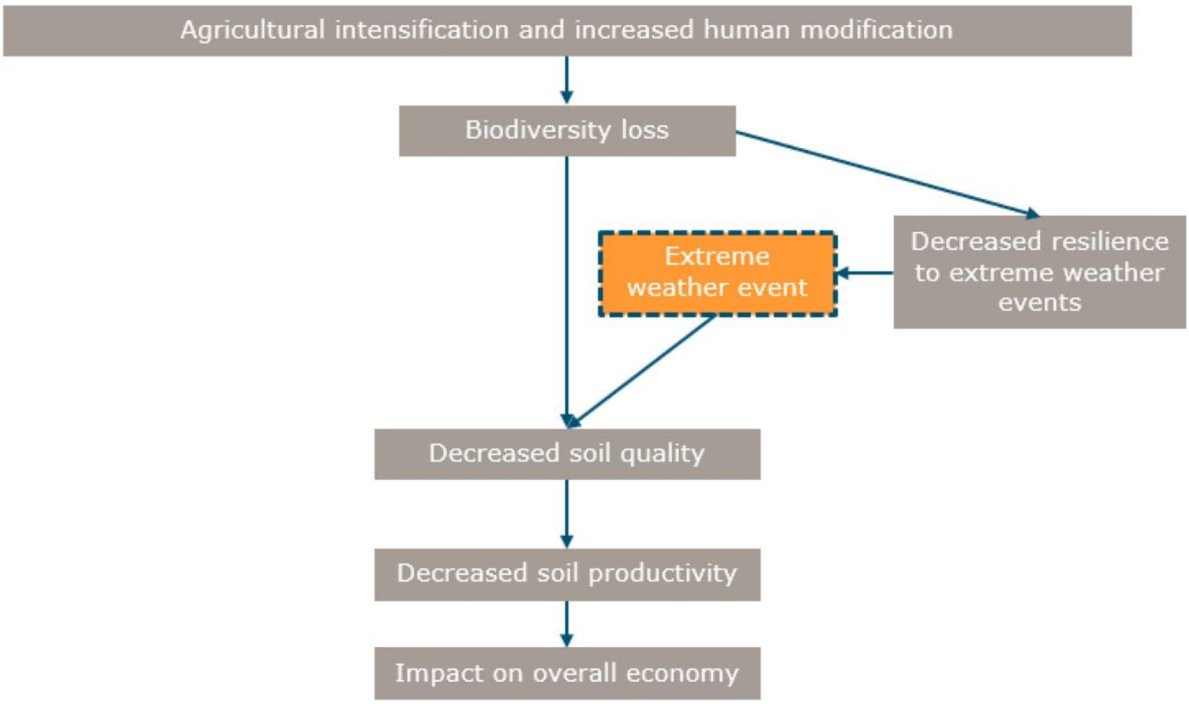

Figure 2: Soil quality loss scenario framework. The figure shows that agricultural intensification and increased human modification of nature decrease the (soil) biodiversity level in nature. Decreased biodiversity influences the soil quality by negatively affecting soil organic matter content, soil structure, and nutrient cycling. A reduction in soil quality impacts the productivity of the crops that grow on these soils. We also consider the joint impact of biodiversity loss and climate change, where biodiversity loss decreases soil resilience and the ability to withstand extreme climate change. In the case of extreme climate events, this is translated into additional loss of productivity. The soil productivity uniformly affects all crops depending on their land use. Consequently, no crop level dependence rate for soil

productivity is introduced, whereas crop insect pollination dependency rates are incorporated into the framework for pollination services scenarios.Source: BiROFin project.

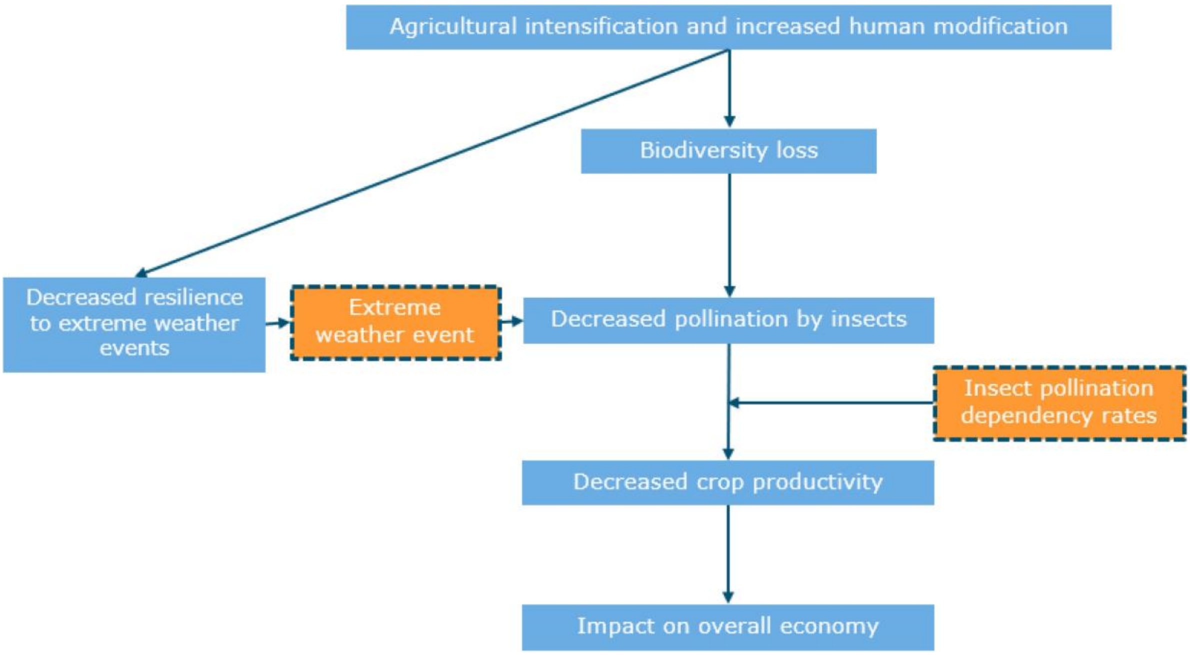

Figure 3: Pollination services scenario framework. The figure shows that agricultural intensification and increased human modification of nature decrease the biodiversity level in nature. Decreased biodiversity decreases pollination by insects through two mechanisms. The first is a direct impact, in which decreased biodiversity loss reduces insect pollination. Additionally, we consider the joint impact of biodiversity loss and climate change. More insects die, further decreasing pollination by insects. Agricultural intensification and human modifications can directly decrease pollination services. For instance, the increased use of pesticides can kill wild pollinators. In the resilience to extreme climate events pathway, these changes also weaken the ecosystem's resilience, making pollinator population more vulnerable; for instance, an adverse weather event can be fatal to insect pollinators and their population growth, further decreasing pollination services. Different crops depend on insect pollinators to varying degrees. As a result of reduced pollination services, the productivity levels of crops decline in proportion to their dependency on pollination. Source: BiROFin project.

1.2.1. Good soil quality provision

The exact impact of (soil) biodiversity, the diversity of animal and plant species, bacteria and fungi in the soil, on crop yield, crop quality and potential health benefits via the provision of good soil quality for all crops everywhere on the planet has not been quantified yet. . However, the importance of soil biodiversity for these issues is widely recognised (Nielsen et al., 2015; Rillig et al., 2018). Appendix # provides a summary overview of how soil biodiversity supports a wide array of ecosystem services that are essential for crop productivity, environmental sustainability, and long-term soil health. It also lists the numerous ways in which human (agricultural) activities impact soil biodiversity.

In the current assessment, in locations with no pressure on biodiversity, we assume that biodiversity has not been lost, thereby no crop productivity is lost due to biodiversity loss. sity loss. However, if soil biodiversity is under maximum pressure (when both HMI and PARI equal 1), we assume that the agricultural productivity of all crops would maximally decrease by 50% if no countermeasures are taken to compensate for the loss by adding more inputs (e.g., nutrients, applying pesticides, irrigating crops, etc.). So, the impact of biodiversity loss on productivity will only sometimes be tangible for the farmers. No studies exist that directly confirm this assumption. However, several studies clearly indicate the substantial role of soil biodiversity on crop productivity. Fonte et al. (2023) found that earthworms contribute to roughly 6.5% of global grain production and 2.3% of legume production. According to this study, the earthworm contribution is especially notable in the global South, where earthworms contribute 10% of the grain production in sub-Saharan Africa and 8% in Latin America and the Caribbean. Bender and van der Heijden (2015) found that an enriched soil-life with soil organisms <2 mm and arbuscular mycorrhizal fungi (AMF) increased smaise crop yield with 22% in the first year of the experiment. N uptake by the crop increased 29% and P uptake even 110% and strongly reduced leaching losses of N (-51%, corresponding to a reduction of 76 kg N ha-1). In the second year, wheat biomass increased 17% and P contents 80%, but the differences were lower than in the first year.

It is important to note that a loss of biodiversity, e.g. due to agricultural intensification, does not automatically lead to a loss of crop productivity. Furthermore, despite the importance of biodiversity for soil quality, increasing biodiversity by e.g. farmland diversification does not automatically mean that yields will increase. Jones et al. (2023) found that farmland diversification led to win-win outcomes for biodiversity and yield in 23% of 764 cases, while a win for biodiversity coupled with a loss in yield was the most likely outcome (28% of cases). They, however, demonstrated that a win-win was significantly more likely when several diversification measures were combined, when no agrochemicals were applied, when diversification occurred in temperate climates, and when diversification enhanced belowground taxa.

1.2.2. Pollination

Our analysis assumes that the decline in biodiversity indicates the loss of insect populations, and thus, pollinators affecting agricultural production. Similar to soil biodiversity, there are no global, regional, or even local data available on the number of insect species or their population sizes. Recent studies do suggest significant declines. Hallmann et al. (2017) found that the total biomass of flying insects in protected areas in Germany declined by more than 75% from 1989 to 2016. In our analysis, we assume that the calculated biodiversity loss also indicates the loss of insects and, thus, pollinators.

Unlike soil quality impact calculation, we assess the impact by applying information on each crop's pollination dependence and introduce the productivity loss at the crop level, which cannot be compensated by adding more inputs, as in the case of soil productivity loss. The ratios of insect pollinator dependency are derived from Aizen et al. (2016) and Klein et al. (2007). Using methods similar to those for calculating economic losses by Bauer and Wing (2016) and La Notte et al. (2020), we posit that reductions in pollination services by insects, as outlined in the scenario, result in diminished crop yields according to their specific insect pollinator dependence ratios (PDRs). We compile these ratios from the aforementioned studies and utilise FAOSTAT data on past agricultural output to estimate the decrease in crop production that aligns with the reductions in pollination services projected by our scenario. For instance, a complete loss of 100% in pollination services would lead to a crop production reduction equivalent to the crop's PDR. Conversely, a 50% decline in pollination services would correspond to a production reduction equal to the crop's PDR multiplied by 0.5. As different countries grow varying amounts of pollinator-dependent crops, this methodology results in differences in the effects of lost pollination services across countries. For instance, on one hand, Germany does not produce pollinator-dependent nuts, so it is not negatively affected by shocks to nut production, but it does produce fruits, with fruit production relying on pollinators at a rate of 32%. On the other hand, Italy produces nuts, and its nut production is 34% dependent on pollinators, while fruit production is 23% dependent on pollinators as they produce fewer fruits. For more information, please consult the prior research conducted by Pamuk et al. (2023).

1.2.3. Implications of (future) climate change and extreme climate events

The survival of species is very much determined by extreme climate events. Therefore, rapid climate change is expected to have severe consequences for biodiversity as weather extremes increase more quickly than the increased average temperature. The impact of climate change on biodiversity is becoming more and more visible. Müller et al. (2023), e.g., found that changes in weather conditions mainly explain the insect decline observed by (Hallmann et al., 2017). Outhwaite et al. (2022) demonstrated that both insect abundance and species richness declined significantly with a stronger increase in temperature. The observed decline in insect abundance and species richness was highest in high-intensity agricultural areas followed by low-intensity agriculture, secondary vegetation and primary vegetation. In primary vegetation, the species richness even increased with increasing temperature. So, areas with more biodiversity might be more resilient to climate change impacts.

Climate change and climate extremes also directly impact crops, and these effects are becoming more and more clear. According to Monteleone et al. (2023)Weather extremes have been responsible for widespread economic damage on a global scale in recent decades. The agricultural sector took a quarter of the impact caused by weather extremes, especially in low- and middle-income countries. But even in high-income countries, yield losses due to extreme climate are relevant. van Oort et al. (2023), e.g., showed that two large scale weather extremes had a major impact on crop yields. The 1998 extremely wet harvesting period had a major negative impact on all tuber crops (potato, sugar beet, onion). The 2018 extremely dry summer period had a major negative impact on grass and onion. Onions (-28% and ware potatoes (-21%) were the most vulnerable. Sugar beet (-15%), silage smaise (-13%) and winter wheat (-14%) were more robust. A region with poor access to irrigation experienced much larger losses. Coffee production in 2023/2024 in Vietnam, Indonesia and Brazil were respectively 20%, 16.5% and 7.1% lower due to extreme climate impact (Amrouk et al., 2025).

With the projected future change in climate, more agricultural impacts can be expected. Hasegawa et al. (2022) analysed 8703 projected crop yield simulations of four major crops (maise, rice, soybean and wheat) in 91 countries under major emission scenarios for the 21st century, with and without adaptation measures, published in 202 studies between 1984 and 2020. They showed that substantial average yield losses can be expected due to climate change. The highest 30-year average projected yield losses per world region are projected for the RCP8.5 climate change scenario and for the end of the century (2070-2100). The highest yield loss projected for Maize is 28% (Central and South America), 42% for rice

(North America), 41% for soybean (Central and South America) and 40% for wheat (Central and South America). Yield losses in individual years can be substantially higher. Furthermore, it is unclear to what extent also extreme climate events have been taken into account.

Given its importance, our scenario framework does considers extreme climate events to better account for climate change's impact on biodiversity and, thus, the provision of ecosystem services. We also assume that crops and insect populations are more resilient to extreme climate events under higher biodiversity conditions. Biodiversity loss diminishes soil's resilience and, thus, its ability to support plants against extreme climate and rapid climate change. For pollinators, especially insect pollinators, we consider the sensitivity of insects towards weather conditions and assume that when the risk for climate extremes of a region is high, the additional risk of pollinator loss is also high (Müller et al., 2023; Outhwaite et al., 2022).

To account for extreme events, we developed an Extreme climate Index (EWI) based on data from the IPCC-WGI interactive Atlas for the SSP2-RCP 4.5 pathway (Gutiérrez, 2021). We identified three climate variables that are indicative of the risk of the occurrence of extreme climate events, and each variable was scaled from 0 to 1:

1. The rate of change in mean annual temperature in °C per decade (Tm), see Figure 4. An average annual change of 1°C per 10 years results in a score of 1 and a 0.5°C per decade in a score of 0.5. Hereby, we assume that a change in temperature of 1°C per decade (= 10°C C per century) will have dramatic ecological impacts.
2. The Standardised Precipitation Index, or SPI. This index captures how observed precipitation deviates from the climatological average over a given time period, see Figure 5. SPI values of more than 100% or less than -100% are set to 1.
3. The rate of changes in the number of days when maximum temperatures exceed 35°C (Tx35), see Figure 6. This is the threshold that is critical for maise pollination and production. In our analysis, an increase of 40 days or more till 2050 compared to the baseline (1981-2010) will set the indicator to 1.

The value of the EWI is the maximum value of one of the three variables (EWI = max(Tm, Tx35, SPI)).

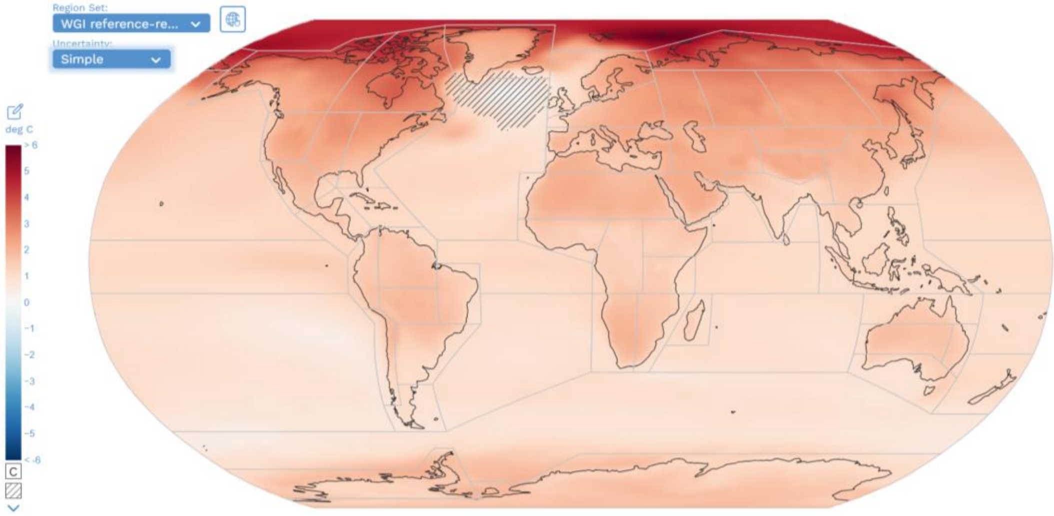

Figure 4 Annual mean temperature change in °C for the medium term (2041-2060) under an SSP2-4.5 scenario relative to 1981-2010 (Gutiérrez et al., 2021; Iturbide et al., 2021)

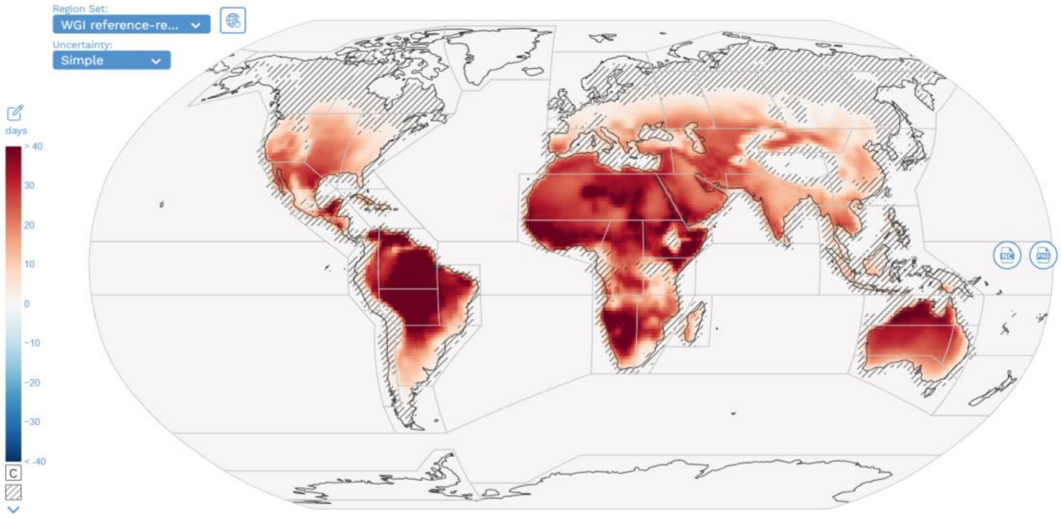

Figure 5: Change in the number of days per year with a maximum temperature above 35 °C over the medium term (2041-2060) relative to 1981-2010 (Gutiérrez et al., 2021; Iturbide et al., 2021)

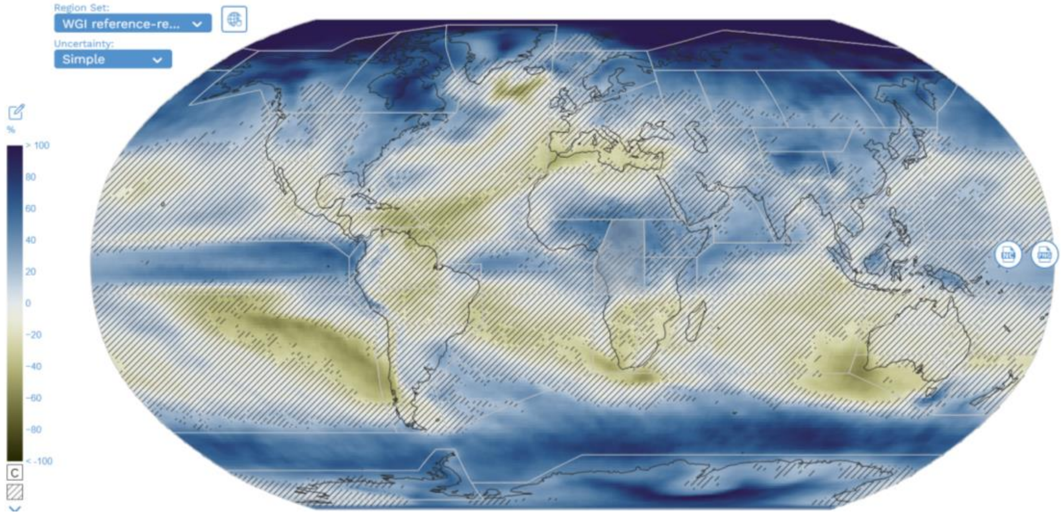

Figure 6: Change in the Standard Precipitation Index (SPI-6 months) between the reference period 1981-2010

1.2.4. Linking biodiversity index, extreme climate events, crop productivity, and pollination loss, and soil quality and pollination used in our macro models.

We start linking the biodiversity index, biodiversity loss, induced soil productivity loss first without considering extreme climate events, with the assumption of when BI = 1 (full biodiversity) There is no biodiversity loss, induced soil productivity loss, or loss of insect pollination. We also assume that when BI = 0 there is a 50% loss in soil productivity or a loss of pollination services, which can maximum soil productivity or pollination loss linked to biodiversity level. Let's denote the biodiversity loss induced by historical soil productivity loss or insect pollinator loss in a particular year and country as $\Delta P_{t,c}$ where t denotes the year and c shows the country/region. Then in our scenario work, we can formulate $\Delta P_{t,c}$ as follows:

$$\Delta P_{t,c} = \left[0.5 \times \left(1 - BI_{t,c}\right)\right]$$

In our scenario studies, t equals either 2019 or 2050. Then ΔP_t shows the historical soil productivity loss or pollination loss linked with biodiversity level in 2019 and 2050.

We link biodiversity induced soil productivity and pollination loss with extreme events using $[\left[1 - 0.5 \times \left(1 - BI_{2050,c}\right)\right] \times [\left(-0.4 \times BI_{2050,c}\right)] \times EWI_{2050,c}$. Here [(−0.4×BI)+0.8] is the maximum additional crop productivity or pollination services loss that can be experienced due to extreme climate events (EWI). We assume that when biodiversity is under high pressure (BI=0) and the county or region is under high climate disastrous risks (EWI=1), the maximum productivity loss will be 80%. When BI is 1, this loss can be a maximum of 40%.

Combining those two, the historical total biodiversity loss induced soil productivity or pollination loss as of 2050 in the case of extreme climate events in 2050 is formulated as follows

$$\Delta P_{2050,c}^{EWI} = [0.5 \times (1 - BI_{2050,c})] + ([1 - 0.5 \times (1 - BI_{2050,c})] \times [(-0.4 \times BI_{2050,c})] \times EWI_{2050,c})$$

The first term shows the direct impact pathway's effect, and the second term indicates the resilience to extreme climate events pathway's effect on soil productivity or pollination services loss.

The thresholds of 40% loss of crop productivity under the most extreme climate extremes imaginable in a maximum biodiversity situation and an 80% loss in a minimum biodiversity situation are, of course, assumptions. The severity of the impacts of extreme climate events on crop yield depends on numerous factors, including the severity of the weather event, the type of weather event, the timing of the event in relation to the life cycle of the crop, the type of crop, the agricultural management practices in place or applied to prevent the impact, the soil type and soil quality and the biodiversity situation. Monteleone et al. (2023) analysed fifty-two articles that determined crop vulnerability scores for different weather extremes, including drought and flooding. The highest estimate for the maize yield loss under the highest possible drought index score is 80%. Yield losses of rice due to flooding amount to a maximum of 100% with increasing water depth. The extreme projected yield losses justify our selection of high losses under very extreme climate conditions.

In relation to the decline of pollination services, we assess the ultimate effect on productivity by examining the reliance on insect pollinators for each crop type. To accomplish this, we apply ratios of insect pollinator dependency from Aizen et al. (2016) and Klein et al. (2007). Using methods similar to those for calculating economic losses by Bauer and Wing (2016) and La Notte et al. (2020), we posit that reductions in pollination services by insects, as outlined in the scenario, result in diminished crop yields according to their specific insect pollinator dependence ratios (PDRs).

We compile these ratios from the aforementioned studies and utilise FAOSTAT data on past agricultural output to estimate the decrease in crop production that aligns with the reductions in pollination services projected by our scenario. For instance, a complete loss of 100% in pollination services would lead to a crop production reduction equivalent to the crop's PDR. Conversely, a 50% decline in pollination services would correspond to a production reduction equal to the crop's PDR multiplied by 0.5.

Then if a crop's dependency on pollination is $W_{c,p}$ where p denotes crop, then the total productivity loss due to biodiversity loss induced pollination loss without extreme climate events can be formulated as

$$\Delta PP_{t,c,p} = W_{c,p} \times \Delta P_{t,c}$$

where $\Delta PP_{t,c}$ is the historical productivity loss as of 2019 and 2050 at crop level due to pollinator loss without considering extreme climate events. When extreme climate events as of 2050 are considered, we can write the following formula

$$\Delta PP_{2050,c,p}^{EWI} = W_{c,p} \times \Delta P_{2050,c}^{EWI}$$

where $\Delta PP_{2050,c}^{EWI}$ is the historical crop productivity loss as of 2050 due to pollinator loss at crop level

1.3. Summary of the scenario setup

Six future scenarios are used to assess crop productivity loss in 2050 compared to 2019, considering the impact of changes in biodiversity on soil quality and pollination, both with and without accounting for the effects of extreme climate events. Table 1 shows the list of scenarios varying in terms of soil quality and productivity, pollination services, crop productivity, and extreme climate events in the future, the soil productivity and pollination loss shocks used at each scenario. Crop productivity changes between 2019 and 2050 are estimated for 56 distinct regions and countries.[7] Please note that when estimating our macroeconomic model, we have also developed two additional combined scenarios: soil quality and pollination, with and without extreme climate events. For these scenarios, the crop productivity changes from the original scenarios are used together.

Table 1: Scenario setup

[7] The list of countries and regions for our estimations are determined by their importance to the portfolios of our financial sector partners and they can be found in 2_Annex_MAGNET_CGE_documentation on BiROFin website.

Scenario	Soil quality and productivity change	Pollination services and crop productivity change	Extreme climate events	Soil quality and pollination loss shocks
1. *Soil quality scenario without extreme climate event*	Yes	No	No	$\Delta P_{2050,c} - \Delta P_{2019,c}$
2. *Soil quality scenario with extreme climate events*	Yes	No	Yes	$\Delta P_{2050}^{EWI} - \Delta P_{2019}$
3. *Pollination scenario without extreme climate events*	No	Yes	No	$\Delta PP_{2050,c,p} - \Delta PP_{2019,c,p}$
4. *Pollination scenario with extreme climate events*	No	Yes	Yes	$\Delta PP_{2050,c,p}^{EWI} - \Delta PP_{2019,c,p}$
5. *Combinded soil quality and pollination scenario without extreme climate even*	Yes	Yes	No	$\left(\Delta P_{2050,c} - \Delta P_{2019,c}\right)$ & $(\Delta PP_{2050,c,p} - \Delta PP_{2019,c,p})$
6. *Combinded soil quality and pollination scenario with extreme climate event*	Yes	Yes	Yes	$(\Delta P_{2050}^{EWI} - \Delta P_{2019})$ and $\Delta PP_{2050,c,p}^{EWI} - \Delta PP_{2019,c,p}$
7. *Reference scenario*	No	No	No	

Those scenario outcomes are compared with a reference scenario to estimate the economic impact of a loss in agricultural productivity via the reduction in the provision of good soil quality and pollination services. The reference scenario does not account for a change in the provision of good soil quality and pollination by biodiversity, and the world economy follows a path as depicted in socioeconomic pathways-middle of the road (SSP2) where social, economic, and technological trends do not shift markedly from historical patterns towards 2050.[8] The scenario component used in the benchmark MAGNET model equivalent includes the commonly used characteristics of the SSP2-RCP45 scenario, excluding the climate change-related characteristics.[9]

1.4. Example preliminary outcomes from soil quality scenario

This section presents preliminary soil productivity changes at the country level, as anticipated by our soil quality scenarios, as an example. Pollination scenario outcomes on crop productivity levels are not presented as they are crop-country-specific, need more detailed elaboration and are left for the full report, which will be published next year.

[8] For more details on SSP scenarios please see Fricko et al. (2017) and Riahi et al. (2017).

[9] Excluding climate change related characteristics does not have an important implication in our estimations, as this scenario serves as a counterfactual for estimating the effect of soil quality and pollination loss on the economy under other scenarios which are generated by taking into account SSP3 (high challenges to climate mitigation and adaptation) with RCP 6.0 (moderate level climate change) scenario.

Preliminary analysis highlights that European countries faced the most significant agricultural productivity losses via a loss in providing good soil quality due to pressures on biodiversity up to 2019 (see Figure 2). The estimates for this period indicate that European countries experienced the highest levels of productivity loss up to 2019. In contrast, lower loss levels are estimated for African nations and countries like Russia, Australia, and Canada. Our study uses these estimates for soil productivity and pollination loss from the 2010s as benchmark levels for comparison with future losses.

The expected change in productivity by 2050 in the soil quality scenario with climate change-induced changes in extreme climate events varies significantly among countries (see Figure 3). So, it shows the productivity that is projected to be lost in addition to what has been lost until 2019 (please refer to Figure 2 for the changes that occurred up to 2019) and highlights the varying degrees of productivity decline caused by biodiversity loss-induced soil quality loss with an elevated effect due to climate change. For instance, the productivity decline in Nigeria is projected to be 4 times the productivity decline in Ireland by 2050 compared to 2019.

Specifically, productivity is expected to decrease most in cocoa-producing African countries, including Cameroon, Ghana, Ivory Coast, and Nigeria, followed closely by Brazil, North Africa and the Middle East. In contrast, countries like the United Kingdom, Ireland, the Philippines, Taiwan, and the Netherlands are projected to experience the lowest decreases due to the same factors. Countries projected to face more significant productivity loss between 2019 and 2050, like Nigeria, cocoa- producing African countries, are expected to experience more human modification, agricultural intensification, and, more importantly, more extreme climate events than those with less severe productivity declines.

2. Soil biodiversity, its ecosystem services and human impacts

Soil biodiversity, the diversity of animal and plant species, bacteria and fungi in the soil, has numerous impacts on the soil quality. Soil biodiversity plays a critical role in agricultural systems by supporting a wide array of ecosystem services that are essential for crop productivity, environmental sustainability, and long-term soil health. Below is a detailed description of the main ecosystem services provided by soil biodiversity in agriculture and of the various impacts of human activities on soil biodiversity.

2.1. Ecosystem services provided by soil biodiversity

Nutrient cycling and soil fertility

Soil organisms, such as bacteria, fungi, nematodes, and earthworms, are key players in the decomposition of organic matter and the cycling of nutrients like nitrogen (N), phosphorus (P), and potassium (K). Microbes break down organic matter into simpler compounds, making nutrients available to plants. This process is fundamental for maintaining soil fertility. Furthermore, certain bacteria (e.g., Rhizobia) form symbiotic relationships with legumes, converting atmospheric nitrogen into forms that plants can use, reducing the need for synthetic fertilisers. Mycorrhizal fungi enhance plant access to phosphorus by extending the root network, thereby improving plant nutrient uptake. Also, earthworms and other decomposers physically break down plant residues, facilitating faster decomposition and nutrient recycling.

Soil structure and water regulation

Soil organisms influence the physical structure of the soil, which impacts its ability to store water, maintain porosity, and resist erosion. Microorganisms like fungi produce sticky substances that bind soil particles together, forming aggregates. These aggregates improve soil porosity, root penetration, and water infiltration. Earthworms and other soil fauna create channels and burrows, improving soil aeration, water infiltration, and drainage. This also prevents waterlogging, enhances root growth, and increases the soil's capacity to retain water during droughts. Healthy soil biodiversity also enhances soil structure, which in turn reduces soil erosion by stabilising the soil surface. This reduces nutrient loss and maintains productive topsoil.

Pest and disease control

Soil biodiversity helps regulate the populations of plant pathogens and pest species, reducing the need for chemical pesticides. Predatory soil organisms, such as nematodes, mites, and predatory insects, prey on harmful pests, maintaining pest populations below damaging levels. Soil microbes like certain fungi (e.g., Trichoderma) and bacteria (e.g., *Bacillus subtilis*) can suppress plant pathogens by producing antibiotics, outcompeting harmful microbes, or inducing plant resistance mechanisms. Diverse soil ecosystems are more resilient to invasions by pathogens or pests, as high biodiversity enhances the system's ability to self-regulate and prevent outbreaks.

Carbon sequestration and climate regulation

Soils store more carbon than the atmosphere and vegetation combined, and soil biodiversity is key to regulating this carbon pool. Soil organisms help sequester carbon by breaking down plant material and stabilising organic matter in the soil. Stable organic matter (humus) stores carbon for long periods, reducing atmospheric CO_2 levels. Certain soil microorganisms regulate the production and consumption of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). For example, some bacteria can consume methane, a potent greenhouse gas.

Pollination support

While not directly a function of soil biodiversity, soil health indirectly supports pollinator populations by maintaining flowering plant diversity and providing habitat for ground-nesting pollinators, such as solitary bees. Healthy, biodiverse soils promote diverse plant communities, which in turn support a variety of pollinators essential for crop production.

Detoxification and bioremediation

Soil organisms help detoxify and break down harmful substances such as pesticides, heavy metals, and pollutants, preventing them from entering the food chain or groundwater. Certain microbes can degrade chemical residues, reducing the toxicity of agricultural inputs and preventing contamination of the surrounding environment. Soil microorganisms can immobilise or transform heavy metals into less bioavailable forms, reducing their uptake by plants and minimising the risk of contamination in crops.

Supporting plant growth and health

Soil biodiversity directly enhances plant health by promoting symbiotic relationships and improving the efficiency of resource use. Mycorrhizal fungi form associations with plant roots, improving nutrient uptake and increasing plants' resistance to environmental stresses like drought or nutrient-poor soils. Soil bacteria and fungi can produce growth-promoting substances such as hormones (e.g., auxins) and vitamins, enhancing plant development.

Cultural services

Although less tangible in agricultural contexts, soil biodiversity contributes to cultural services by supporting traditional farming practices and sustainable land-use systems. Traditional farming systems often rely on the preservation of rich soil biodiversity to maintain productivity in the absence of industrial inputs, linking soil health with cultural heritage and sustainable land management practices.

Negative impact of human activities on soil biodiversity

Unfortunately there is hardly information available on soil biodiversity. We do know, however, that many human activities negatively impact soil biodiversity. In agricultural areas, many of these activities are aimed at smaximising short-term agricultural productivity but can harm the long-term health of soil ecosystems. Below, the most important activities that negatively impact soil biodiversity are presented.

Intensive tillage

Frequent and deep tilling breaks up soil structure, destroying the habitats of soil organisms. It also disrupts soil aggregates, reducing soil porosity and compacting the soil, which limits air and water movement essential for microbial and faunal life. Furthermore, tillage accelerates the decomposition of organic matter by exposing it to oxygen, leading to a rapid loss of carbon in the soil and a decrease in food sources for soil organisms.

Monocropping

Monocropping, or growing the same crop continuously, limits the variety of organic residues (roots, leaves, and other plant material) entering the soil. This reduces food sources for a diverse community of soil organisms, leading to a decline in soil biodiversity. Monocropping can also create conditions favorable for the build-up of pests and diseases that harm soil organisms. A lack of crop diversity reduces the natural suppression of these issues, often leading to increased chemical use (pesticides and herbicides), further harming soil biodiversity.

Chemical inputs (pesticides, herbicides, and synthetic fertilisers)

The widespread use of chemical pesticides and herbicides can kill beneficial soil organisms like earthworms, insects, and microbes. Some chemicals, such as glyphosate, can persist in the soil, further disrupting microbial communities. Synthetic fertilisers, particularly nitrogen-based fertilisers, can alter the soil's nutrient balance. Excess nitrogen, for example, can suppress beneficial nitrogen-fixing bacteria while promoting other microbial groups, leading to a loss of microbial diversity and an imbalance in soil processes.

Soil compaction

Compaction, often caused by heavy machinery or overgrazing by livestock, reduces soil porosity, making it difficult for water, air, and roots to penetrate the soil. This can suffocate soil organisms and reduce their populations, especially larger soil fauna like earthworms and insects. Compacted soils provide fewer habitable spaces for soil organisms to thrive, leading to a decline in species diversity and abundance.

Overgrazing by livestock

Overgrazing reduces plant cover, which leads to a loss of organic matter input into the soil. This diminishes the food supply for soil organisms and increases the risk of erosion, further reducing habitat quality. Livestock trampling can compact the soil, particularly in areas where stocking rates are too high, affecting water infiltration and air movement, and consequently reducing the viability of soil biota.

Reduction in organic matter inputs

Agricultural practices that remove crop residues (e.g., for biofuel or fodder) or do not incorporate organic matter (such as manure or compost) reduce Soil Organic Matter (SOM) content. Without adequate organic inputs, soil organisms lack food, leading to a decline in soil biodiversity. The absence of cover crops or organic mulches reduces the supply of plant material that feeds soil organisms and protects them from extreme temperatures and moisture fluctuations.

Irrigation mismanagement

Improper irrigation can lead to waterlogged soils, which suffocate aerobic soil organisms and reduce biodiversity. Alternatively, excessive irrigation in arid regions can cause soil salinisation, which negatively affects most soil organisms, especially microbes and plants, thus reducing soil biodiversity. Over-irrigation can increase soil erosion and leach essential nutrients, creating poor soil conditions for organisms to survive. The loss of topsoil, which is rich in organic matter and soil life, directly reduces soil biodiversity.

Erosion

Soil erosion caused by wind or water can strip away the nutrient-rich topsoil layer where most soil organisms reside. This reduces both the quantity and quality of habitat for soil biodiversity, particularly in areas where protective vegetation is sparse due to overgrazing or poor agricultural practices. Erosion reduces organic matter content and soil structure, further depleting the food sources and homes of soil organisms.

Loss of habitat diversity

In many agricultural systems, natural features like hedgerows, grass strips, and small patches of forests or wetlands are removed to increase arable land. These areas often provide habitat for beneficial insects, birds, and other wildlife that contribute to soil biodiversity. The loss of such habitat diversity reduces overall biodiversity and disrupts soil ecosystems. As natural areas around farms are fragmented, the migration and dispersal of soil organisms become more difficult, reducing their population and diversity in agricultural soils.

Pollution and heavy metals

The use of contaminated irrigation water, industrial runoff, or excessive use of certain chemical fertilisers can lead to the accumulation of heavy metals (such as cadmium, lead, and arsenic) in the soil. These contaminants can be toxic to soil organisms, reducing microbial activity and diversity. Soil pollution from industrial or agricultural chemicals inhibits the growth and reproduction of soil organisms, slowing decomposition processes and reducing the overall health of the soil ecosystem.

Human induced climate change and extreme climate events

Climate change can lead to more frequent droughts, floods, or extreme temperature fluctuations, all of which negatively affect soil organisms. Drought reduces moisture levels necessary for microbial and faunal activity, while flooding can lead to oxygen deprivation in the soil, suffocating many organisms. High temperatures and extreme climate events can accelerate the breakdown of organic matter or cause its erosion, reducing the food sources needed for maintaining healthy soil biodiversity.

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