# Measures for adaptation to climate change through water retention and cooling by transpiration

## A catalogue of measures for a drought-prone area in eastern Germany

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## Abstract

As climate change progresses, summer droughts are becoming more frequent and severe in some regions. One example is the Elbe-Elster district (southern Brandenburg, Germany), where rising temperatures are increasingly limiting water availability. Therefore, within the framework of the IAWAK-EE research project, we have compiled measures with which the available water can be retained longer in the area or in the soil. The retained water is then available to the plants for evapotranspiration, which cools the land surface.

The measures are assigned to the various land use groups of agriculture, forestry and water management, settlement areas and nature conservation. In the context of the IAWAK-EE project, they form the basis for spatially concrete proposals and for the selection of cost-effective measures. This report presents the selected measures in the form of standardized measure sheets.

*Keywords: Climate adaptation, water retention, evapotranspiration, land use, agriculture, forestry, water management, settlement, nature conservation*

## 1 Introduction

The design of the measures was developed in the research project »Information-supported anticipatory water balance-based adaptation to climate change« (IAWAK-EE), funded by the German Ministry of Research and Education (BMBF). Adaptation to climate change confronts the actors in the Elbe-Elster district, the project area, primarily with increasing water scarcity. At the same time, annual precipitation is 556.8 mm, which is quite low (Pfeifer et al., 2021). Due to rising temperatures, even with constant precipitation, the climatic water balance is becoming increasingly negative (B. Zimmermann & Hildmann, 2021). Therefore, we looked for measures to retain more water in the landscape. The retained water is to serve as a water supply for the vegetation. It has a positive effect on plant growth by alleviating drought periods and improving the yield security of crops. Above all, the evaporation process cools the land surface, which we investigated via satellite images.

The cooling of the landscape through the evaporation process contributes to the attenuation of temperature extremes and climate change. Here, climate adaptation goes beyond coping with the consequences of climate change by positively influencing the microclimate. The cooling effects benefit not only humans, but also plants and ani-

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mals. Species that are particularly less tolerant to heat are already declining (e.g. Reif et al., 2008; Schleuning et al., 2016; Bartholy, 2012). Soil is also affected by climate change (e.g. Brevik, 2013; Jansson & Hofmockel, 2020; Classen et al., 2015; Gelybó et al., 2018). Hence, the cooling effects influences soil biota and the associated decomposition processes of organic matter. Finally, a cooler land surface builds up a lower temperature gradient into the layer of air above it, so that atmospheric moisture is more likely to remain in the area and thus is available for the formation of dew, for example. The work of Makarieva et al., 2021; Makarieva et al., 2022a; Makarieva et al., 2022b even concludes that if evaporation on the continent is too low, a tipping point may be passed, the supply of moist air from the Atlantic may be blocked and an arid climate regime may develop.

For climate adaptation measures to be effective, they must be implemented on a large scale. Therefore, we compiled measures from all relevant sectors in the district: agriculture and forestry, the settlement sector, nature conservation and water management. Since the Elbe-Elster district is sparsely populated by German standards (i.e. settlement area approx. 4.8% of the total area), the focus of the measures is on rural areas.

The water retention measures are intended to be effective throughout the year. Water surpluses from the winter half-year should be used as far as possible in the summer half-year. In addition, precipitation is to be retained in the summer half-year in the same way in order to alleviate drought periods. In this way, the measures also have a further function where they attenuate run-off from the land surface during heavy rainfall events and thus also contribute to flood protection.

In selecting the present catalogue of measures, we were guided by the landscape conditions of the region, which is characterized by a low relief landscape and sandy soils. In the past, the water balance of the landscape was significantly altered, especially by complex ameliorations and lignite mining. Large parts of the forests are characterized by pine monocultures with high vulnerability to climate change. Some further measures are conceivable, but were not included in the catalogue for the time being due to their minor importance in the study area or due to a lack of input data for spatial classification (see below).

Landscape water retention measures have already been identified in other research, but usually with a different focus and adapted to other regions (e.g. Sušnik et al., 2022; Keesstra et al., 2018; Mubareka et al., 2013; Tóth, 2019; Hildmann, 2009; Sieker et al., 2007b). They are often referred to as »Natural Water Retention Measures« (NWRM) or »Nature Based Solutions« (NBS). If the approach presented here is transferred to other regions, the measures may need to be adapted and supplemented. This applies in particular to landscapes with a more pronounced relief or with different precipitation patterns.

Within the framework of the IAWAK-EE project, the measures presented here will be located in the individual polygons of the land use map in a site-specific and site-dependent manner using algorithms developed for this purpose. We will then evaluate their effectiveness in terms of their contribution to cooling the landscape and thus to climate adaptation. In parallel, the costs of the measures are calculated so that the most cost-effective measures (the set of those measures which achieve the highest cooling effect for given costs) can be selected using optimization algorithms.

## 2 Land use category: Agriculture

### 2.1 A-I-1: Agroforestry systems (alley cropping)

#### 2.1.1 Aim of the measure

The combined cultivation of conventional arable crops with rows of woody plants and/or hedge strips can influence the microclimate and thus the water retention of agricultural land.

#### 2.1.2 Description and implementation

In agroforestry, the cultivation of perennial woody plants is combined with the cultivation of annual crops or with the use of grassland (Grünewald et al., 2009). In this process, either

*Figure 1: Water retention in the landscape – if possible, such natural solutions should also be permitted.*

*Figure 2: Agroforestry systems such as timber strips contribute to improving the microclimate.*

long-term profitable woods or trees that provide short-term wood (energy utilization) or fruits are planted (DIESTEL, 2018). Agroforestry systems offer the advantage over conventional land management in which the plant cover absorbs light above ground in several stages staggered in height and a stable microclimate (shading, wind protection) is created in the vicinity of the ground (SPIECKER et al., 2009). In the process, the soil dries out less, making more water available for plant transpiration. Trees and shrubs have high evaporation rates in summer, retain precipitation on the foliage, and promote dew and frost formation. Such cropping systems are able to increase local evapotranspiration during the period between harvest of crops such as cereals or canola until fall (KAESER et al., 2010). In winter, stem run-off from deciduous trees and shrubs recharges groundwater, providing plants with a greater supply of water for transpiration in the following spring (DIESTEL, 2018).

Establishment of tree strips with fast-growing species (alley cropping) on cropland to produce wood chips for energy use opens the possibility of an economic use of the complete area of an agroforestry system. The growth of tree species that are capable of growing on the forest floor is harvested at regular time intervals. Such systems are already being tested, for example, in Thuringia (BÄRWOLFF et al., 2016) or in the district of Spree-Neiße (BÖHM et al., 2014; KANZLER et al., 2015; KANZLER et al., 2016) on agricultural fields. The trees under consideration are poplar cultivars that can achieve high growth rates even on sites far from groundwater. They are usually crosses of the Aigeiros (black poplar) and Tacamahaca (balsam poplar) sections. Current, high performing clones include Max 1 (*P. maximowiczii x P. nigra*), Max 4, hybrid 275/NE 42 (*P. maximowiczii x P. trichocarpa*), or Matrix 49.

The trees are usually planted as 0.2 m long cuttings. Two different approaches should be distinguished with respect to planting density and spacing, because these parameters depend on the selected rotation period. The rotation time, in turn, influences the potentially achievable tree dimensions and the choice of a suitable harvesting technique must be chosen accordingly.

On the one hand, poplar strips can be managed in short rotation periods of 3 to 5 years. Such systems are used exclusively for the production of wood chips for energy recovery. A strip consists of 5 rows of trees, with a row spacing of 2.4 m. This spacing allows for mechanical weed control during the establishment phase using conventional agricultural techniques, which is usually required to achieve good establishment success. The distance between individual plants in the row is 0,4 m, resulting in a total of about 10,000 trees per hectare in the tree strip. With this type of cultivation, the trees can reach growing heights of 5 to 10 m, depending on the location. A conventional self-propelled forage harvester with a harvesting attachment can be used for harvesting because the maximum diameters of the individual trunks can still be handled by this technology. Guidance on establishment and management can be found, for example, in Aust et al., 2013; Behr et al., 2012; Unseld et al., 2010.

On the other hand, larger and taller trees can be targeted for use as wood chips or industrial timber. In this case, the rotation time must be extended and forestry harvesting technology (e.g. harvester with feller-buncher head, motor-manual felling) must be used because the cutting neck diameter becomes too large for short rotation technology. The number of trees and the planting pattern must be reduced to ensure that the stand space requirements of the individual plants in the stand are served as optimally as possible. The rotation period can then be up to 20 years. Böhm et al., 2020 structures describe, for example, poplar strips in an agroforestry system south of Senftenberg (Germany) with a row spacing of 2.70 m and a plant spacing in the row of 1.00 m, which are to be managed in a minimum ten-year rotation. Plants with even wider spacing (e.g., 3 x 2 to 3 x 5 m) are then used mainly for the production of industrial timber. They are harvested for the first time after 20 years at the latest (Unseld et al., 2010).

The spacing of the individual woody strips on the field should be based on the technical specifications for the cultivation of the annual crop between the strips. In addition, it should be taken into account up to which distance in the lee from the individual strip positive effects are still expected. To ensure the most permanent windbreak effect possible, it is recommended for harvesting short rotation strips to harvest only every other strip at a time (Böhm et al., 2020). The distance between the strips should not be greater than 50 m. We therefore recommend a strip spacing of 48 m, which corresponds, for example, to twice the working width of a 24 m wide boom of a field sprayer. Strip spacing of 96 m and 144 m, for example, were also investigated in addition to 48 m (Bärwolff et al., 2016). Kanzler et al., 2015 also considered narrower strips with a 24 m spacing. If possible, the strips should be oriented in transverse to the main wind direction on the site, i.e., from north to south in the Elbe-Elster district.

For planting the cuttings in spring, a planting bed preparation must be carried out. This is done either without ploughing or with a cultivator or by plough. Professional service providers with appropriate planting techniques are usually used for planting. After planting, the young stands must be maintained more or less intensively until they are established, depending on weed occurrence. For example, a conventional tractor with a disc harrow can be used between the rows of trees.

Following indications from Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie, 2008; Thüringer Landesamt für Landwirtschaft und Ländlichen Raum, 2020; Landesanstalt für Landwirtschaft, Forsten und Gartenbau Sachsen-Anhalt, 2014; Landwirtschaftliches Technologiezentrum Augustenberg, 2018; Dobers et al., 2003, the following crop rotations are possible for the cultivation of annual crops between the tree strips (tab. 1, WIC = winter intercrop).

### 2.1.3 Expected effectiveness

The effectiveness depends on the distance and orientation of the rows of copses or hedges, the type and age of the copses (structure), the relief and vegetation of the surrounding area, local winds, large-scale weather conditions, and the replenishment of groundwater reservoirs in winter (Diestel, 2018). The greatest effects are expected when the strips of woody vegetation or hedgerows are established in a north-south direction. In studies with black locust hedges on a reclamation site in the Welzow-Süd open pit mine, a decrease in air temperature (at a height of 1 m) of 0.4 K was achieved on the leeward side of the field strips from June to August. In the centre of the arable strips, the air temperature was 0.6 K lower than in neighbouring open areas without shading and wind protection by woody hedges. In an agroforestry system with poplars, up to 3 % higher water content was found in the soil on the leeward side (0-0.1 m depth) at a distance of four to eight meters from the grove strip in the second year of stand (Grünewald et al., 2009). Bärwolff et al., 2016 found a significant reduction in wind speed up to 72 meters away on the downwind side of poplar strips. In contrast, an influence of other parameters, such as air humidity, soil moisture, soil and air temperature could not be detected. Böhm et al., 2020 were able to demonstrate a significant reduction in wind speed in agroforestry systems with poplars that were managed for the production of woodchips in short rotation periods.

### 2.1.4 Costs

**Opportunity costs:** Generally, opportunity costs arise for farms in the form of economic losses due to the change in the management of the agricultural land. Instead of cultivating crops that maximize profit – known as standard crop rotation (SCR) – farmers plant crops or manage the agricultural land in a way that increases its water retention capacity (WRC). To determine the opportunity cost for the 30-year observation period, the sales revenue and cultivation costs of SCR and WRC must be compared per hectare per year. Future costs and revenues must be thereby discounted to present values. In general terms, this may be expressed in the mathematical terms:

$$OC = \sum_{t=1}^{30} \frac{(R_{SCR} - C_{SCR})_t}{(1+r)^t} - \sum_{t=1}^{30} \frac{(R_{WRC} - C_{WRC})_t}{(1+r)^t} \tag{1}$$

with

| | |
|---|---|
| OC | opportunity costs |
| R | revenue |
| C | costs |
| R | discount rate |
| SCR | standard crop rotation |
| WRC | water retention capacity enhancing measure |

The standard cost of crop cultivation consists of labour, fuel consumption, depreciation, interest payments, operating supplies, and fertilizers as well as pesticides. KTBL, 2022 provides figures for this per hectare cultivated. Sales revenues are the crop yield per hectare multiplied by the market price of the cultivated arable crop. Data on the long-term average of prices can be obtained from KTBL and other sources (Sächsisches Staatsministerium für Energie, 2021; Bundesministerium für Ernährung und Landwirtschaft, 2021) for various arable crops per decitonne or ton. Amt für Statistik Berlin-Brandenburg, 2019 publishes long-term average yields for various arable crops at the county level in Brandenburg. It is assumed that on a field with the average soil quality (Ackerzahl) of 32.6 in the Elbe-Elster district, this yield per hectare can be generated. On fields with above-average soil quality, the yield is correspondingly higher, and on fields with below-average soil quality, the yield is correspondingly lower. According to Roth, 1956, yield increases linearly by 1.5 grain units when the soil quality is 5 points higher.

*Table 1: Crop rotations*

| Site quality | Crop rotation elements and sequence |
|---|---|
| Ackerzahl <25 | Winter rye – WIC – Silage corn – Spelt – WIC – Silage corn – WIC – Blue lupin |
| Ackerzahl >=25 | Winter barley – Winter rape – Winter wheat – WIC – Silage corn – WIC – Field pea |

In agroforestry systems (alley cropping) opportunity costs arise in two ways. First, cropland is converted to agroforestry strips, which means that cropland yields can no longer be generated on that land. These lost profits must be offset against the profits generated by the alternative use of the land as agroforestry strips for the 30-year period under consideration. In addition, the crop rotation is adjusted on the residual arable land. Accordingly, differences in arable profit generation between the standard crop rotation and the agroforestry system crop rotation must be taken into account. In principle, it can be assumed that agroforestry strips have an influence on the yield on the remaining tillage area. However, this cannot be systematically recorded across the board, as there are mutually offsetting effects that differ in individual cases. On one hand, more shade leads to more water availability, which has a positive influence on plant growth. On the other hand, shade also hinders plant growth. Due to the non-generalizability of these effects, they are not considered here.

The profit of agroforestry strips can be determined depending on whether the forest is managed with short rotation periods (3-5 years) for woodchip production or with long-term rotation periods (up to 20 years) for industrial timber production. Average market prices and long-term price developments for forest chips can be obtained for Germany as a whole and differentiated by region from C.A.R.M.E.N, 2022. In addition, Statistisches Bundesamt, 2022 provides data on prices and yields for industrial wood. Average crop yields and process costs are provided by the KTBL performance cost calculator for energy crops KTBL, 2022. For both short- and longer-term rotations, it should be noted that farmers generally incur higher transportation costs (Toews, 2009). Typically, farmers supply heat generation plants within a radius of up to 50 km (Hering et al., 2013). On average, we therefore apply transport costs for a supply of 25 km.

**Investment costs:** In the beginning, costs are incurred by planting trees. Establishment costs differ depending on whether agroforestry strips are established with short rotation periods of 3 to 5 years for woodchip production or with longer rotation periods of up to 20 years for industrial timber production. KTBL, 2022 provides cost data for planting.

**Management costs:** The agroforestry strips must be regularly maintained, especially during the growing-in phase. Again, KTBL, 2022 provides standard costs for machinery and labour input. Incurring management costs are taken into account when determining the profit of agroforestry strips as part of the opportunity cost calculation.

### 2.1.5 Synergy effects

Due to the permanent use or rotation periods of up to 10 years, the woody plants permanently bind carbon and can contribute to climate protection as a $CO_2$ sink. The annual leaf fall contributes to humus formation. Compared to less structured agricultural landscapes, agroforestry systems have a higher biodiversity. Due to the potentially higher water availability, increased yields are possible (depending on the arable crop cultivated). Farms achieve a diversification of their product range and thus a spreading of risks against failures of conventional crops or uncertain market situations.

#### 2.1.6 Obstacles

In the immediate vicinity of the rows of trees, the root system may cause a decrease in soil water content. Over time, this effect can extend to larger areas due to root growth (water competition) and lead to reduced yields spatially limited to the arable strips near the groves. Therefore, in agroforestry systems with rather narrow cropland strips, negative effects due to interspecific competition may be greater than positive effects (Grünewald et al., 2009). Increased air and soil moisture contents may lead to increased infestation with pests on the leeward side, which would require intensified plant protection measures (cost factor). If the wooded strips are planted in an east-west direction, it can be assumed that there will be greater shading to the north of the strips, which may result in lower yields depending on the type of crop. Winter cereals react only with strong shading (50 %). However, silage maize is already impaired at low levels of shading (12 %), while potatoes are comparatively insensitive to shading (V. Schulz et al., 2017).

Legal uncertainties exist regarding the long-term use of the groves/hedges/trees in relation to the terms of the leased areas. Adaptation/change in standard farm land management and marketing is necessary in terms of machinery technology, methodology and time (possibly cost factors), maintenance measures (value timber production), production and sales markets. Agroforestry systems cause additional costs at the beginning of the measure or lead to reduced revenues (lower yields due to smaller agricultural area, planting and maintenance of the trees). Due to the long-term commitment of capital and land, some farm flexibility is lost. In agroforestry systems, farms also do not receive area-based EU direct payments for the share of land with woody crops under the current legal situation, which leads to further financial disadvantages compared to non-agroforestry areas.

#### 2.1.7 Stakeholders

Farmers, land owners/landlords

### 2.2 A-I-2: Landscape structure elements

#### 2.2.1 Aim of the measure

Landscape features such as hedgerows and field copses can inhibit surface run-off during precipitation, thereby promoting decentralized water retention. It also slows the airflow over the agricultural land, improving the microclimate.

#### 2.2.2 Description and implementation

Species selection should be site-specific and include native tree and shrub species. In Brandenburg, there is a decree on the use of native woody plants when planting in open land (Ministerium für Landwirtschaft, Umwelt und Klimaschutz, 2019). Suitable woody species are listed in Appendix 1. A grouping of these species in terms of their suitability for the open landscape and under climate change conditions was made in Roloff & Grundmann, 2008. Examples of native and suitable species include field maple, intermittent hawthorn, blackthorn, common hazel, broom, European spindle tree, wild apple, dog rose, hedge rose, black elderberry, rowan, sessile oak, and hornbeam.

Ideally, bare-root, 2- to 3-year-old transplanted seedlings in assortments of 0.3/0.5 to 0.7/0.9 m from forest nurseries should be considered for planting. Between 3,000 and 5,000 plants per ha should be planted in a triangular formation.The stand area per plant should be 2-3 m$^2$, and the distance between the rows should be 1.0 to 1.5 m. At least 3 to 5 planting rows should be planted. Single trees can be integrated and grow as overstory. Fencing against game browsing is usually recommended.

Field margins are predominantly wood-free, today mostly unused fringe strips that border, accompany and subdivide agricultural land. Field margins can be credited as ecological priority areas within the framework of greening of the current agricultural funding period and can thus contribute to the fulfilment of greening obligations (Landwirtschaftskammer Nordrhein-Westfalen, 2022). With a width between 2 and 10 m, they are eligible for premiums as cross compliance-relevant landscape elements

*Figure 3: Landscape structural elements such as rows of trees and hedges are beneficial for cooling the landscape.*

and may not be removed. Use of plant protection products and fertilization are generally not permitted, as these are non-agricultural areas. The storage of manure or waste on field margins is not permitted. The preservation of field margins is in the foreground, if necessary with an upgrading through targeted maintenance (mulching every 2 to 4 years - not between 15.3. and 15.7. - preferably in September) or widening.

A new creation of field margins along roads or field paths, but especially also for the subdivision of arable fields, can be carried out by sowing a perennial flowering plant mixture with a conventional sowing machine as band sowing. Prior to this, land preparation with turning or non-turning tillage and subsequent seedbed preparation must usually be carried out to create an ideal germination bed. Regional seed should be used and site conditions should be considered to ensure the best possible site adaptation of the plant species used (Durka et al., 2019; Wieden, 2015).

### 2.2.3 Expected effectiveness

Subdividing fields by hedgerows, copses, grass or herbaceous strips helps to improve water retention. Such biotope structures, laid out parallel to the contour line, shorten slope lengths that affect run-off, cross run-off paths that run in fall lines, slow down surface run-off, and thus lead to greater infiltration of precipitation water. In addition, permanent rooting in the area of the structural elements themselves leads to a higher infiltration capacity of the soil. Root-intensive tree species such as alders increase the soil pore volume and improve the infiltration and water storage capacity of the soil in the medium term (Gewässerentwicklung mbH, 2018).

Permanent unrestrained airflow transports large amounts of water released by plants via transpiration away from agricultural land, preventing microclimate development in the stand. Moreover, the in situ cooling capacity of evaporated water cannot be used. At a ground-level wind speed of 2.3 m $s^{-1}$, water vapour can be displaced about 8.3 km within one hour (Lischeid, 2010). Hedgerows, copses and field margins slow down the air flow. As a result, absolute evaporation decreases in the area of the windbreak compared to the fully windy open field (Kühne et al., 2018; Wendt, 1951), but the transpired water is kept above the cropland and can have a local cooling effect. Structural elements also contribute to the cooling of agricultural land through permanent water uptake and transpiration themselves. Evaporation rates of up to 8 mm per day have also been found in hawthorn hedgerows (*Crataegus monogyna* Jacq.) (Herbst et al., 2007).

New plantings usually take several years to achieve the desired effectiveness and must therefore always be combined with other measures such as increasing soil cover on cropland and/or conservation tillage. Effectiveness also depends on other factors such as soil compaction, the width of the structural elements and their area fraction, or the amount of surface run-off that occurs. The wind break effect of hedges is determined by the type and density of the hedge, wind strength, and wind direction. Hedges can provide wind protection up to a distance of 25 times their height, i.e. at a height of 4 m, a reduction in wind speed is still possible at a distance of 100 m in purely mathematical terms (Kühne et al., 2018). Measures to structure the land should be implemented on at least 5 % of the agricultural area. With larger surface areas (up to 20 %), even stronger effects can occur (Sieker et al., 2007a).

### 2.2.4 Costs

**Opportunity costs:** In principle, the calculation of the opportunity costs of landscape structure elements takes place analogously to the cost calculation of agroforestry systems (measure A-I-1, chapter 2.1 for details) and grassland management in cases where grass or herbaceous strips are created (measure A-II-1, chapter 2.3). However, it should be noted that, in contrast to agroforestry strips, structural elements usually do not generate any or only low yields – for example, in the form of wood chip production. Accordingly, only the costs of the landscape structure elements are systematically considered here. Also grass strips incur only costs as they are too small to generate notable fodder yields that can be commercially harvested.

**Investment costs:** Analogous approach as for agroforestry systems. Prices for landscape structure elements from native tree and shrub species are determined based on information from local forest tree nurseries (Landesbetrieb Forst Brandenburg, 2022a). The need for seed mixtures for grass or herbaceous strips and corresponding prices, as well as information on the costs of this measure are determined analogously to the costs incurred in fulfilling greening obligations of the EU green direct payments to farmers. KTBL, 2022 publishes data on the establishment of flower strips.

**Management costs:** Analogous approach as for agroforestry systems in cases where hedgerows and copses strips are created. Insofar as grass or herbaceous strips are created, we assume that costs similar to grassland or meadow management are incurred, for example, through mowing these areas. For a detailed description of costs of grassland management see measure A-II-1, chapter 2.3.

### 2.2.5 Synergy effects

Hedges and copses counteract the isolation of habitats and serve as feeding, breeding and rearing sites (habitat function, increase in biodiversity, biotope networking). In addition, they contribute as structural elements to the visual enhancement of monotonous landscapes. Subdividing measures can contribute to the buffer and filter function of the natural balance by reducing the input of nutrients and sediments into adjacent biotopes. Hedges, copses and other structural elements can be counted as cross-compliance areas (ÖVF) and thus offer the possibility of financial support (greening premium).

Some of the effects of landscape structure elements on yield or crop quality on adjacent land can be considered positive. For example, Cleugh, 1998, after reviewing numerous studies, found that windbreaks can improve crop growth. Winter wheat yield was 15 % higher on plots with windbreaks in Nebraska than on comparative plots without these structural elements (Brandle et al., 1984). Kort, 1988 named positive yield responses ranging from 6 to 44 % for windbreaks in the temperate climate zone. Bärwolff et al., 2016, however, could not demonstrate clear influences and results when investigating an agroforestry system with poplar strips in Thuringia.

### 2.2.6 Obstacles

The shadowing and root competition of landscape structure elements can have a negative effect on the emergence of cultivated field crops in the immediate vicinity. From an economic point of view, the measure is not very attractive, since the withdrawal of agricultural land for the construction of structural elements to promote water retention reduces the expected yield (reduction in the size of the field, yield losses due to larger headland areas) and leads to a loss of income. This can result in higher labour and machinery costs. In addition, financial expenditures must be made for the planting (costs for seeds or seedlings, process costs) and possibly for the maintenance of the structural elements (e.g. fences to prevent browsing by game, irrigation, pruning of trees, hedges and shrubs). Funding instruments can contribute to the implementation of the measure as a financial incentive.

### 2.2.7 Stakeholders

Landowners (farmers), agro-structural development planning, public authorities / local authorities (municipalities)

## 2.3 A-II-1: Converting arable land into permanent grassland

### 2.3.1 Aim of the measure

The conversion of intensively farmed arable land into permanent grassland ensures constant transpiration due to the continuous vegetation cover. In addition, in the medium to long term, water infiltration and percolation can be increased and surface runoff reduced, resulting in improved water retention in the soil.

### 2.3.2 Description and implementation

Permanent grassland has a perennial vegetation cover of grasses, legumes and herbs. The conversion of arable land to permanent grassland for the cultivation of grasses or other green fodder crops is particularly useful on slopes and valleys at risk of erosion and in floodplains of alluvial areas, but may also be considered on low-yield marginal sites.

The conversion of arable land into extensively used grassland is feasible and can be subsidized with €556 per ha and year if the prerequisites are met (use along watercourse edges or on sites at risk of water erosion) (Ministerium für Landwirtschaft, Umwelt und Klimaschutz des Landes Brandenburg, 2020). A site-adapted working speed (< 5 km $h^{-1}$) for the protection of ground nesting birds and other small animals must be maintained in extensive cultivation. Grassland must be mowed at least once a year, and the mown material must be removed (mulching is prohibited). The fertilizer guidelines and restrictions for extensive grassland use must be observed.

### 2.3.3 Expected effectiveness

A reduction in flow velocity and erosion control can be achieved even in the short term. With increasing root penetration and the establishment of species with deep and large roots (large soil pores), the infiltration capacity for rainwater improves and the soil water storage increases. For continued effectiveness, subsequent conversion of permanent grassland back to cropland must be avoided. In order to maintain a high infiltration capacity on grassland areas, they must be managed in a soil-conserving manner. Permanent grassland holds up to 2 l $m^{-2}$ in »drip« after precipitation.

### 2.3.4 Costs

**Opportunity cost:** Generally, permanent pasture is less economically lucrative than cropland. Accordingly, there are opportunity costs in the form of different economic returns. Lost profits are taken into account by comparing the sales revenues and cultivation costs for arable land and permanent grassland per hectare for the total period under consideration of 30 years. To ensure comparability of the figures, future costs and revenues must be discounted and expressed in present values. It should also be noted that the ban on converting permanent grassland to arable land, which has been in force since 2015 for applicants for agricultural subsidies in Germany, means that permanent grassland can only be converted back to arable land at the end of the 30-year observation period in exceptional cases.

*Figure 4: Permanent grassland can retain rainwater and cool the area through evapotranspiration.*

The law stipulates that permanent grassland that has been used for more than 5 years can generally only be converted to arable land if a compensatory area is created or it is not sensitive grassland (e.g., AGRARHEUTE, 2019). Due to the lower productivity of permanent pasture, there is a loss in value of the land converted to permanent pasture. This lower sales value of permanent grassland must be taken into account after the end of the period under consideration as the difference between the sales value of cropland and permanent grassland.

The standard cost of cultivation consists of labour, fuel consumption, depreciation, interest payments, operating supplies, and fertilizer. The KTBL, 2022 provides figures on this per cultivated hectare for both arable crops and permanent grassland . Sales revenue is the yield per hectare multiplied by the market price of the cultivated arable crop or permanent grassland. Data on the long-term average of prices are published by KTBL, 2022 and other official sources for various agricultural products (SÄCHSISCHES STAATSMINISTERIUM FÜR ENERGIE, 2021; BUNDESMINISTERIUM FÜR ERNÄHRUNG UND LANDWIRTSCHAFT, 2021). The provides information on long-term average yields of arable crops and permanent grassland products at the county level in Brandenburg.

**Investment costs:** Costs are incurred when converting to permanent grassland, as a grass mixture is initially sown and with the soil compacted. In addition, full yields are not generated until full meadow emergence.

**Management costs:** None

### 2.3.5 Synergy effects

Soil under grassland that is not subject to invasive tillage and is only used extensively is less compacted and is characterized by a higher earthworm density and a higher proportion of macropores (BUNDESAMT FÜR NATURSCHUTZ, 2014). The permanent, closed turf increases surface roughness, reducing flow velocity and the amount of surface run-off from precipitation and reducing soil silting. Overall, this improves water infiltration (ALHASSOUN, 2009). In addition, more intensive and permanent rooting contributes to the reduction of soil erosion (BUNDESAMT FÜR NATURSCHUTZ, 2014).

Depending on landscape structure, species composition and intensity of use, an improvement in habitat function and biotope connectivity can be achieved for animal and plant species of the open landscape. Reduced nitrate inputs contribute to groundwater protection. Since the population's awareness of nature conservation is often associated with meadows and pastures, the creation of permanent grassland can improve the image of agriculture.

### 2.3.6 Obstacles

Conversion to permanent grassland results in the permanent loss of arable land used for agricultural purposes, causing yield and profit deficits for farms (including foregone contribution margins for otherwise used crop rotations). For owners, the sale value of the land is reduced. When converting to permanent grassland, so-called establishment costs are incurred for sowing and for the seed. Costs are also incurred for grassland maintenance in order to maintain and promote an intact and, as far as possible, closed sward. A later conversion of permanent grassland into new arable land results in the release of climate-damaging gases ($CO_2$, $N_2O$).

### 2.3.7 Stakeholders

Farms, landowners, special-purpose associations, state office for the environment, lower nature conservation authorities

## 2.4 A-II-2: Cultivating permanent crops

### 2.4.1 Aim of the measure

Evapotranspiration increases by a longer soil cover and more intensive rooting of permanent crops compared to annual crops.

### 2.4.2 Description and implementation

Permanent crops are cultivated on an area for several years without intermediate ploughing or tillage. The measure is effective if tillage is restricted to the first year for sowing or planting the permanent crop and if the field is only tilled for harvesting purposes in the following years.

The growing cup plant (*Silphium perfoliatum*) can be sown for establishment in spring (Heimler et al., 2021). Drill or precision seeding equipment can be used for this purpose. The seedbed should be as fine-crumbled as possible and sufficiently reconsolidated. Weed control in the year of establishment can be either mechanical, or with pesticides. The target value of N fertilization is 130 to 160 kg/ha, depending on yield expectations. Harvesting usually takes place from the 2nd year of growth. For example, a self-propelled forage harvester with a row-independent maize harvesting attachment can be used for this purpose (Hartmann et al., 2017). The shredded material serves mainly as silage substrate in biogas plants.

Rhizome cuttings are used for the establishment of new miscanthus stands, which are spread with a vegetable planter, for example (Fritz et al., 2009). Young plants can also be used (Becker et al., 2014). Plant density is usually 10,000 plants per ha (Fritz et al., 2009). Planting is done in early spring in a weed-free, sufficiently fine-crumbled and reconsolidated planting bed. Weed control during the establishment phase can be mechanical, but herbicides from corn and cereal crops can also be used. N fertilization at 50 to 75 kg/ha is usually sufficient. Harvesting takes place after the second year of growth in spring, when the stalks of the plants have completely dried. A self-propelled forage harvester with a row-independent corn harvesting attachment is also the method of choice here (Becker et al., 2014). The harvested material can be used for heating purposes, electricity generation, as a natural insulating material in house construction or as bedding.

### 2.4.3 Expected effectiveness

Annual arable crops, especially those with wide row spacing and slow youth development, carry the risk of soil erosion and nutrient leaching (Förster et al., 2020). In contrast, the cultivation of perennial crops (in this case: cup plant, miscanthus) enables not only a permanently closed ground cover but also the development of a deeper-reaching root system (Förster et al., 2020). Therefore, during dry periods, water supply from the subsoil can maintain the transpiration activity of the plants. Mulch application in established stands also suppresses evaporation and protects the upper soil layer from drying out. Surface run-off is reduced, water infiltration into the soil is improved, and wind erosion

*Figure 5: Miscanthus as an example of a permanent crop.*

is suppressed (Becker et al., 2014). Success of the measure occurs after the permanent crop is established, when the root system has developed and a mulch layer is formed.

### 2.4.4 Costs

**Opportunity Cost:** Opportunity cost is the difference in the profit of the maximizing crop rotation (SCR) and growing permanent crops. The profit is the difference between the sales revenue of the cultivated one-year arable crops and the cost of cultivating the cultivated one-year arable crops. To determine the profit of permanent crops, the annual cost of the permanent crop must be subtracted from the sales revenue of the cultivated permanent crop that occurs at the end of the perennial cropping period. To determine the opportunity cost for the total 30-year period, the sales revenue and the cultivation costs for the two rotations per acre per year must be compared. Future costs and revenues must be discounted.

Profits for the standard crop rotation are determined in the same manner like in the measure A-I-1. Revenues and costs of the permanent crops of cup plant and miscanthus consist of the costs in the year of planting, the revenues and costs in harvest years, and the costs of recultivation at the end of the life of the permanent crop. There are generally no additional costs in non-harvest years. According to KTBL, 2022, costs in the planting year consist of soil sampling, ploughing and harrowing, fertilizing, seeding or planting, plant protection measures, hoeing, mulching, and stand boning; in harvest years, they consist of soil sampling, fertilizing, liming, chopping or baling, and removal of the harvested crop; and in the case of recultivation, in addition to harvest costs, they consist of ploughing, plant protection measures, and irrigation, if necessary. The KTBL's output and cost calculator for crop cultivation KTBL, 2022 not only provides information on cost items, but also gives standard information on average yields and market prices. Yields of Miscanthus are to a large extent dependent on soil quality (H. Biertümpfel et al., 2011). Field trials indicate that sites with medium soil quality are most suitable for cultivation (Becker et al., 2014). The yield as a function of the number of acres is calculated analogously to the procedure for the standard crop rotation (see measure A-I-1, chapter 2.1). Since no statistical data regarding crop yields are available due to the vanishingly low occurrence of Miscanthus cultivation in the region, we follow scientific estimates that assume 13.5 tons of yield per hectare in the state of Brandenburg (Tavakoli-Hashjini et al., 2020). With an average soil value (Ackerzahl) of 33.8 (Ministerium Für Landwirtschaft, Umwelt and Und Klimaschutz, 2022), the state of Brandenburg has an approximately similar soil value as the Elbe-Elster district (32.8), so that the values for the entire state should also be valid for the Elbe-Elster district. Due to similar data, the procedure for calculating the yield of cup plant is analogous. Depending on soil quality, the yield amounts to 13 to 20 tons of dry matter per hectare (Paul, 2015; A. Biertümpfel, 2021). According to scientific studies, the yield in the first year of cultivation in the state of Brandenburg is 8.6 tons of dry matter per hectare with corresponding increases from the second year of cultivation (A. Biertümpfel & Conrad, 2013).

**Investment costs:** None

**Management costs:** None

#### 2.4.5 Synergy effects

Soil erosion is virtually eliminated by continuous vegetation, especially since crop residues and dead plant parts remain on the surface as a mulch layer (Förster et al., 2020). Long-term soil dormancy promotes humus build-up, and the measure can thus also contribute to climate protection (carbon sink). Permanent crops contribute to increasing the diversity of crops and habitats in the landscape. They thus expand the range of cover options and habitats for fauna in the agricultural landscape. For example, they can be attractive flowering plants for insects (e.g., cup plant) and provide nectar and pollen over a long period of time by flowering for several months (Hartmann et al., 2017). Permanent crops can also make better use of nitrogen in the soil, reducing the risk of leaching (Förster et al., 2020).

#### 2.4.6 Obstacles

The cultivation of permanent crops is usually less productive and inferior to breeding-optimized, conventional arable crops (Förster et al., 2020). In addition, yield performance depends on location and is strongly influenced by establishment success in the first year. Lower yields and revenue losses, e.g., compared to classic cereal or corn cultivation, can be the result. The establishment of a permanent crop is often not preferred on leased land whose availability is only assured for a short period of time. If lease terms are short and leased land changes frequently, there is a risk that investment costs will not be recouped. Depending on the crop cultivated, harvesting and profit can sometimes only be achieved after several years (e.g. for Miscanthus: first harvest from the third year of cultivation (Becker et al., 2014). In addition, the establishment of the permanent crop can be associated with considerable time and costs, especially on larger fields/cultivated areas (e.g. for Miscanthus: manual planting of rhizomes) (Fritz et al., 2009).

### 2.5 A-II-3: Permanent soil cover

#### 2.5.1 Aim of the measure

The measure is intended to prevent water and wind erosion and to promote the retention of precipitation water in the soil.

#### 2.5.2 Description and implementation

The crop rotation design significantly influences the duration and frequency of the occurrence of periods without or with reduced ground cover. Therefore, for the implementation of the measure, crop rotations suitable for the location are planned, which integrate crop types with close row spacing or have reduced ground cover only over short periods (table 2). Consideration was given to indications from Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie, 2008; Dobers et al., 2003; Technologie- und Förderzentrum, 2007; Thüringer Landesamt für Landwirtschaft und Ländlichen Raum, 2020; Bilau, 2017; Bayerische Landesanstalt für Landwirtschaft, 2006; Bayerische Landesanstalt für Landwirtschaft, 2016. Crops with wide row spacing or longer periods without or with reduced ground cover, such as silage maize or potatoes, were deliberately not included (tab. 2).

Intercrops are grown whenever possible and appropriate. The selection of relevant and site-suitable fear species for sites with a »Ackerzahl« (german soil quality index) smaller than 25 is limited. Winter oilseed rape reaches its lower limit

*Figure 6: The later catch crop is already sown under the grain.*

*Table 2: Crop rotations (WIC = winter intercrop, SZF = summer intercrop, Ackerzahl = German soil quality index)*

| Soil quality | Crop rotation elements and sequence |
|---|---|
| Ackerzahl <25 | Spelt - Green rye - Buckwheat - WIC - alfalfa - alfalfa – Winter rye - SZF - Winterroggen - Kleegras |
| Ackerzahl >=25 | Winter wheat – Winter barley- clover grass – Winter rape - WIC - sunflower |

of suitability for cultivation here, but was nevertheless taken into account in order to avoid an overemphasis on cereal species. In addition, for phytosanitary reasons, multi-year cultivation breaks must be observed when growing alfalfa and winter oilseed rape. The integration of alfalfa and clover-grass as a mixture for forage use serves to add humus, especially on the light sites, and also supports weed control in the crop rotation. The symbiontically fixed nitrogen can also be well utilized by the following crops. Intercrops can be sown, for example, with a slug pellet spreader mounted on the disc harrow or cultivator used for stubble ploughing. Seeding of cereals, legumes, legume-grass mixtures and buckwheat is done as band seeding with mechanical or pneumatic drills. Sunflowers are sown using single-grain technology with the closest possible row spacing. Winter intercrops are incorporated before alfalfa or sunflowers in the spring using a disc harrow or cultivator.

To save time and costs, intercrop seeding can be done at the same time as stubble tillage following harvest of the main crop. In this case, tillage measures that result in increased water loss should be avoided. Low-cost catch crops such as mustard or oil radish or mixtures with several plant species are suitable.

### 2.5.3 Expected effectiveness

A change in precipitation distribution (higher precipitation in winter months) and more frequent heavy precipitation events in spring and summer increase the risk of water erosion, especially on uncovered agricultural soils and when growing slow-growing and low-cover row crops such as potatoes, corn, or sugar beets. The period of highest erosivity for individual precipitation in Germany is between May and September (Brunotte et al., 2016). However, increased run-off can also be expected in winter when high-yield precipitation hits insufficiently covered soil. In this context, the degree of soil cover can regulate erosion effects as well as surface run-off (Blume et al., 2011). As soil cover increases, the erosion hazard is reduced.

The risk of wind erosion is particularly significant during periods of low or no soil cover, for example between tillage and sowing until after the crop has emerged and at the same time there is high wind, especially in spring when tilling corn, potatoes or sugar beets. According to J. Brunotte, 2007, a soil cover of 50 % reduces soil erosion by up to 95 %. Intercrops grown early after the main crop has been harvested (including freezing) provide higher soil cover in the winter months when summer crops are planted later and can promote water retention until the beginning of the next growing season.

The protective effect against water erosion is already achieved with more than 30 % uniform soil cover. However, the effective efficiency, i.e. the possible water retention on the surface, also depends on various factors such as the topography, the soil type, possible harmful compaction, the cultivated crop or the general management, as well as the duration and intensity of the precipitation event. In sprinkler trials on loess soils (70 mm $m^{-2}$), undersowing was found to decrease surface run-off from 36 to 12 %, which arithmetically corresponds to a water retention of 168 $m^3$ per ha.

### 2.5.4 Costs

**Opportunity costs:** In the permanent land cover measure, the main opportunity costs for farms are in the form of economic losses due to changes in crop rotation. Instead of cultivating cropland with crop rotations that maximize profit farmers plant crops that cover cropland over longer periods but also generate less revenue per acre. To determine the opportunity cost for the total 30-year period, the sales revenue and cultivation costs for the two rotations per hectare per year must be compared. Future costs and revenues must be discounted.

Revenues and costs of the profit maximizing crop rotation and the permanent land cover measure are calculated with the method and based on data sources described in measure A-I-1, chapter 2.1.

**Investment costs:** None

**Management costs:** None

### 2.5.5 Synergy effects

If soil loss due to erosion can be reduced or avoided, the preservation of soil fertility and yield capacity of agricultural land is promoted. Intercrops and undersown crops stabilize the soil structure by forming a dense root system and thus make the soil more load-bearing overall, which means that load inputs, e.g. for harvesting the cover crop, have a less invasive effect and can counteract harmful compaction. This is particularly effective on sandy sites with rather low structural stability. Nutrient losses through leaching are reduced. Clover species and alfalfa can serve as pollen and nectar sources for numerous insects.

### 2.5.6 Obstacles

The cultivation of catch crops is possibly (depending on the farm's crop rotation design and the available technology) associated with additional costs and operations or machinery use. In early autumn, working time may be lacking if the harvest and the new cultivation of main crops on other fields have to be carried out at the same time. A late main crop harvest due to weather-related delays in ripening can prevent intercropping. In regions with low precipitation or pronounced spring drought, the water consumption of the catch crop can jeopardize the cultivation of the following main crop.

### 2.5.7 Stakeholders

Farmers

## 2.6 A-III-1: Conservation (non-turning) tillage

### 2.6.1 Aim of the measure

Mulching and no-till reduce unproductive evaporation from the upper soil layers and improve water infiltration and soil aeration. This is accompanied by deeper and more intensive rooting.

*Figure 7: Mulch and no-till can help improve the water balance of crops.*

### 2.6.2 Description and implementation

By using non-turning tillage implements (e.g. cultivator, disc harrow) or by direct seeding, the soil structure in the topsoil is preserved and more crop residues remain on the soil surface as a soil-covering mulch layer or these are only incorporated at shallow depths. By largely preserving the pore system, undisturbed water infiltration is ensured, which simultaneously reduces surface run-off and water erosion. During heavy precipitation events, more water can thus be absorbed into the soil and ultimately retained on the surface. The measure should achieve a soil cover with plant residues of at least 30 %. Macropores can form (deep burrowing earthworms, deep reaching dead plant roots) and remain for a long time. This allows more precipitation water to reach deeper soil layers. The development of compacted tillage bottoms can be counteracted by annually changing tillage depths in no-till tillage (Epperlein & Ellmer, 2006).

For effective field weed control (without increased use of total herbicides), post-emergent crops and germinating weeds can be cut off a few millimetres below the soil surface with appropriate technical equipment (e.g., cultivator with goosefoot share). This leaves organic material close to the surface and the weeds dry out quickly and die. Leaving a sufficiently thick mulch cover (> 70 dt DM $ha^{-1}$) can also effectively suppress weeds.

The need for a crop rotation adapted to the needs of conservation tillage is pointed out by Dobers et al., 2003. Crop rotation elements are combined under different aspects. As objectives of the crop rotation design can be named: Weed control, disease/pest control, soil loosening by roots, humus supply, nitrogen accumulation, better utilization of organic fertilizers, avoidance of yield depression by fertilizers or pesticides, labour compensation, utilization of site yield potential, and yield maximization. In addition, purely practical considerations regarding the harvest dates of the previous crop and the optimum sowing date for the following crop play a role. Based on this, crop rotations were developed for conservation tillage in the Elbe-Elster district (table 3), which basically take into account the different conditions of the site. Notes from Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie, 2008; Dobers et al., 2003; Technologie- und Förderzentrum, 2007; Thüringer Landesamt für Landwirtschaft und Ländlichen Raum, 2020; Landesanstalt für Landwirtschaft, Forsten und Gartenbau Sachsen-Anhalt, 2014; Landwirtschaftliches Technologiezentrum Augustenberg, 2018 were taken into account.

In the crop rotation design, cereals were not

*Table 3: Crop rotations for non-turning tillage (SZF = summer catch crop, WCC = winter catch crop, Ackerzahl = German soil quality index).*

| Site quality | Crop rotation elements and sequence |
|---|---|
| Ackerzahl <25 | Winter rye – WCC – Silage corn – Spelt – WCC – Silage corn – WCC – Blue lupin |
| Ackerzahl >=25 | Winter barley – Winter rape – Winter wheat – WCC – Silage corn – WCC – Field pea |

planted just after cereals in order to avoid the growth of foreign cereals in the subsequent crop. Grain peas and blue lupin are legumes and fix atmospheric nitrogen with the help of nodule bacteria. As a result, nitrogen fertilization is usually not necessary. A total of 50 to >200 kg N/ha can be fixed, of which 40 to 150 kg N/ha remains available to the subsequent crop (Landesanstalt für Landwirtschaft, Forsten und Gartenbau Sachsen-Anhalt, 2014). However, a cropping break of 4 to 5 years is necessary for these crops for phytosanitary reasons.

Maize, peas and lupins are usually sown using precision seeding techniques, whereas cereals and canola are sown using band seeding. Cultivators or disc harrows can be used for tillage during stubble fall and for seedbed preparation.

### 2.6.3 Expected effectiveness

Conservation tillage can result in higher soil moisture and lower evaporation than conventional turning tillage with the plough (Blevins et al., 1983; Copec et al., 2015). In field studies, a higher matrix potential was found in the soil under mulch and no-till (compared to ploughed soil). The mesopores of the upper soil layers dried out less frequently after mulch and no-till (Düll & Flaig, 2014; Flaig & Schickler, 2012). Also in deeper soil layers (up to 0.4 m depth), higher water contents were found with mulch seeding. The mulch layer of dead plant residues present in mulch and no-till helps to reduce unproductive evaporation from the upper soil layers. In addition, due to the lack of compaction layers, such as plough horizons and a higher proportion of earthworm burrows, the water infiltration rate on sites with conservation tillage is significantly higher than with ploughing (Chervet et al., 2006).

The measure may only show a significant effect after many years of application and depends on the soil condition (soil type, humus, pre-existing pedogenic and geogenic impairments) and the implementation by the farm. The activity of soil organisms creates water-stable aggregates, which result in an improvement of water infiltration and improved soil aeration (Epperlein & Ellmer, 2006). Plants react to this with deeper and more intensive rooting. The influence of conservation tillage on yields is not uniform. As a rule, the yields of turning and conservation tillage do not differ on average in the long term. However, Epperlein & Ellmer, 2006 found, for example, that forage peas yielded about 9 % less with mulch tillage than with ploughing.

### 2.6.4 Costs

**Opportunity costs:** The opportunity costs consist of the profit between the profit maximizing crop rotation – the so-called standard crop rotation (SCR) – and the crop rotation of non-turning tillage (NWB). For details on calculating the profit of the standard crop rotation, see measure A-I-1, chapter 2.1. The profit of the non-turning tillage is the revenue of the alternative crop rotation minus the costs. The costs of SCR and NWB differ in that costly tillage steps can be saved with non-turning tillage in NWB. However, reduced tillage requires more plant protection measures that increase costs. KTBL, 2022 shows the differences in the tillage steps and the associated costs in the cost and performance calculator for crop cultivation.


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**Investment costs:** None

**Management costs:** None

### 2.6.5 Synergy effects

Securing yields by preserving soil fertility. Surface run-off is avoided or reduced through better/faster water infiltration and the mulch application. The less soil is lost to erosion, the more fertility and water holding capacity is retained, which ultimately has a lasting positive effect on the yield capacity of the area.

Soil protection through stable soil structure - load inputs have a less intensive/invasive effect and cause less harmful compaction. On the one hand, this has positive effects on water infiltration and also reduces surface run-off. On the other hand, plants can root deeper and make better use of soil water if compaction in the topsoil or below the topsoil is minimized or avoided.

Promotion of soil biology through less invasive soil intervention (increase in earthworm activity) in the upper soil layers (Krauss et al., 2020). This form of tillage requires less labour and energy.

### 2.6.6 Obstacles

Mulch application can result in delayed drying and slower warming of the land in spring. The soil must be sufficiently dry for technical equipment to be able to drive over it (higher load-bearing capacity and less susceptible to compaction). Soil temperature requirements of the seed (depending on the crop) must be met for germination.

Alternative methods of field weed control and crop protection measures become necessary, such as efficient mechanical weed control measures, crop rotation adjustment, and straw management. Effective mechanical weed control (e.g. using a cultivator) requires a surface that is as plane as possible with shallow and precise depth control.

Possible increased conversion costs (3 to 5 years) and possibly lower yields at the beginning would have to be compensated by financial incentives. Financial advantage of no-till only occurs if yields are comparable and if equipment no longer needed is disposed of by the farm after conversion.

### 2.6.7 Stakeholders

Farmers

## 2.7 A-III-2 Organic fertilization

### 2.7.1 Aim of the measure

Through the continuous application of organic matter with a high humus production value (especially compost, manure, straw) and the use of novel soil amendments based on biochar and biochar substrates, the water retention capacity in the topsoil of arable land is improved. This can delay desiccation in water shortage situations, thus ensuring longer-lasting transpiration and thus also the cooling capacity of the arable crop.

### 2.7.2 Description and implementation

Sandy soils are mostly characterized by a high proportion of macropores, which are responsible for aeration and water infiltration. In contrast, the proportion of mesopores, which determine the usable field capacity of the soil, is comparatively low, which is why soil water storage is often severely limited compared to silty soils. If there is an additional lack of water-storing soil organic matter, drought stress and a decrease in the transpiration capacity of plants can quickly occur, especially in the case of less deep-rooted crops and low groundwater tables, if precipitation is absent for a long time and the upper soil layers dry out. Organic matter indirectly influences the pore size distribution through its aggregating effect (Schindler, 1989) and thus determines the water storage capacity (field capacity), especially in soils with a high sand content.

Soils used for arable farming basically contain less carbon compared to soils under natural vegetation, because tillage leads to a reduction of the carbon content by up to 40 % (Christopher Poeplau, 2014). The goal of the measure is to increase the amount of long-term stable humus in the soil by adding organic matter. When the supply level


*Figure 8: Various feedstocks such as manure, compost and biochar (substrates) can be considered for organic fertilisation.*

of soils with organic matter is increased, an improvement in soil water storage can be expected (Weber et al., 2007).

Compost has a high proportion of humus-active organic substances due to its comparatively wide C/N ratio, in contrast to fermentation residues or liquid manure, and is therefore preferable to other organic fertilizers. Digestate from biogas plants and liquid manure also contribute less to humus formation, as the permissible application rates are severely limited by the high nitrogen and phosphorus contents (Ehnts, 2018).

Following the example of terra preta, especially in soils with a coarse-grained texture, a positive influence on the hydraulic properties can alternatively be expected by adding stable carbon compounds. In addition to porous biochar obtained by pyrolysis from plant biomass or residues, biochar substrates produced with these by fermentation and/or composting are also suitable for this purpose. The application, similar to a fertilizer measure, can be carried out after delivery, for example, using on-farm compost or manure spreaders. The soil amendment of choice is then incorporated in a way that is gentle on the soil. The measure can be repeated at intervals of several years.

Crop rotations for the implementation of the measure were developed for the site conditions in the Elbe-Elster district (tab. 4). Notes from Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie, 2008; Dobers et al., 2003; Technologie- und Förderzentrum, 2007; Thüringer Landesamt für Landwirtschaft und Ländlichen Raum, 2020; Landesanstalt für Landwirtschaft, Forsten und Gartenbau Sachsen-Anhalt, 2014; Landwirtschaftliches Technologiezentrum Augustenberg, 2018 were taken into account.

Soil preparation for sowing can be done in the usual way, i.e. either with non-turning implements such as a heavy cultivator or turning with a plough.

### 2.7.3 Expected effectiveness

Efficacy depends on the quality and quantity of soil amendments used. Fertilization with compost generally has a positive effect on aggregate stability, reduces bulk density, and leads to an increase in pore volume and an increase in water storage capacity, especially on sandy soils (Kolbe, 2012; Fuchs et al., 2004). In cohesive soils, a reduction in bulk density can result in better aeration and water infiltration into the topsoil. Compost can store about five times its own weight in water (Ehnts, 2018). The application of compost also leads to an increase in organic carbon content in the topsoil (Mayer, 2004). For example, one ton of compost (FM) provides about 70 kg of humus-C (Fechner, 2014), which is creditable

*Table 4: Crop rotations for organic fertilization (SZF = summer catch crop, WCC = winter catch crop, Ackerzahl = German soil quality index).*

| Site quality | Crop rotation elements and sequence |
|---|---|
| Ackerzahl <25 | Winter rye – WCC – Silage corn – Spelt – WCC – Silage corn – WCC – Blue lupin |
| Ackerzahl >=25 | Winter barley – Winter rape – Winter wheat – WCC – Silage corn – WCC – Field pea |

for humus reproduction in the soil.

However, the potential of soils to store carbon in the long term is limited (Wiesmeier et al., 2017). Organic matter is subject to constant microbial degradation in the soil. Depending on changes in land management, an equilibrium between supply and degradation is established after a certain period of time. Clay-humus complexes are able to stabilize humus against degradation. However, the soils in the Elbe-Elster district predominantly have rather low clay and silt contents. Zimmer, 2020 also state that the effect of arable measures is limited and annually expected changes in carbon content are smaller than 0.1 %. Brunotte et al., 2016 point out that the humus contents found in arable soils are a result of site and management factors. In addition, management measures, such as organic fertilization, influence the humus content with a share of only 5 - 30 %, whereas about half of the content is due to boundary conditions of climate and weather.

### 2.7.4 Costs

**Opportunity costs:** Costs arise from the application of compost and/or biochar substrate. If compost is not available on-farm in sufficient quantities, compost or biochar substrate must be purchased from local waste disposal associations at appropriate prices and transported to fields at additional cost. As a rule, another operation is also required by the mechanical distribution of the organic manure on the fields, since organic manure does not usually completely replace mineral fertilizers. (KTBL, 2022) publishes data on the costs of the work step. In the long term, organic fertilization can lead to improved soil quality and better yields. However, we lack data for the situation in the case study area and yield effects are case-specific and cannot be generalized. According to an evaluation of 325 individual case results, the yield effects of biochar substrates are low (Haubold-Rosar et al., 2016; Luyten-Naujoks, 2017). For this reason and due to the fact that humus accumulation only takes place in the very long term (Zorn & Schröter, 2015a; Sächsisches Staatsministerium für Energie, 2015), the influence on yields is not considered in the calculations here.

**Investment costs:** None

**Management costs:** None

### 2.7.5 Synergy effects

Humus or organic soil matter acts as a store for nutrients (especially nitrogen, sulfur and phosphorus), which become available through microbial mineralization processes and thus serve plant nutrition. This can improve the yield capacity of the site as well as the quality of the products produced (Körschens, 1997; Dreymann et al., 2003; Benkenstein et al., 2008; Rößler et al., 2015; Zorn & Schröter, 2015b). The application of compost or soil conditioners helps to close material cycles in the sense of the Closed Substance Cycle Waste Management Act and thus supports sustainable resource management. As described above, reduced soil compaction allows plants to root deeper and make better use of soil water.

Compost is also an organic fertilizer in its own right. Its content of total nitrogen is about 1.1 to 1.5 %, depending on the origin of the raw material and its composition (M. Schulz et al., 2018).

The contents of phosphate ($P_2O_5$) and potassium ($K_2O$) are 0.6 % and 1.1 %, respectively (Hermann et al., 2017). 30 t DM of compost contain 444 kg of pure nitrogen at an assumed N content of 1.48 % (M. Schulz et al., 2018). According to DüV, 5 % of this can be taken into account in the nutrient balance for other composts as having an effect on plants in the year of application, i.e. 22 kg. For the three subsequent years, deductions of 4 % in the first subsequent year and 3 % in each subsequent year of the amount of total nitrogen applied with the compost must be taken into account. Additional mineral fertilizer applications to supply nutrients to the cultivated crops must be reduced accordingly.

A positive effect on the yield of crops can be assumed in principle on the basis of the effects of organic matter described above, but a blanket quantification is probably not possible, since the effect depends on many factors, such as the initial humus content before the start of the measures, the type and intensity of soil cultivation, or the clay and silt content at the specific site.

### 2.7.6 Obstacles

The maximum possible application rates of compost are limited. According to §6 of the Biowaste Ordinance (BioAbfVO), up to 30 t of dry matter compost may be applied within 3 years. In addition, according to §6 Fertilizer Ordinance, when compost is applied, the total amount of nitrogen applied in three years must not exceed 510 kg ha-1 on farm average. In addition, fertilizer application must be based on the actual needs of the crop. If low yields are expected and the soil is already well supplied with P, for example, this will result in correspondingly low possible compost applications, since the P content in the compost is counted as 100 % when determining fertilizer requirements. Livestock farms and/or farms supplying a biogas plant are faced with the problem that the manure produced (liquid manure, digestate) can be combined with compost, but the annual N limit of 170 kg/ha must be complied with. If high amounts of farm manure are produced on a farm, this restricts the possible application rate of compost, as manure is usually used first on farms with high livestock numbers. Conversely, the farms would have to create/hold larger storage capacities for the manure produced in order to be able to apply correspondingly higher quantities of compost.

If no RAL (Deutsches Institut für Gütesicherung und Kennzeichnung e.V.) quality-assured composts are used, there is an obligation to have the soils in question tested for their heavy metal content and pH value before using compost for the first time. Depending on the size of the area to be used for composting, these tests may involve considerable costs. The dark color of humus increases the heat adsorption of the soil, which can lead to faster heating and higher water losses through evaporation.

The amount of compost available is limited. At the composting plant in Freienhufen (Brandenburg, Germany), about 5,000 t fresh matter of compost are produced annually from organic waste garbage cans originating from the association area of the Schwarze Elster waste disposal association (Dutschmann, oral communication, 20.05.2021). Two-thirds of the biomass delivered comes from the Elbe-Elster district. About 80 % of the compost is currently utilized in agriculture, i.e. 4,000 t fresh matter. Assuming an application rate of 20 t dry matter/ha at intervals of 3 years and an assumed dry matter content of 60 %, 120 ha per year or within 3 years a backdrop of a total of 360 ha of arable land can thus be supplied with compost.

Biochar is produced from organic feedstock, originally by pyrolysis, in the absence of air at temperatures between 400°C and 1100°C (Möller & Höper, 2015). Water is split off in the process. With increasing pressure, higher temperatures or longer residence time in the reactor, the stability of the biochar produced is increased compared to mircobial decomposition. In addition, there is the process of hydrothermal carbonization (HTC), which takes place at high pressures and lower temperatures. HTC carbon differs from pyrolysis carbon and is less permanently stable in soil. Biochar is further processed into biochar products, mixing with other organic materials such as compost, green grit, or digestate. Due to production costs, the application of novel soil amendments based on biochar and biochar substrates in agriculture is significantly more expensive than the use of mineral fertilizers. In addition, it can be assumed that comparatively high application rates are required for effective improvement of soil water storage (biochar substrates: > 30 t $ha^{-1}$). Furthermore, the variety of possible source materials and properties of biochar makes a uniform evaluation with respect to different soil functions difficult. At the beginning of the measure, the wide C/N ratios may also result in N fixation at the soil amendment, which may lead to an increased N fertilizer requirement or initially lower yields.

### 2.7.7 Stakeholders

Farmers, municipal associations, SMEs in the supply and disposal sector, producers and distributors of soil amendments.

## 2.8 A-III-3: Slope parallel management

### 2.8.1 Aim of the measure

Cross-field cultivation tracks that run across the slope create small, damming barriers that promote area-wide small-scale surface water retention.

### 2.8.2 Description and implementation

Instead of tilling in the direction of the slope, tillage of the field is done across the slope, creating swale and rill structures that can provide resistance to surface run-off and thus improve water infiltration. The measure is suitable for slopes with a maximum slope of 15 % and a width of up to 100 m; the risk of water breakthrough and gully erosion generally increases on slopes > 15 % (Billen & Aurbacher, 2007). If the slope length in the direction of the main slope is longer than the critical slope length ($HL_{krit}$), which depends on the slope gradient (HN), breakthrough of cross structures by surface run-off is to be expected. The critical slope length can be calculated using the following formula (Auerswald, 1992),

$$HL_{krit} = 170 \cdot e^{-0{,}13 \cdot HN} \quad (2)$$

and decreases with increasing slope. However, a significant increase in water infiltration can only be expected for slopes < 9 % (Seibert & Auerswald, 2020). The measure is easier to implement in agricultural practice than the methodologically related contour management. When planning, it should be noted that disadvantages arise with regard to management if the length of the field is significantly shortened compared to the original direction of cultivation. Another prerequisite is that the field can be accessed or driven over via field or farm roads parallel to the slope.

### 2.8.3 Efficiency

The effectiveness is difficult to determine on a large-scale measure, but modelling assumes a reduction in surface run-off of about 5 %. The measure is particularly effective in conjunction with mulch seeding and when the erosively effective slope length is small (Billen & Aurbacher, 2007).

### 2.8.4 Costs

**Opportunity costs:** Due to the change in the direction of cultivation, cross-field cultivation increases the amount of work and time required and thus also the use of machinery. In principle, the amount of additional process costs is case-specific and depends on the concrete conditions on site. For reasons of operationality in the calculation of opportunity costs, we apply a flat rate increase of 5 % of the process costs. Expert discussions revealed that an increase in costs of 5 % on average can be expected.

**Investment costs:** None

**Management costs:** None

### 2.8.5 Synergy effects

Mitigation of surface run-off counteracts soil erosion and thus promotes the preservation of soil fertility and yield capacity of agricultural land.

*Figure 9: Ploughing with the slope increases erosion – therefore tillage should be transverse to the slope.*

#### 2.8.6 Obstacles

When cultivating potatoes and sugar beets on slopes > 15 %, sowing and harvesting problems are to be expected. Yield and quality losses may occur, which may have to be compensated financially. Long-term average yields can serve as a guide. If there are no lateral access roads in the direction of the slope, there will be more crossings of the lateral edge areas of the field (headland), especially during the recovery and removal of harvested material, which is associated with higher overall load inputs and greater compaction of the soil. More work and time can be required if the length of the field is considerably shortened by changing the direction of cultivation.

#### 2.8.7 Stakeholders

Farmers, contractors

### 2.9 A-IV-1: Cultivating deep-rooted crops

#### 2.9.1 Aim of the measure

Cultivating crops with deep root system enables the use of water reserves in the subsoil and also ensures plant transpiration when precipitation fails and the water reserve in the topsoil is depleted.

Description/implementation The water supply of plants depends not only on the available water in the root zone of the soil, but also on the ability of plant roots to reach subsoil horizons. The latter is influenced by site-specific factors such as the rootability of the soil space (plow soil compaction, highly cohesive soil layers) and the genetic characteristics of the cultivated plants.

Shallow-rooted crops such as potatoes, spring barley and field bean draw soil water only to depths of 0.9 to 1.5 m, and even the roots of grasses hardly reach deeper than 0.5 m (Blume et al., 2010). Water replenishment from shallow groundwater may also benefit only deep-rooting arable crops. According to Blume et al., 2010, these include winter wheat, winter rape, sugar beet and alfalfa in Central Europe. However, the actual rooting depth is always also site-dependent. Depending on the rootability of the soil, alfalfa already reaches a depth of 1.5 to 1.8 m in the first year and can penetrate two to three meters deep into the soil with its taproot in the following years (Langer, 1968; Jung, 2003), whereby a water supply can also be guaranteed from the deeper subsoil. In the third main year of use, a finely branched fine root system was also observed down to a depth of 2 m (Frühwirth, 2019). Sunflowers can reach a rooting depth of up to 5 m, depending on the variety (Schuster & Marquard, 2003). Specific crop rotations adapted to the site conditions in the Elbe-Elster district are planned to implement the measure (tab. 5). Notes from Sächsisches Landesamt für Umwelt, Landwirtschaft und

*Figure 10: Alfalfa is an example of a deep-rooting crop.*

Geologie, 2008; Dobers et al., 2003; Graf et al., 2013; Peyker et al., 2013; Frühwirth, 2019; Jentsch et al., 2016 were taken into account. However, the selection diversity of suitable deep-rooted fruits for the weaker sites is limited in this case. Silage maize, while not generally considered a deep rooter, can establish roots through to depths of 1.5 m and beyond.

On both sites, a two-year cultivation of alfalfa takes place after silage corn and sunflower, respectively. Alfalfa is sown in early spring after the winter catch crop is incorporated and remains on the site for two years. Alfalfa and winter oilseed rape are deep-rooted crops. Oilseed radish is recommended as a deep-rooted winter intercrop as well.

Tillage can be done with non-turning equipment (cultivator, disk harrow or combinations) or turning with a plough. For subsequent seeding of winter cereals, canola or alfalfa, a seeding combination can be used for simultaneous seedbed preparation and seeding. Corn, sunflowers, and sugar beets are seeded with a precision drill, which is generally not equipped with seedbed preparation tools, so a seedbed preparation operation using a fine cultivator, short disc harrow, or similar suitable equipment must be scheduled beforehand.

The winter intercrop is incorporated in the spring with a disc harrow, cultivator or plough. The ploughing of alfalfa before sowing winter rape immediately after the last harvest of the emergence in summer (usually in early August).

### 2.9.2 Expected effectiveness

The effectiveness of the measure in terms of transpiration is determined by the amount of plant-available water in deeper soil layers, the rootability of the soil and the influence of groundwater.

### 2.9.3 Costs

**Opportunity costs:** The measure differs mainly by the changed crop rotation. Accordingly, the profit between the standard crop rotation and the crop rotation of deep-rooted crops is to be considered as opportunity costs. The calculation is analogous to the procedure described e.g. in the measure A-I-1 (chapter 2.1) and using KTBL data (KTBL, 2022).

**Investment costs:** None

**Management costs:** None

### 2.9.4 Synergy effects

Deep-rooted plants can retrieve nutrients shifted to deeper soil layers from the topsoil. Subsoil rooting creates macropores through which seepage water can infiltrate faster and deeper into

*Table 5: Crop rotations for deep rooted crops (SZF = summer catch crop, WCC = winter catch crop, Ackerzahl = German soil quality index).*

| Site quality | Crop rotation elements and sequence |
|---|---|
| Ackerzahl <25 | Winter rape - Winter rye - WCC - Silage corn - WCC - Alfalfa - Alfalfa |
| Ackerzahl >=25 | Winter rape – Winter wheat - WCC - Sugar beet - WCC - Sunflower – WCC - Alfalfa - Alfalfa |

the soil, which can ultimately benefit groundwater recharge as well as replenish deep soil water supplies.

#### 2.9.5 Obstacles

If shallow-rooted crops such as potatoes are completely omitted from the crop rotation, this can have economic disadvantages.

#### 2.9.6 Stakeholders

Farmers

### 2.10 A-V-1: Afforestation of marginal arable land

#### 2.10.1 Aim of the measure

Since forests have higher year-round evapotranspiration than croplands, they help to cool the landscape.

#### 2.10.2 Description and implementation

In an afforestation, trees are planted on an area previously used for agriculture in order to create a permanent forest as defined by the Forest Act. The arable status of the area is thereby lost. The distinction from short rotation plantations, which are not regarded as forest, occurs through the much longer rotation periods of forests of 80 to 200 years and the associated species composition.

Afforestation in accordance with §9 of the Brandenburg State Forest Act requires official approval. In Brandenburg, the responsible lower forestry authority (Oberförsterei) in the area is the point of contact; in the Elbe-Elster district, these are the Oberförstereien Herzberg and Hohenleipisch. In the procedure, the responsible lower nature conservation authority is involved as a public concern in accordance with §5 LWaldG.

In principle, stakeholders have a free choice of tree species for afforestation. Specifications from the management of the state forest do not apply here. However, restrictions may arise from the statement of the lower nature conservation authority. Furthermore, in the case of a possible intended certification, the corresponding specifications for the use of tree species must be observed (FSC Deutschland, 2020; Deutschland, 2020), for example with regard to the use of non-native tree species.

It is worth considering the stand target types for the forests of the state of Brandenburg (Luthardt, 2006) when selecting species in order to make a selection that is appropriate for the site and to ensure the development of long-term stable forest stands based on scientific knowledge and experience of the forestry institutions. Different main tree species are assigned to the respective stand target types, which are combined with other tree species depending on groundwater influence and nutrient level. Stand target types that come close to a natural forest structure should be preferred. The district Elbe-Elster is located in the area of the climatic zones moderately dry and dry. Depending on the climate zone and stem site form group, different stand target types for marginal terrestrial sites can be considered for orientation.

Marginal sites are not subject to a uniform definition. Agricultural lands with Ackerzahl (German soil quality) below 23 are classified as Marginal Site (Landbaugebiet) V according to H. Hanff, n.d. The measure targets these areas

 *Hildmann, Zimmermann, Schlepphorst, Rösel, Kleinschmidt, Kruber, Lukas, Joshi, Hecker, Witt, Sturm, Wätzold 2022, DOI: 10.5281/zenodo.6811079*

*Figure 11: Impression of reforestation with oaks.*

because they are where the lowest yields of agricultural crops are achieved nationwide as part of good agricultural practice. However, a direct translation of the site conditions of agricultural land into the forest site information needed to derive stand target types is not straightforward. Historically, the description and weighting of site conditions on cropland and in forests were based on different assumptions and methods. However, the range of eligible tree species is limited. Marginal agricultural sites are assigned here to the range of moderately nutrient-rich forest sites as a general rule. These sites are used for agriculture, among other things, because there is some site-specific preference over the fairly poor and poor forest sites.

Stand target types with common pine are assigned to poor and rather poor as well as dry and medium fresh moderately nutritious sites (Luthardt, 2006). Planting of European larch, Douglas fir, red oak, and black locust is not recommended here for ecological reasons. Due to physiological limitations (lack of shading on afforestation areas), we exclude common beech as the main tree species with more than 90 % share in the stand. Thus, we propose a composition of sessile oak (*Quercus petraea*), common beech (*Fagus sylvatica*) and hornbeam (*Carpinus betulus*) in equal proportions.

The use of suitable planting material and thus the assurance of origin is of particular importance due to the long lifecycle of the forest trees. Only approved propagation material from the area of origin in which the afforestation area is located should be used. In addition, tested source material should preferably be used, as it has proven its superiority in the relevant growth characteristics. Preference should be given to rooted fresh plants that have been dug up immediately before transport to the area (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung des Landes Brandenburg, 2004). Different assortments are available depending on the tree species and can be obtained from regional forest nurseries. For example, for oaks, 1-year-old oak seedlings (0.15-0.30 m growth height) or 2-year-old bolted plants (0.3 to 0.6 m shoot length) are well suited. Planting density should not be less than 6,000 plants per hectare. Other secondary tree species, such as lime or maple species, can be mixed in.

The forest edge should consist of native shrubs and woody plants. For concrete implementation, please refer to the measures sheet on landscape structure elements. It is strongly recommended that the entire afforestation area be fenced to protect it from game browsing.

### 2.10.3 Expected effectiveness

Forests have higher evapotranspiration compared to arable crops due to, among other things, their large total leaf area and the year-round interception of the canopy and bark. As a result, the amount of seepage under forests is lower than under agricultural land tilled with annual crops. Due to their higher evapotranspiration capacity, forests contribute to the cooling of the landscape.

### 2.10.4 Costs

**Opportunity costs:** Opportunity costs arise from the fact that no more yields can be obtained on land that is converted from arable land to forest. These lost profits have to be offset against the profits generated by the alternative use of the land as forest for the period under consideration of 30 years (for details on profit calculation of the standard crop rotation (SCR), see measure A-I-1, chapter 2.1). To determine the profits of forest management, the discounted present values of the costs must be deducted from the forest yields. Yields can be determined in a time-dependent manner by calculating yield characteristic value calculators of the Brandenburg State Forestry Office (LFB) in a standardized manner for the most important tree species in Brandenburg depending on the area credit rating (LFE, 2001). With an observation period of 30 years, it should be noted that due to the long lifetime of a forest of up to 200 years, yields usually arise only far in the future after the observation period of 30 years, for example through plenter or femel operation. This future increase in value must be discounted accordingly and included in the profit calculation. As this is an afforestation, we assume that, except for thinning measures, which usually take 5-10 years and may already lead to timber yields (Heymann, 2022), no timber is felled for marketing in the first 30 years. Accordingly, there are no significant costs for felling and harvesting timber.

**Investment costs:** Investment costs are incurred at the beginning of afforestation and consist of material and labour costs for planting. Planting costs depend on the type and age of the seedlings and their number. Many tree nurseries show prices for the individual seedling tree species online (e. g. Forstbaumschule, 2022; Paulownia Baumschule Schröder, 2022) or are available on request (e. g. tree nurseries of Landesbetrieb Forst Brandenburg, 2022b). The actual number of seedlings depends on the composition of the forest (Sachsenforst, 2016a). In addition, it must be taken into account that 400 m² per hectare are omitted due to the distance requirement of 1 metre to agricultural land and 2000 m² due to the 5 metre shrubs at the forest edge (for details see description of the measure). Labour costs are also incurred during planting. Alternatively, afforestation with seed is cheaper, especially for the expensive sessile oaks and hornbeams (Sachsenforst, 2016a). In addition, a fence against browsing by game should be built and the costs for creating a strip should be taken into account (for details on the cost calculation, see the measure A-I-2, chapter 2.2).

**Management costs:** For afforestation, there are ongoing costs for young stand maintenance in the form of thinning measures every 5 to 10 years, possibly removal of fencing after 3 years. Costs incurred are calculated according to the standard procedures given in the literature, taking into account the average expected labour and material costs for maintenance (Sachsenforst, 2016a; Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft, 2021).

### 2.10.5 Synergy effects

Forests make a significant contribution to reducing or preventing soil erosion as they form a natural barrier for surface water run-off and provide permanent ground cover. They are a natural wind barrier and, like hedgerows, can help improve the microclimate on upwind adjacent agricultural land. Purely beyond their influences on the water balance, forests with a native tree species composition have multiple ecological functions and also serve recreational purposes.

### 2.10.6 Obstacles

Shading and root competition from forests can negatively impact the emergence of cultivated field crops in close proximity.

### 2.10.7 Stakeholders

Landowners (farmers), landscape planners, public authorities / local authorities (municipalities), forestry authorities.

# 3 Land use category: Forestry

## 3.1 F-I-1: Reforestation

### 3.1.1 Aim of the measure

The objective of the measure is to reforest forest stands with site-adapted tree species, which were severely affected by natural disturbances such as storms, droughts, insect infections or forest fires. As an indicator for a severe disturbance, a change in crown closure of ≥ 25 % in the period from 2015 to 2018 was chosen. This measure is also recommended for small clearings after tree harvest.

### 3.1.2 Description and implementation

If forest stands are severely affected by windthrow, drought, forest fire, or pest infestation, replanting should be done with site-adapted tree species. Preferably, natural regeneration is used. If this is not sufficient, or in the case of large areas, direct seeding is preferable to planting. Additional costs may be incurred if action is not taken immediately after the calamity and the stands become grassy or boggy (e.g. blackberry). In this case, competition from grasses and shrubs must be reduced using appropriate methods (brush cutters, etc.), often repeatedly until the new forest stand is established. If the thinning is very severe (complete loss of the mature forest canopy), the risk of failure for the seedlings increases because they are not protected from heat and desiccation. The selection of stand target types is analogous to the forest conversion measure.

### 3.1.3 Expected effectiveness

The expected effectiveness is the same as in measure F-II-2, chapter 3.3.

### 3.1.4 Costs

**Opportunity costs:** The costs are calculated according to the procedure described in the measure A-V-1, chapter 2.10.

**Investment costs:** The costs are basically calculated according to the procedure described in the measure A-V-1, chapter 2.10. However, since these are small areas in the forest, no bush strip is created and the establishment of a distance strip to adjacent areas is dispensed with. In contrast to initial afforestation, costs are incurred for damage repair (e. g. clear-cutting). These costs are calculated as standard, taking into account the average expected labour and material costs for felling work and, if necessary, wood removal, based on Sachsenforst, 2016b; Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft, 2021.

**Management costs:** The costs are calculated according to the procedure described in the measure A-V-1, chapter 2.10.

### 3.1.5 Synergy effects

Synergy effects the same as in measure F-II-2, chapter 3.3.

### 3.1.6 Obstacles

Obstacles are the same as in measure F-II-2, chapter 3.3.

### 3.1.7 Stakeholders

Private and public forest owners.

## 3.2 F-II-1: Forest outer edge development

### 3.2.1 Aim of the measure

The objective of the measure is to create a structurally rich forest outer edge for the internal stabilization of the forest stand, to improve the internal forest climate and to protect against extreme weather events.

*Figure 12: Deciduous trees such as oaks were planted under the remaining canopy.*

*Figure 13: A structurally rich forest outer edge in transition to a wetland.*

### 3.2.2 Description and implementation

In general, a distinction is made between forest outer and interior edges. The former is located in the boundary area to other types of use, while forest interior edges represent boundary lines between different forest types or structures. Forest edges count as part of the woodland area (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung des Landes Brandenburg, 2004).

For the development of near-natural, ecologically diverse and stabilizing forest outer edges, a multifaceted transition zone from forest to open land should be aimed for, in which the elements of herbaceous, shrub and tree layers are intermixed in a mosaic-like manner. For this purpose, a sufficient width of 20 to 30 m is necessary (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung des Landes Brandenburg, 2004). However, the existing forest edges in Brandenburg mainly consist of the eaves of the main tree species only, with corresponding stability risks for the forests (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung des Landes Brandenburg, 2004).

In addition, the forest edge should not be laid out straight, but with small protrusions. This additionally increases the diversity with shady and sunny sides as well as the ecological value. Measures for the preservation and development of forest edges are based on the development phases of the respective forest stand. They essentially focus on allowing and supporting naturally occurring processes such as natural regeneration under a thinned canopy, maintenance of native shrubs and second-order trees, or promotion of individual, large-crowned trees. The herbaceous margin requires regular maintenance, preferably by mowing in the fall.

When creating a new forest edge, it is recommended to use a planting plan. The selection of tree and shrub species should be based on existing, surrounding forest edges, hedges and field copses (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung des Landes Brandenburg, 2004). The silvicultural guideline (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung des Landes Brandenburg, 2004) as well as Roloff et al., 2008 list possible tree and shrub species for planting forest edges. Fencing is usually required during the establishment phase. Maintenance measures depend on the degree of competition and grass encroachment. For permanent protection, care must be taken to maintain sufficient distance from adjacent areas such as fields. In addition, an agreement should be made with the adjacent land user to avoid damage to the forest edge, e.g., by branching overhanging trees.

### 3.2.3 Expected effectiveness

The structurally rich forest edge can be regarded as a buffer zone for the forest stand. It exerts a balancing influence on radiation, temperature and moisture conditions in the forest stand behind it (Ministerium für Landwirtschaft, Umwelt und Klimaschutz, 2020). This protects the stand interior climate from temperature extremes and aging caused by wind (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung des Landes Brandenburg, 2004).

### 3.2.4 Costs

**Opportunity costs:** They occur as the forgone profit of cultivating commercial forest on the outer forest edges. The forgone profit needs to be added to the costs of cultivating structurally rich outer forest edges. For a detailed description of the costs calculation for structurally rich outer forest edges please see measure A-I-2, chapter 2.2.

**Investment costs:** Investment costs for structurally rich outer forest edges are calculated according to the procedure described in the measure A-I-2, chapter 2.2.

**Management costs:** Management costs for structurally rich outer forest edges are calculated according to the procedure described in the measure A-I-2, chapter 2.2.

### 3.2.5 Synergy effects

Forest edges protect the forest from wind and water erosion, pollution from agriculture and industry, frost and storm damage, and forest fires, among other things (Ministerium für Landwirtschaft, Umwelt und Klimaschutz, 2020; Ministerium für Landwirtschaft, Umweltschutz und Raumordnung des Landes Brandenburg, 2004). The forest edge stores large amounts of carbon, greater than in the forest interior (Meeussen et al., 2021). It creates numerous habitats for various animal species like birds (McCollin, 1998; Terraube et al., 2016) and mammals (Schlinkert et al., 2016). Much of the woody vegetation consists of fruit trees and fruit-bearing shrubs, which provide food and breeding habitat for wildlife. Because the forest edge is a striped landscape element that combines numerous habitats, it also serves as a biotope link between open areas and the forest. Ultimately, a flowering and fruit-bearing forest edge is an aesthetic landscape element.

### 3.2.6 Obstacles

With the establishment of a structurally rich forest edge with sufficient width, part of the area used for forestry and thus yield is lost. This concerns only those forest owners whose forest stands are located on the edge of a forest.

Especially in the absence of herbaceous margins, adverse effects of forest edges can occur, such as root competition of trees by nutrient and water withdrawal, shadow effect and transmission of diseases to crops by intermediate host functions of different tree and shrub species (Ministerium für Landwirtschaft, Umweltschutz und Raumordnung des Landes Brandenburg, 2004).

### 3.2.7 Stakeholders

Private and public forest owners.

## 3.3 F-II-2: Ecological forest conversion

### 3.3.1 Aim of the measure

The objective of the measure is to increase the summer cooling capacity of a forest area while simultaneously increasing water storage and groundwater recharge in the winter months. To this end, the proportion of deciduous forest in the forest area is to be increased.

### 3.3.2 Description and implementation

Ecological forest conversion means the conversion of coniferous forests that are far from their natural state into near-natural mixed and deciduous forests (Jenssen & al., 2006). An essential element is the increase of the naturalness of the tree species composition, which is usually associated with a change in the regeneration and education of the forest stands: from clear-cutting operation to pre-regeneration operation (natural or artificial regeneration under the umbrella of the old stand), which results in an unevenly-aged stand depending on the type of pre-regeneration operation (plenter or femel operation, etc.).

At the national level, the conversion of monocultures into site-appropriate, climate-adapted mixed stands is being discussed in numerous contexts (e.g., German Climate Change Adaptation Strategy and National Biodiversity Strategy). Since pine forests have an unfavorable effect on the landscape water balance and are susceptible to calamities of various kinds, the focus in Brandenburg is on the conversion of pine monocultures (Ibisch & Blumroeder, 2020). As early as 1993, the state forest program called for the conversion of pure coniferous stands into more structurally rich mixed and deciduous forests (Ministerium für Ernährung, Landwirtschaft und Forsten des Landes Brandenburg (MELF), 1993). Various forestry directives for Brandenburg have since focused on and promoted forest conversion (e.g. EU Forestry Directive, extended until 31.12.2025).

Regarding tree species selection for conversion stands under climate change conditions, there is a lively discourse. Due to the large variability within tree species and the habitats they colonize, there is a wide range of possible responses to climate change-induced stressors, and therefore no exact limits of adaptation can be determined at the species level (Landeskompetenzzentrum Forst Eberswalde, 2017). Therefore, to minimize risks, structurally rich and site-adapted mixed stands of several tree species are recommended (Stähr et al., 2006; Bundesamt für Naturschutz, 2020).

Forest conversion is generally already possible by promoting natural regeneration (fencing, careful thinning if necessary). In the absence of suitable seed trees in the neighbourhood or due to other unfavourable factors, active forest conversion by seeding or planting is necessary, also to supplement natural spontaneous regeneration. It is often done as a pre-planting under a thinned conifer canopy, with the degree of thinning adjusted to the light requirements and growth progress of the target tree species. (Landesbetrieb Forst Brandenburg, 2022b). Other methods such as replanting and supplementing patchy regeneration are possible. Since the occurrence of sufficient natural regeneration cannot be estimated across the board and there are still a number of imponderables associated with seeding (scarce and expensive seed, not yet a routine method), planting under the thinned canopy can be considered usual practice.

For the state of Brandenburg, a recent study determined the forest conversion potential for treatment units (state forest) or partial areas (non-state forest) (Grüll et al., 2020). The main basis was formed by the stand target types, which

*Figure 14: Forest conversion through natural regeneration with oaks.*

correspond to the medium- to long-term objectives for site-appropriate stand conditions (LUTHARDT, 2006). The necessity of forest conversion was then attested to the treatment units whose current stocking (stand type) does not correspond to the stand target types recommended for the respective site. A large proportion of these are pure pine stands.

### 3.3.3 Expected effectiveness

Site-adapted deciduous trees, if sufficient water is available, can evaporate more water than conifers during the summer months and therefore have a more balanced, cooler stand climate (L. ZIMMERMANN et al., 2008). The forest floor in deciduous and mixed deciduous forests is also less heated by evaporation compared to pine forests, which can result in a more humid and cooler forest interior climate.

### 3.3.4 Costs

**Opportunity costs:** To determine the opportunity costs, the discounted profits resulting from the alternative use of the forest area as a pine monoculture must be deducted from the profits of the converted ecological forest. In the first 30 years of forest conversion, the profits do not differ significantly, since – apart from possible yields from initial thinning – both pine monocultures and mixed forests do not deliver any significant yields. In the further course, due to the higher economic efficiency of pine monocultures, the profits of the two forms of management differ significantly. This future increase in value is calculated with the yield calculator of the Brandenburg State Forestry Office (LFE, 2001) and included in the profit calculation on a discounted basis.

**Investment costs:** Costs are incurred through continuous forest regeneration or the conversion of mono-pine stands to a mixed deciduous forest. In a pre-regeneration operation, the average cutting rate per hectare is around 5 $m^3$ (ERNÄHRUNG UND LANDWIRTSCHAFT, 2016). With an average pine stock of 284 Vfm/ha in Brandenburg (MINISTERIUM FÜR LÄNDLICHE ENTWICKLUNG, UMWELT UND LANDWIRTSCHAFT, 2012), this corresponds to an annual felling rate of about 2 %. This means that per hectare, approx. 200 m2 are reforested annually with a mixed deciduous forest of sessile oak, red beech and hornbeam. The costs for afforestation of deciduous forest are calculated analogously to the procedure for measure A-V-1, chapter 2.10.

**Management costs:** Ongoing costs are incurred in the form of cultivation/young stand maintenance in the form of thinning measures every 5 to 10 years, possibly removal of fencing after 3 years, which reduce the profit from forest management.

Costs incurred are calculated according to the standard procedures given in the literature, taking into account the average expected labour and material costs (cf. e.g. Sachsenforst, 2016b; Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft, 2021).

#### 3.3.5 Synergy effects

Compared to pure pine stands, deciduous and mixed stands have lower interception evaporation and higher deep percolation (Jenssen & al., 2006). Therefore, they contribute more to groundwater recharge (Ellison et al., 2017; Gutsch et al., 2011; Müller, 2019). For example, Gutsch et al., 2011 demonstrated significantly higher overall monthly infiltration rates for oaks than for pines in Brandenburg. Deciduous and mixed stands reduce the risk of forest fires due to their wetter forest interior climate, while conifers (especially pines) experience an increase in fire risk with drought (Schelhaas et al., 2003). Deciduous forests are also considered less susceptible to windthrow than coniferous forests on the vast majority of sites (Schelhaas et al., 2003). Mixing pines and oaks in mixed deciduous forests can help reduce the forest's vulnerability to calamities during periods of drought (Steckel et al., 2020).

In the long term, forest conversion should minimize the risk of logging failure.

#### 3.3.6 Obstacles

Moving away from monocultures of pine requires a general rethinking, especially for owners of smaller forest areas. Uncertainties arise, for example, from the more difficult estimation of the economic performance of mixed forests compared to pure stands. Forest conversion in the maintenance and early regeneration phase (age of the upper stand < 80 years) is also generally associated with economic losses.

The fragmented ownership of forests is often problematic. Areas of private forest owners are often small, which is why many actors have to work together for a large-scale forest conversion. Similarly, forest conversion usually requires forest owners who have a large forest area to adjust their management strategy.

Due to high game populations, fencing of forest conversion areas is often unavoidable. A large-scale conversion of hunting can lead to reduced game browsing and successful natural regeneration.

#### 3.3.7 Stakeholders

Private and public forest owners.

# 4 Land use category: Settlements

## 4.1 S-I-1: Tree rows along roads out of town

### 4.1.1 Aim of the measure

The aim of this measure is to provide shade and increase evapotranspiration by planting trees along roads outside towns.

### 4.1.2 Description/implementation

The trees are planted as a row of trees either along one side of the road or on both sides. In view of the climatic changes, we recommend the littleleaf lime (*Tilia cordata*) as an avenue tree. The Greenspire or Merkur varieties are well suited. They tolerate drought stress and have a suitable growth habit. Each tree needs a planting hole of 12 $m^3$. The trees are planted at a distance of 10 m from each other and 4 m from the road. Between the row of trees and the road, a trench with cohesive material can absorb the rainwater running off the road and allow it to slowly seep away.

Maintenance is carried out in the first few years after planting as a shape pruning. Later, further maintenance measures will be necessary to ensure road safety. In summer, irrigation may be necessary, especially in the first years after planting.

### 4.1.3 Expected effectiveness

The expected effectiveness is the same as in measure S-I-2, chapter 4.2


*Hildmann, Zimmermann, Schlepphorst, Rösel, Kleinschmidt, Kruber, Lukas, Joshi, Hecker, Witt, Sturm, Wätzold 2022, DOI: 10.5281/zenodo.6811079*

*Figure 15: Rows of trees also help to structure the landscape and slow down the wind.*

### 4.1.4 Costs

As in the other sectors, the costs in the settlement area consist of the opportunity costs from alternative use, the investment costs, and the management costs. In this sector, however, there is a distinctive aspect; The lifespan of the measures (e. g., installation of a green roof) and their respective alternative use (e. g. installation of a black roof) may be different from each other and also longer or shorter in the timeframe of 30 years that we used to calculate the costs of all measures. This means that in the case of a short lifespan, management costs are calculated twice (or once plus the proportion of the lifespan remaining until the end of the calculation period). In the case of a longer lifespan, only the proportion of the costs that fall within the calculation period are considered, and the proportion of the costs that fall outside the calculation period are not. Future costs are discounted. The lifespan of potential measures are taken from the depreciation tables of the federal Ministry of finance. These are the tables for the depreciation of general wear and tear in commonly used assets (Bundesministerium der Finanzen, 2000), for agriculture and animal husbandry (Bundesministerium der Finanzen, 1996), and for viticulture and wine trade (Bundesministerium der Finanzen, 1991).

**Opportunity costs:** Since the trees are planted on the verges of the roads, opportunity costs only arise if the trees rows have to be planted on arable land or grassland due to space requirements.

**Investment costs:** The investment costs for the tree rows in non-urban areas are calculated like the investment costs for the tree groups in urban areas, despite the use of different species.

**Management costs:** The management costs for the tree rows in the non-urban areas are calculated in the same way as the management costs for the tree groups. It can be assumed, however, that higher costs will result with regard to the maintenance of the trees, as road safety requires that they be maintained at shorter intervals. If applicable, the management costs associated with the previous landscaping will be omitted.

### 4.1.5 Synergy effects

If the row of trees is planted between the road and a bike or pedestrian path, pedestrians or cyclists also benefit from the shade of the trees. For their part, the trees benefit from the road runoff as additional irrigation if the material of the ditch has a water-storing function. As a landscape structure element, the rows of trees break up the often poorly structured agricultural landscape, slow down high wind speeds, minimize wind erosion and snow drifts and improve orientation in fog and twilight. In addition, they provide habitats for birds, which can have a positive effect on the natural control of arable pests.

### 4.1.6 Obstacles

Lack of space in particular can prevent the creation of an avenue or row of trees if there are only a few metres between the road and the farmland.

### 4.1.7 Stakeholders

The road maintenance department.

## 4.2 S-I-2: Tree rows in urban areas

### 4.2.1 Aim of the measure

The measure intends to provide a local reduction in air temperature and an increase in air humidity through the shading effect and evaporation potential of trees along roads or other areas in settlements.

### 4.2.2 Description and implementation

Trees can be planted at the roadside or in green areas, either on one or both sides of the road or paths. If necessary, prior unsealing is required. The measure can be divided into two variants.

Variant 1 With tree disc: The trees are planted at 8 metre intervals in a 3 m long and 1 m wide tree disc along traffic areas. The tree discs are sown with a grass mixture. A Globosum maple (*Acer platanoides*) with a trunk height of 2.2 m and a trunk circumference of 0.08-0.1 m is recommended.

Variant 2 Without tree disc: No tree disc is required if the trees are planted on a green area bordering a path. A Globosum maple (*Acer platanoides*) with a trunk height of 2.2 m and a trunk circumference of 0.08-0.1 m can also be used for this. The trees can be planted at a distance of 8 m.

For stabilization in the growing phase, the trees will each receive a frame of three planting stakes. Irrigation is also recommended, for example with the help of an irrigation bag (60 litres). The irrigation bag is filled once a week. Irrigation is mainly necessary for newly planted trees. After a few years, watering is only done when needed.

### 4.2.3 Expected effectiveness

The cooling capacity of a tree species depends on its leaf area index, its drought stress tolerance, and its height and age. For example, a littleleaf lime has a 35 % larger leaf area index (LAI) than a black locust resulting in a difference in temperature reduction of 2.8 K vs. 1.9 K (Rahman et al., 2020b). Also, tree rows cool better when they form a closed crown, thus increasing the shaded area (Rahman et al., 2020b). It should also be noted that the evapotranspiration of trees over a grassy area is significantly higher than over a sealed area (Rahman et al., 2020a). Shading by urban trees can achieve a cooling of 8.5 to 16.4 K on grass and asphalt, respectively, on particularly hot summer days (Speak et al., 2020). Since the grass surface itself evaporates and cools, the additional cooling from the tree shade is less than for surfaces that do not cool themselves, such as asphalt. Also Gillner et al., 2015 show a temperature difference of 15.2 K between the asphalt surface with and without shading by trees.

### 4.2.4 Costs

**Opportunity costs:** In most cases, tree rows are planted on existing green spaces or the verges alongside roads. In these cases, there are no opportunity costs. If tree rows are planted on parking lots, then opportunity costs may arise due to lost parking spaces. In such cases, the costs are calculated based on the local average rental costs for a parking space.

**Investment costs:** The costs for the measure are calculated per tree. It is assumed that the area has already been unsealed. Accordingly, the investment costs for tree rows in urban areas are calculated in the same way as the investment costs for tree groups in urban areas, even if different species are used.

*Figure 16: Large-crowned trees in particular contribute to cooling in urban areas.*

**Management costs:** The management costs for the tree rows in urban areas are calculated in the same way as the management costs for the tree rows outside urban areas.

#### 4.2.5 Synergy effects

More urban greenery improves air quality and people's quality of life. In addition, new habitats are created, especially for birds. The different shading effects of tree species also lead to differences in their impact on people. A dense canopy of winter lime trees reduces the temperature under the tree more than that of black locust trees, which leads to improved thermal comfort (Rahman et al., 2020a).

#### 4.2.6 Obstacles

Obstacles can arise when there is not enough space for the trees to develop, possibly due to buildings or pedestrian and cycle paths. Thus, there is always competition for use. Even if a road is renovated, it is unlikely that changes will be made and trees planted afterwards. However, the maintenance or upkeep of street trees can also be an obstacle for financial reasons. In the future, watering the trees will play an increasingly important role, not only in the growth phase.

#### 4.2.7 Stakeholders

The municipality, the district or the federal government.

### 4.3 S-I-3: Erecting pergolas

#### 4.3.1 Aim of the measure

Covering walkways with a pergola aims at cooling the area that is frequently used by people in the city. Pavements are often sealed, rarely in the shade and thus strongly heated. The pergola shades the walkway and increases the cooling capacity through evaporation.

#### 4.3.2 Description/implementation

The pergola (»Green Cocoon«) consists of an elongated trellis frame that spans a sealed surface, such as a pavement or car park, in large arches or as a flat roof on pillars. The »roof« of the pergola consists of climbing plants, e. g. *Wisteria*. The plants are planted in the ground at a distance of 3 m next to the pillars. In summer, the plants need to be watered if necessary.

#### 4.3.3 Costs

**Opportunity costs:** We assume that the walkways would continue to function as walkways. Thus, no economic use is lost due to the covering of the walkways and no opportunity costs arise.

*Figure 17: Pergola in a castle garden as inspiration.*

In principle, open spaces would have costs associated with the loss of alternate usage. However, these are difficult to calculate and are therefore not considered.

**Investment costs:** The costs per pergola and rolling metre are based on a joist construction. They consist of the labour and material costs for erecting and anchoring the construction, and for the painting and greening of the pergola.

**Management costs:** Maintenance costs are incurred for repainting the pergolas, for soil maintenance and for plant upkeep. The life span of the pergolas is based on the life span of pergolas in vineyards. Irrigation is required in the first few years.

### 4.3.4 Expected effectiveness

Shaded walkways are most common in hot and dry regions of the world, although the use of pergolas for shading is rare (e.g. in Bangkok). Only as exhibition objects (Expo 2020 in Dubai) or theoretical planning can pergolas be found for shading walkways, pedestrian zones and car parks. But there are already research projects that prove the positive effect of a pergola. The air temperature under a pergola can be on average 8.1 K lower than over a concrete roof (Alexandri & Jones, 2006).

### 4.3.5 Synergy effects

More urban greenery improves people's quality of life. It also contributes to human health as it prevents people from being too exposed to direct and prolonged solar radiation.

### 4.3.6 Obstacles

The pergola requires maintenance and adequate watering. The financial and logistical costs could be an obstacle in the decision for a pergola. Furthermore, lack of space could be another barrier. It may be necessary to create a planting hole for the plants. This may increase the cost of construction.

### 4.3.7 Stakeholders

Public property owners

## 4.4 S-II-1: Tree groups in settlement areas

### 4.4.1 Aim of the measure

The measure intends to provide a local reduction in air temperature and an increase in humidity through the shading effect and evaporation potential of groups of trees in settlement areas.


*Figure 18: Tree groups in settlement areas can balance the microclimate.*

### 4.4.2 Description/implementation

Open spaces in the settlement area or parts of properties that can be planted with trees up to 60 % of the unsealed area. The local conditions and the development potential of the woody plants must be taken into account. The 60 % refers to the ground area covered by a developed canopy of trees and takes into account that some area without trees is always required for providing enough sunny places and for purposes like drying clothes. If necessary, the area must be unsealed beforehand (calculated without unsealing). Two variants are distinguished for this measure:

*Variant 1:* Create new groups of trees: If possible, trees should be planted in groups of 3, as this will optimize the cooling potential. Native deciduous tree species such as oaks, maples and lime trees are suitable. For the cost calculation, *Acer platanoides* is selected as a high trunk (transplanted 3 times) with wire root ball and a trunk circumference of 0.16-0.18 m. The trees will be planted as a group with a spacing of 10 m. In this way they will form a closed canopy in the future. An open space should be left around the groups of trees to ensure air exchange with the surrounding area. The number of trees is determined by taking 60 % of the unsealed open space and dividing it by 250 m$^2$ (equivalent to the crown extension in Variant 2).

*Variant 2:* Densify tree groups: Any gaps in the existing tree groups, e.g. trees that have failed due to disease and have been removed, can be replaced by new trees. The recommended tree is a sycamore maple (*Acer pseudoplatanus*) as a high trunk with wire root ball and a trunk circumference of 0.16-0.18 m. If the existing stand is of other tree species, this tree species can be chosen for the new tree. Individual trees are added, each with a crown extension of 100 m$^2$.

For stabilization in the growing phase, each trees will receive a frame of three planting stakes. Irrigation is also recommended, for example with the help of an irrigation bag (60 litres). The irrigation bag is filled once a week. Irrigation is mainly necessary for newly planted trees. After a few years, watering is only done when needed.

### 4.4.3 Expected effectiveness

The cooling capacity of a tree species depends on its leaf area index, its drought stress tolerance, and its height and age. Trees in groups achieve a higher cooling effect than solitary or scattered trees (Rahman et al., 2020b; Zhao et al., 2018; Fan et al., 2015; Myint et al., 2015; Greene & Kedron, 2018).

### 4.4.4 Costs

**Opportunity costs:** The costs for the measure are calculated per tree. It is assumed that the area has already been unsealed. Since the trees are planted on existing green spaces, the use of the area does not change significantly, and no further opportunity costs arise from any change of intended use.

**Investment costs:** The investment costs consist of the costs for purchasing and planting the tree. This includes the costs for plant watering during the first weeks and for the installation of a frame made of stakes and rope as a protection for the young tree.

**Management costs:** In the first two years, increased care via frequent pruning and watering during dry summers is essential. After that, the trees require regular inspection and pruning to ensure compliance with traffic safety regulations. Where appropriate, the management costs for the previous surface must then be deducted.

### 4.4.5 Synergy effects

More urban greenery improves air quality and people's quality of life. In addition, new habitats are created, especially for birds (Strohbach et al., 2013). Furthermore, urban trees contribute to carbon fixation (Strohbach & Haase, 2012).

### 4.4.6 Obstacles

Trees need to be cared for. Irrigation is required especially in the growing phase after planting. Too little space also inhibits tree development. Trees need to be pruned from time to time and fallen leaves collected. If gaps in an existing group of trees are filled with young trees, these are shaded by the larger trees, which can impair their development.

### 4.4.7 Stakeholders

Private and public property owners

## 4.5 S-II-2: Afforestation of urban brownfield sites

### 4.5.1 Aim of the measure

The aim of this measure is to increase the proportion of trees with high evapotranspiration capacity.

### 4.5.2 Description/implementation

Sessile oaks, copper beeches and hornbeams of 2-3 years old are planted, which come from a forest nursery. Since the trees should be dense at this stage, it is recommended to plant at least 6000 trees per ha. The conservation area is fenced with a game fence to protect it from game browsing. The area must be maintained by removing overgrowing plants (bracken, grasses, brambles) once in the summer months and shortly before winter. Maintenance is no longer required once the trees overtop the companion vegetation. The forest edge should be planted with native tree and shrub species. Common hazel, rock pear, hawthorn, dogwood, honeysuckle, dog rose, raspberry, elderberry and spindle tree etc. are particularly suitable.

Furthermore, two variants are conceivable for afforestation – with and without previous unsealing of the area. Any fallow land that is no longer used, both in public spaces and on private property, can be unsealed. Unsealing involves removing the impervious material and then applying new soil. This can, for example, come from other building sites where excavated soil is produced.

### 4.5.3 Expected effectiveness

The effect of this measure, i.e. the evaporation capacity of the new forest stand, depends on the density of the vegetation and its water supply. The effect changes over time. For the calculation, a stand with an age of 30 years is assumed.

### 4.5.4 Costs

**Opportunity costs:** The opportunity costs are highly dependent on the selected site. For fallow areas, for example, there are no opportunity costs in the form of foregone economic use. A profit may be generated from forestry use. This profit will be calculated in the same way as for the measure A-V-1, chapter 2.10.

**Investment costs:** The investment costs are calculated in the same way as for the measure A-V-1,

*Figure 19: Reforestation of a brownfield site in an urban area.*

chapter 2.10. In some cases, however, additional costs may be incurred for unsealing.

**Management costs:** The cost calculation is the same as for the measure A-V-1, chapter 2.10.

### 4.5.5 Synergy effects

Possible synergy effects result from the new habitats for animals and plants. Afforestation reduces the fragmentation of forest areas in settlement areas. This facilitates the migration of animals that depend on contiguous biotopes. Forests on formerly sealed surfaces prevent surface run-off and erosion, which relieves pressure on the sewage system and the water network. In addition, landscape aesthetic aspects play an important role for the well-being of people. The wood can be used for private or commercial purposes in due course.

### 4.5.6 Obstacles

The unsealing process incurs costs. If the site is contaminated, the necessary remediation of the area can cause additional costs. If the ownership of the brownfield site has not been clarified, this can hinder or even prevent planning, implementation and financing. Some brownfield sites have developed into areas of conservation value. These include, above all, unused buildings that serve as roosts for bats.

### 4.5.7 Stakeholders

Private and public property owners

## 4.6 S-III-1: Infiltration swales in gardens - Rain gardens

### 4.6.1 Aim of the measure

The aim is to infiltrate rainwater from roofs at the place where it accumulates. This also opens up the possibility that some water can evaporate again.

### 4.6.2 Description/implementation

Rainwater flows from the roof via the gutter and downpipe and is directed into a vegetated infiltration basin.To avoid polluting the soil with heavy metals, it may be necessary to install a filter system. This is located below the downpipe and cleans the water before it is fed into the percolation trough. When creating the swale, care should be taken to ensure sufficient distance from the building (at least 5 m) and from the groundwater (at least 1.5 m). Otherwise, the infiltration swale can overflow during heavy rains and possibly cause moisture damage to the building. The size of the swale depends on the expected water amounts and thus on the roof area. The vegetated swale should cover 20 % of the size of the roof area effective for run-off (Bortolini & Zanin, 2018). The infiltration swale is designed

*Figure 20: Infiltration swales can be designed close to nature with native wetland plants.*

to allow water to flow into it over a gentle slope. The bottom depth should be 0.3 m. The soil volume of the seepage path, normalized to 1 m² of bed area, is 1.2 m³, of which 0.1 m³ (0.15 m) is topsoil with 1-3 mass % humus. The sides of the infiltration swale are lined with cohesive material, the filling material should have a low fine grain content (fine sand-silt mixture) and thus a medium water storage capacity ($10^{-6}$ m/s). This way, the water is stored in the swale for longer and can only seep downwards or evaporate via the plants. The greening can be done in two variants:

Variant 1: Grass and herb mixture: A conventional seed mixture of grasses and herbaceous plants is sown into the infiltration swale. Maintenance is carried out by mowing as with conventional lawns. The mown material must be cleared away so that the swale can always fulfil its function. Deposited sediment should also be removed.

Variant 2: Perennial planting: The infiltration swale is planted with suitable perennials that can tolerate a higher water supply for a short time and have a high evaporation rate, for example garden meadowsweet and meadow iris. 5 perennials are planted per square metre. The intervention on the plot is relatively small, while a long operating period can be expected (Osheen & Singh, 2019). This variant is used for the cost efficiency calculation.

### 4.6.3 Expected effectiveness

Evaporation takes place via the plants in the infiltration swale and thus depends on the amount of precipitation, the storage capacity of the substrate and the temperature. Due to the comparatively small size of the swale, cooling will be localized.

Various studies reported evaporation rates between 1.5 and 9 mm/d or a share in precipitation of 21 to 84 % (Ebrahimian et al., 2019). The wide range of values results from the many different parameters and their variation. In the study by Bortolini & Zanin, 2018, a large swale achieved an evaporation performance of 13 % (7 % for a small swale).

### 4.6.4 Costs

**Opportunity costs:** Opportunity costs are incurred in the form of foregone alternative use of the garden. These are, however, difficult to calculate in financial terms. Therefore, they are not considered.

**Investment costs:** For the installation, costs arise for the creation and tamping of the swale, for the installation of the rainwater pipe, as well as for the planting of the vegetation. For variant 1 (swale planted with grass and herbs), these costs are for the labour involved in seeding and the costs of the seeds. For variant 2 (swale planted with perennials), costs are incurred for planting the perennials and for the perennials themselves.

**Management costs:** For both variants, costs arise by way of horticultural maintenance, removal of foliage and other debris, and, if necessary, restoration of permeability and prevention of gullying and ridging. The costs for mowing a swale are equivalent to the costs for lawn maintenance (Matzinger et al., 2017) and are calculated according to the measure S-V-1, chapter 4.10.

### 4.6.5 Synergy effects

Since the soil in the infiltration swale will not fully store the amount of water from the roof surface, a considerable part of the run-off water contributes to groundwater recharge. In addition, the sewer system is relieved, especially during heavy rainfall events. Depending on local regulations, the property owner may no longer have to pay drainage fees.

If the plants absorb the nutrients that enter the infiltration swale with the roof run-off water, this improves the quality of the leachate, which flows to the groundwater and consequently also its quality (Denman et al., 2016).

### 4.6.6 Obstacles

Obstacles are be mainly the required space for the infiltration swale. The larger the roof area, the larger the swale must be. There may not be enough space on some properties. In addition, the existing garden design must be interfered with if the building itself is not newly constructed.

### 4.6.7 Stakeholders

All private and public property owners who have buildings on their property from which rainwater can be collected.

## 4.7 S-III-2: Infiltration swales for traffic areas

### 4.7.1 Aim of the measure

The intention is to allow rainwater from traffic areas to seep into vegetated swales and evaporate close to the site. This is intended to achieve a cooling effect in the immediate vicinity.

### 4.7.2 Description/implementation

Rainwater flows from traffic areas such as car parks, parking pockets and streets into parallel infiltration swales, which can be designed in different ways. Generally, the swale consists of soil material. The vegetation can either be grass (variant 1) or grass and trees (variant 2).

*Variant 1:* Infiltration swales with grass: The infiltration swales with grass have an extension of approx. 20 % of the run-off-impacting traffic area. The design of the swale is carried out for each running metre of run-off-impacting traffic area, whereby a maximum of 1.5 $m^2$ of bed area is required. With a seepage distance of 1 metre and a topsoil layer of 0.2 metre, this results in a total of approx. 1.8 $m^3$ of swale material. This volume is divided into 0.2 $m^3$ topsoil with 1-3 mass % humus and 1.7 $m^3$ fine sand-silt mixture with a water permeability of $10^{-5}$ m/s. The infiltration swale requires little maintenance. If sediment and other particles have accumulated on the grass surface, this should be removed from time to time.

*Variant 2:* Infiltration swales with grass and trees: Trees in the infiltration swale increase the evaporation capacity of the area (Szota et al., 2018). The trees need to be maintained, i.e. pruned and watered if necessary. If sediment and other particles have accumulated on the grass surface, they should be removed. A swale with a tree is 2 m wide, 6 m long and 1.8 m deep (0.30 m bottom depth). This corresponds to a volume of 18 $m^3$. The recommended tree species is English oak (*Quercus robur*). The available area determines the number of swale-tree sections. The soil material of the planting hole should have a $k_f$-value of $10^{-6}$ m/s. Of the 18 $m^3$, 2 $m^3$ should be topsoil material with 1-2 % humus content.

*Figure 21: Existing roadside ditches could be converted into infiltration swales.*

### 4.7.3 Expected effectiveness

Infiltration swales with grass and trees have a more positive effect on run-off reduction than other swale or retention systems (Bixler et al., 2020). They provide a higher amount of evaporation in the infiltration swale than a pure grass area (Tirpak et al., 2019). The amount of daily evapotranspiration depends on the tree species, the degree of cover, the ground cover and the stand size (Zardo et al., 2017). Depending on various parameters, the transpiration level differs:

| Transpiration height [%] | Evaporation [mm/d] | Source |
|---|---|---|
| 46 and 72 % | | Schachenbroch et al., 2016 |
| 8.2 to 37.5 % | 3.2 (max.) | Tirpak et al., 2019 |
| 17 % | 3,4 | Thom et al., 2020 |

### 4.7.4 Costs

**Opportunity costs:** In most instances, the land could not be used economically before and so no opportunity costs occur. On parking lots alone, opportunity costs can arise due to the loss of the potential to park. The costs are calculated based on the local rental costs for a parking space.

**Investment costs:** The investment costs consist of the costs for creating a swale as defined in the measure S-III-1 (chapter 4.6), the costs for planting a tree as defined in the measure S-I-2 (chapter 4.2) and, if applicable, the costs for unsealing. The latter is only incurred on parking lots.

**Management costs:** The management costs vary according to the type of measure implemented. There are always costs for lawn maintenance. These are calculated as described in the measure S-V-1, chapter 4.10. For infiltration swales with trees, additional costs arise from the maintenance of trees, following the cost calculation for the measure S-I-1, chapter 4.1.

### 4.7.5 Synergy effects

The infiltration basins allow for faster run-off of rainwater during heavy rain events, thus reducing the risk of flooding of the traffic area and overloading the sewer system. The non-evaporated leachate reaches the groundwater and contributes to its recharge (Bonneau et al., 2017). The filtering effect of the soil material cleans the leachate of dissolved and particulate pollutants, which is contaminated in many ways through contact with the traffic surfaces (Gavrić et al., 2019). The nitrogen loads carried are also reduced by the processes in the infiltration basin (Dagenais et al., 2018).

At the same time, the trees provide shade and thus additionally cool their mostly sealed, direct surroundings. The run-off water drained into the swale simultaneously serves to irrigate the trees and stores the water over a longer period of time. In the growing phase, newly planted trees benefit from targeted irrigation through better growth, provided that there is no waterlogging in the root zone (Grey et al., 2018).

### 4.7.6 Obstacles

Obstacles could mainly be the required space for the basin. The larger the traffic area, the larger the infiltration basin must be. In addition, there is the maintenance effort. In the case of existing traffic areas, especially car parks, part of the sealed surface would have to be removed, thus reducing the area.

### 4.7.7 Stakeholders

Municipalities, private individuals, road maintenance authorities responsible for the creation and maintenance of traffic areas.

## 4.8 S-IV-1: Green walls

### 4.8.1 Aim of the measure

The greening of façades is intended to reduce the heating up of buildings in cities through the evaporation capacity and shade cast by the plants.

### 4.8.2 Description/implementation

For the implementation, climbing aids are attached to the building walls and the plants are planted in the ground.

**Creepers and plants** The buildings are divided into three types, as the requirements for the climbing aids and the plants differ:

- Type 1: Apartment block, at least 4 storeys: The two large building façades without windows on the short sides of apartment blocks are ideally suited for façade planting. Apartment blocks often have a height of approx. 12 m, which makes it necessary to use fastening hooks at a distance of 1 metre. The common clematis (*Clematis vitalba*) is suitable as a climbing plant, as it can also reach a height of 12 m. 1 plants are required per 3 metre climbing rack.
- Type 2: Residential building, up to 3 storeys: A green facade for this type of building must take into account the windows on each side of the building. For this, a flexible climbing frame is recommended, which consists of vertically and horizontally attached ropes and can thus leave out the windows. The recommended plant is the *Clematis montana* woodland vine, which can climb up to 10 m. The distance between the plants is 0.75 metre. The height of the trellis should be limited to 4.5 m, otherwise the maintenance effort becomes too high and complicated.
- Type 3: Non-residential buildings: This building type corresponds to warehouses, for example, which have no windows. Since the size of the façade area varies, it is suggested to use a tendril module on half of the building surface. The recommended plant is *Clematis vitalba*, planted at a distance of 3 m.

**Irrigation** Irrigation is recommended for the façade greening. A water consumption of 3 litres per day per plant is calculated. In addition, a longer vegetation period of 233 days is assumed in the future, during which the plants must be watered. This would mean a water consumption of 700 litres or 0.7 $m^3$ per plant.

In order to ensure irrigation during the entire vegetation period, sufficient water for the expected dry periods is to be stored in a cistern. Up to now, dry periods of up to 49.5 days were to be expected, but due to climate change, dry periods may be up to 25.4 days longer in the future (Landesamt für Umwelt Brandenburg, 2016). If the storage is designed for 75 days, irrigation should still be guaranteed even under very unfavourable conditions. The size of the required storage is therefore based on the number of plants (0.23 $m^3$ per plant, e.g. with 8 plants

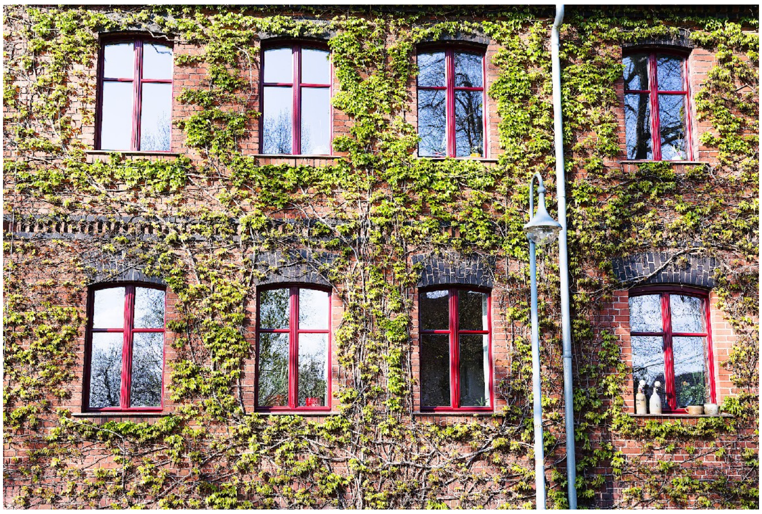

*Figure 22: Facade greenery with wild grapevine during budding in spring.*

this is 1.8 m³ storage volume). The prerequisite is that a sufficiently large roof area is available from which the water is collected. Based on 566 mm annual precipitation in the region, 2.5 m² of roof area per plant can be expected.

### 4.8.3 Costs

**Opportunity costs:** Although the installation requires very little space, the plants and the trellis system are installed at a slight distance from the wall (Regelwerksausschuss Fassadenbegrünung, 2018). In theory, these areas generate opportunity costs in the form of foregone alternate use of this space. The size of these areas, however, and the resulting financial losses, are difficult to quantify. Therefore, they are not considered.

**Investment costs:** We assume that the exterior wall is structurally sound at the beginning of the calculation period and that, in the case of both the measure and alternative use, the exterior wall is painted at the onset of the time frame covered by the project. During installation, costs are incurred for material and labour costs for installing the trellis system, for installing the water storage and irrigation system, and for any planting.

**Management costs:** The measure incurs annual costs for the upkeep of the greenery (including pruning measures) and the upkeep of the irrigation system (Arbeitskreis Fassadenbegrünung, 2000).

### 4.8.4 Expected effectiveness

As the plants evaporate, the air humidity increases and thus reduces the direct air temperature by up to 8.7 K (Shafiee et al., 2020; Lei et al., 2019) in outdoor areas, and 0.8 to 4.8 K indoors (among others Lei et al., 2019). The effect becomes greater the higher the (non-cooled) air temperature (Pérez-Urrestarazu et al., 2016). The temperature difference between a greened façade and one without greening is between 1 and 31.9 K (Besir & Cuce, 2018) and 12 to 20 K (Mazzali et al., 2013), respectively.

### 4.8.5 Synergy effects

Likewise, the protective effect of façade greening can save energy in the building, both for cooling and heating the building. The façade greening absorbs significantly less radiation than a concrete wall. It is also possible to use the façade greening with fruit trees (apricots, pears, apples, peaches, blackberries, kiwis, figs, real wine) or vegetables and herbs (»vertical gardening«). Living plants produce oxygen and store carbon (Charoenkit & Yiemwattana, 2016). In addition, façade greening promotes the immobilization of pollutant particles from adjacent road traffic (Ysebaert et al., 2021). In this context, different plant species show different degrees of effectiveness. If the plant surface is heterogeneous, this improves the effect of pollutant reduction (Weerakkody et al., 2019). The façade greening additionally functions as noise protection and promotes comfort in the building. The network of plants and the use of certain plant species create new habitats for animals. Finally, the plants protect the building fabric from mechanical and chemical environmental influences.

### 4.8.6 Obstacles

Maintenance of greenery is always necessary. Depending on the construction and the plants, the effort required varies and the costs vary accordingly. In addition to the maintenance costs, there is the investment and maintenance of irrigation via a cistern. To anchor the climbing aid, it is necessary to intervene in the masonry. This is either undesirable or the façade is not suitable.

### 4.8.7 Stakeholders

Every owner (public, private) of buildings. This includes residential, commercial and office buildings as well as warehouses and production halls. Car parks can also receive a green façade.

## 4.9 S-IV-2: Green roofs

### 4.9.1 Aim of the measure

Roof surfaces in the settlement area can be used for evaporation by a low vegetation cover and thus to achieve cooling of the immediate surroundings.

### 4.9.2 Description/implementation

For the installation of a green roof, a substructure is installed on flat or slightly sloping roofs of garages, sheds, summerhouses, residential and functional buildings and a waterproofing layer, root protection, storage protection mat, drainage layer, filter fleece and soil substrate are applied in layers. The type of greening depends on the load-bearing capacity of the roof. For inclusion in the optimization calculation and hydrological modelling, a vegetation of a mixture of grasses and low-growing flowering plants is assumed (extensive green roof). Greening with shrubs and small trees is also possible under certain circumstances (intensive green roof). For the cost calculation and location, only an extensive green roof is used, as no individual statements can be made about the required statics for an intensive green roof.

Some precipitation water is retained in the soil substrate; the other part of the water seeps through the build-up layers of the green roof and is gradually released into the sewage system. The stored water, on the other hand, supplies the plants of the green roof. The maintenance of developed and densely overgrown green roofs is low, but necessary when required. Watering should be carried out during the growth and development phase so that the young plants do not dry out in the first year and need to be reseeded. In addition, unwanted plants as well as foliage and litter should be removed. Pruning is also recommended for vigorously growing plants. If necessary, reseeding can be done after the first year or the soil substrate can be filled up. In addition, the plants should be regularly supplied with fertilizer specially developed for green roofs.

The structure and planting of the green roofs can vary depending on the desired design. For further consideration, a growth of herbs, grasses and perennials was assumed, such as fescue, sedges, sage, cinquefoil, thyme or lavender. 15 to 20 stakes and 2 g of seed mixture are needed per $m^2$. The rootable layer should be 0.1 - 0.12 m thick.

### 4.9.3 Costs

**Opportunity costs:** In principle, there are currently no opportunity costs. However, given the increasing efforts in Germany to install photovoltaic systems on roofs, in the future opportunity costs will arise in terms of lost profit from energy production or through higher costs for installing photovoltaic systems on greened roofs.

*Figure 23: An intensively greened roof.*

**Investment costs:** We assume the re-roofing of a blacktop roof as the alternate use. Per German regulations, green roofs — but not black top roofs — require waterproofing that is also root-proof (Arbeitskreis Dachbegrünung, 2002). In practice, root-proof membranes need not cost more than non-root-proof membranes, while offering better protection, and are preferentially installed on most flat roofs (Pfoser & Dierks, 2017). For this comparison, we can therefore assume that the installation of a root-proof membrane is cost-neutral. The installation of the green roof involves labour and material costs for the installation of the green roof layers, and for the greening (Arbeitskreis Dachbegrünung, 2002). The labour and material costs for the construction of a blacktop roof are deduced (Pfoser & Dierks, 2017).

**Management costs:** Roofs need to be maintained to keep them in good condition. The costs for the maintenance of a green roof include the care of the plants and are slightly higher than the costs for the maintenance of a black roof. The costs for the renovation of the blacktop roof are deduced (Pfoser & Dierks, 2017).

### 4.9.4 Expected effectiveness

The plants of green roofs only develop their full evaporation potential after a few years, as a closed vegetation cover has only formed by then.

If a roof is greened, the albedo increases from 0.1 to 0.3. The cooling effect for the immediate surroundings can contribute to reducing the ambient temperature by 0.3 to 3.0 K. In summer, the green roof can reduce the surface temperature by 12 K compared to a normal roof (Besir & Cuce, 2018). The amount of water evaporated corresponds to a reduction in temperature of -0.35 K per day and per mm (Suter et al., 2017). Trees can transpire more and thus have a better cooling capacity than low-growing herbaceous plants. The range of cooling depends on various factors. In addition, the effect decreases with distance from the green roof. At a distance of 1.5 m, reduced temperatures in a range of 0.05 and 0.6 K could be measured. Temperature reductions of 0.3 to 0.7 K could also be measured in the interiors of buildings in cities with temperate climates (Morakinyo et al., 2017).

### 4.9.5 Synergy effects

Possible synergy effects of a green roof consist in additional flowering areas for insects, in buffering precipitation peaks, in an improved indoor climate of the building due to the insulating effect of the green roof construction and in a longer durability of the roof. In addition, heating costs can be reduced by between 10 and 30 % in winter (Besir & Cuce, 2018).

#### 4.9.6 Obstacles

The creation of a green roof is made more difficult if the slope is very steep. Although it is possible to justify this, it is more costly and involves a different layer structure than described above. Inhibiting factors can also be the required maintenance effort and the investment itself. The effort is greater for existing buildings than for new buildings, since the green roof can be planned in from the beginning. In addition, it must be taken into account that the green roof construction has a not inconsiderable weight and thus the statics play a role and must be taken into account before a green roof is installed (approx. 150 $kg/m^2$ in a water-saturated state).

#### 4.9.7 Actors

Private individuals can, for example, green the roofs of sheds, garages, other functional buildings and flat extensions to residential buildings. Public actors can also green flat roofs of administrative and public buildings. If there are flat buildings on company property, these can also be greened.

### 4.10 S-V-1: Unsealing of urban brownfields

#### 4.10.1 Aim of the measure

The aim of this measure is to reintegrate sealed areas that are no longer used into the active water cycle. This requires the removal of the sealed surface and the subsequent revitalization of soil and vegetation on the site. Thus, the precipitation water can percolate on site and be evaporated by the vegetation, leading to a lower surface temperature.

#### 4.10.2 Description/implementation

Any brownfield site that is no longer in use, both in public spaces and on private property, can be unsealed. Unsealing involves removing the impervious material and then applying new soil. This can, for example, come from other building sites where excavated soil is produced. However, the requirements of the Closed Substance Cycle Waste Management Act must be taken into account. For the greening, a grass-herb mixture is sown. Regular mowing is required.

#### 4.10.3 Expected effectiveness

The effect of this measure i.e. the evaporation capacity of the area depends on the density of the vegetation and its water supply. The effect is comparable with other green spaces.

#### 4.10.4 Costs

**Opportunity costs:** We assume that the brownfield sites being unsealed would otherwise remain as brownfield sites. Thus, the unsealing of these areas does not result in a loss of economic revenue and no opportunity costs arise.

**Investment costs:** Unsealing involves costs for the unsealing itself – including the restoration of the soil – and for the creation of the grass surface.

**Management costs:** For the maintenance of the sites, they require mowing. The average costs are determined analogously to Beiersdorf & Ullmann, 2022a.

#### 4.10.5 Synergy effects

Possible synergy effects result from the newly gained habitat for animals and plants. In addition, landscape aesthetic aspects play an important role for people. The fragmentation of the landscape by sealed areas could thus be eliminated and formerly separated biotopes could be reunited. This facilitates the migration of animals that depend on contiguous biotopes. In addition, large amounts of run-off can be prevented during heavy precipitation. This relieves the sewage system and prevents erosion. After revitalization, the area can also be transferred to a new use. In addition to the actual sealed surface, other pollutants on the site that are harmful to the environment can be removed at the same time. Especially in urban areas, unsealing eliminates drainage fees for the area. Another climatic aspect is the creation of air corridors. This can

*Figure 24: An area that is still sealed but has not been used for a long time, which could benefit from the measure.*

be achieved especially when larger building complexes are deconstructed.

#### 4.10.6 Obstacles

The costs of unsealing can be an obstacle if they exceed those for the brownfield site. If it is a contaminated site, unsealing and the necessary land remediation can cause additional costs. If the ownership of the brownfield site has not been clarified, this can hinder or even prevent planning, implementation and financing. Some brownfields can develop into a valuable area for nature conservation through abandonment. These include, above all, unused buildings that serve as roosts for bats.

#### 4.10.7 Stakeholders

Every owner of brownfields can unseal his or her land.

### 4.11 S-V-2: Partial unsealing with grass stones

#### 4.11.1 Aim of the measure

This measure opens up a compromise between a paved area and the possibility of decentralized infiltration of rainwater. Low grass vegetation can establish itself in the open spaces between the grass stones. In this way, not only does the rainwater that falls on the lawn stones seep away and run off, but it is also partially evaporated again via the plants. This is intended to achieve a local cooling effect on an otherwise very heated, sealed surface.

#### 4.11.2 Description/implementation

Turf stones can be used in various forms to pave pavements, car parks and driveways. This measure is implemented in two steps: 1) unsealing and 2) laying grass stones.

However, already sealed surfaces can also be transformed into partially sealed surfaces. The waste produced during unsealing must be disposed of. Afterwards, enough material must be excavated to create a shallow pit. This is filled with gravel and sand to filter the water and stabilize the grass stones. The stones are placed on top and the spaces in between are sown with grass. For the calculation of the costs and the calculation of the effectiveness, a joint proportion of 50 % is calculated (Göbel et al., 2013).

#### 4.11.3 Expected effectiveness

The evaporation performance of this measure depends on the vegetation in the gaps and especially on the proportion of joints. The greater the proportion of joints, the higher the evaporation, as more vegetation is potentially available for evaporation. With a low run-off rate and a

*Figure 25: Grass pavers allow water to seep away and enable low vegetation – they have many advantages over sealed surfaces.*

high infiltration rate, an evaporation rate of approx. 26 % can be expected (Timm et al., 2018). The evaporation results in a cooling effect compared to sealed surfaces. The measurements of Göbel et al., 2013 show an evaporation rate of 65 % of the precipitation with a joint proportion of over 50 %. A comparison between vegetated grass pavers and a neighbouring unvegetated and sealed surface showed a temperature difference of 10 K, whereby vegetated grass pavers can reach a soil temperature of maximum 37 °C and an non-vegetated sealed surface of maximum 47 °C (Schaffitel et al., 2020).

Since the ambient temperature always has an influence on the balanced temperature reduction, the shading of the turf stones, e.g. by trees, must be taken into account.

### 4.11.4 Costs

**Opportunity costs:** We assume that the use of grass pavers does not change the use of the site. We also assume that the substructure of the roads will not change, as the loads to be carried are still the same Regelwerksausschuss Begrünbare Flächenbefestigungen, 2008.

**Investment costs:** When installing grass pavers, costs are incurred for removing and disposing of the old road surface and for laying the grass pavers. In addition, there are costs for seeding.

**Management costs:** There are maintenance costs for mowing the grass or herbs. These are calculated in the same way as for the mowing of unsealed and greened surfaces. Any savings resulting from the non-recurrence of management costs for the previous pavement shall be considered.

### 4.11.5 Synergy effects

The non-evaporated part of the precipitation water can contribute to groundwater recharge as percolating water. No gradient is required, which would otherwise be necessary for the run-off of precipitation water to the sewage system. There are also no costs for the sewage system itself.

### 4.11.6 Obstacles

If there are already paved surfaces made of water-impermeable material, this must first be removed and disposed of before grass stones can be laid. The cost may increase if a suitable foundation has to be laid. Therefore, there are demolition, disposal and new construction costs. There is a maintenance cost for the grass, but this is likely to remain marginal.

### 4.11.7 Stakeholders

Every landowner (public, private) on whose property there are paths and parking areas.

# 5 Land use category: Water management

## 5.1 W-I-1: Active ditch water level management

### 5.1.1 Aim of the measure

Restoration and new construction of adjustable water-retaining structures (»culture dams «) in drainage ditches on agricultural land will retain storm-water as well as water from subsurface drains. This is accompanied by an increase in the groundwater level. The measure can thus prevent or at least delay drought stress on arable land and grassland with a high groundwater level. From an agricultural point of view, the two-sided groundwater regulation is particularly advantageous, as it avoids both too wet and too dry conditions with the help of optimally adjusted ditch water levels. In the case of two-sided groundwater regulation, an optimum groundwater level is set for the area between two inland ditches by regulating the ditch water levels.

### 5.1.2 Description and implementation

Decreasing precipitation and frequency currently lead to rapid drying of the upper soil layers already in spring/early summer. Frequent dry spells accompanied by rising temperatures further increase the water deficit for agricultural crops and quickly lead to drought stress conditions under which stomatal conductivity is reduced, ultimately reducing transpiration rates for entire stands. Sprinkler irrigation can provide relief, but represents an intrusion into groundwater or surface water resources. In general, there are insufficient water resources available for sprinkling all areas considered for this purpose. Therefore, it does not provide a blanket adaptation option to worsening climatic conditions.

Increasing groundwater levels by retaining water in ditches and receiving streams is a different matter, as it increases the amount of water available locally. A prerequisite for water retention is that already existing structures (culture dams) are functional. If this is not the case or if impoundment structures are missing, rehabilitation or new construction is required. The adjustment of the dam height should be carried out under the premise of the greatest possible water retention, but taking into account economic aspects such as trafficability and avoidance of waterlogging.

### 5.1.3 Expected effectiveness

The measure is only effective in very low-relief lowland areas that have been drained by complex meliorations and have an extensive network of inland ditches. The effectiveness results from a reduction of the groundwater flow distance, which can improve the plant water supply in dry periods.

### 5.1.4 Costs

Opportunity, investment and management costs for are calculated according to the procedure described in the measure W-I-2, chapter 5.2.

### 5.1.5 Synergy effects

By reducing or delaying drought stress, agricultural yields are secured. If water quality is sufficient, ditches provide habitat for animals and plants, especially if they are lined with trees or shrubs.

### 5.1.6 Obstacles

The dam management, i.e., the setting of the dam head, is the responsibility of watercourse maintenance associations or authorized land managers. Since the dam level of each dam exerts an influence on the entire catchment area of the ditch system, several land users and owners are usually affected. Thus, there is a high need for coordination, which cannot always be satisfied for capacity reasons. A resulting problem is the unauthorized operation of the dam by the


*Hildmann, Zimmermann, Schlepphorst, Rösel, Kleinschmidt, Kruber, Lukas, Joshi, Hecker, Witt, Sturm, Wätzold 2022, DOI: 10.5281/zenodo.6811079*

*Figure 26: Many culture dams need to be reconstructed and professionally managed in order to have a positive effect.*

land manager, which can run counter to the dam objectives.

Arable crops in particular can be sensitive to high groundwater levels, further emphasizing the importance of optimal dam management. To date, no objective decision support exists for this purpose.

#### 5.1.7 Stakeholders

Agricultural enterprises, water maintenance associations

## 5.2 W-I-2: Closure of ditches in forest areas

### 5.2.1 Aim of the measure

The aim of this measure is to close drainage ditches in the forest in a cascade way to prevent rapid run-off and to retain the water in the area, leading to the restoration of a largely natural water balance. Depending on the site, periodic floodplains are thereby promoted or varying degrees of re-wetting are achieved.

### 5.2.2 Implementation

Many forests have been drained for forestry purposes with the help of ditch systems. In particular, wet forests - forest biotopes strongly influenced by water - such as quarry and bog forests are endangered in their existence and often considerably impaired in their functional capacity (Riecken et al., 2006). They are characterized by a high structural diversity and a large number of ecological niches and are therefore of great importance for the protection of species and biotopes (Blab, 1993).

To restore a near-natural water level in the wooded areas, the existing drainage ditches will be cascaded. For this purpose, trench closures are made by filling sections with earth material and then sealing them. The number of these closures should be chosen depending on the slope of the terrain. Thus, the water is impounded at many points within the forest area. Site inspections, hydrologic studies, and mapping of the ditches are necessary to determine the exact closure points of the ditches. Existing data on the area (e.g., digital terrain model, slope/flow directions, soil type, tree species composition, forest land use objective) should also be considered. This also allows a prediction of the expected re-wetting effect.

The ditch closures are made with the help of a mini-excavator (< 2.5 t). The required material can be obtained by shallow excavation of the topsoil in the vicinity of the ditches (material native to the area). The resulting raw soil sites are also optimal for natural regeneration. Alternatively, sandy loam can be acquired and used as backfill material (non-resident material). For sta-

*Figure 27: By closing ditches in the forest, the water is available to the trees longer.*

bilization, wooden planks about 50 mm thick are first placed vertically next to each other in the ditch and then covered with the earth material and compacted, thus achieving a closure about 1 m wide (Bieker et al., 2018). This is additionally fixed on both sides with water bricks. For very small ditches, the closure material can be placed directly at the specified closure points without wooden planks and compacted with the excavator shovel. If the slope of the terrain exceeds 2%, a complete backfilling of the ditch is preferred.

Suitable sites for the implementation of the measure are forests near groundwater, which are drained by ditches. As a result of the re-wetting, there is usually a natural recolonization with site-appropriate plant communities.

### 5.2.3 Expected effectiveness

The effectiveness results from a rise in groundwater level, especially in areas adjacent to the ditches with possibly developing flooding areas (evaporation); in addition, more water is available to the plants for transpiration. More research is needed on the cooling effects of restored European wet forests.

### 5.2.4 Costs

**Opportunity costs:** None, as the availability of additional water has both negative (waterlogging) and positive (no soil drying) effects on the forest, which can only be measured individually and cannot be offset against each other in a standardized manner.

**Investment costs:** Investment costs are incurred at the beginning of the measures for the construction of the ditch shoring. Material and labour costs are incurred for the shoring. The material costs consist of piles or wooden planks and, if necessary, clay. The labour costs are to be subdivided into planning costs and construction costs. The costs are determined in a standardised way using the landscape management cost file of the Bavarian State Office for the Environment (Beiersdorf & Ullmann, 2022b), which contains information on material and labour costs.

**Management costs:** Maintenance and renewal work may be required during the 30-year observation period to be analysed. The assessment of the running costs is based on the landscape management cost file of the Bavarian State Office for the Environment (Beiersdorf & Ullmann, 2022b).

### 5.2.5 Synergy effects

Wetland forests in particular are areas of high biodiversity, providing a habitat for a variety of specialized animal and plant species such as marsh marigold, iris, moor frog, grass snake, woodcock, crane and black stork. Increased water retention in other forest biotopes also promotes biodiversity as well as tree growth (forestry yield) by reducing potential drought stress during the summer months (Bieker et al., 2018).

Increased water retention (slowing and holding surface run-off) can provide effective protection against flooding. Nearby fish-ponds benefit from the cessation of forest drainage in their watershed: rising groundwater levels also have a positive effect on adjacent areas, potentially preventing ponds from drying out during the summer months. Other synergistic effects include increased impact as carbon sinks and increased landscape aesthetic appeal (nature/hiking tourism).

### 5.2.6 Obstacles

In most cases, the financial outlay and the necessary labour input are low, since often the mere closure of drainage ditches in sections initiates re-wetting and thus the natural regeneration of the forests. However, preliminary investigations are usually necessary to find out the local conditions such as groundwater level, slope or soil properties.

Conflicts of use, especially with forestry, are possible, since many tree species cannot cope with high groundwater levels or periodic flooding, and thus adaptations of use or conversion of the stand become necessary.

In order to be able to carry out the rewetting of true floodplain forests, it may be necessary for the area to be purchased by a nature conservation or similar association. This is particularly recommended when anticipated flooding could result in abandonment of use or when adjustment of use would be uneconomical.

### 5.2.7 Stakeholders

Private and public forest owners, nature conservation associations, water maintenance associations.

## 5.3 W-I-3: Installing supporting sills in inland ditches

### 5.3.1 Aim of the measure

With the help of supporting sills (also called ground sills), the flow in flowing waters is slowed down, which slows down the sinking of groundwater levels. The implementation of this measure makes sense in inland ditches that were created for drainage but are too deep under today's climatic conditions. The higher ditch and groundwater levels benefit the vegetation bordering the ditches and thus also the agricultural and forestry crops. In dry periods, water is available to them for longer, so that their cooling function can be maintained over a longer period of time.

### 5.3.2 Implementation

Numerous inland ditches were constructed to drain lowlands for agricultural purposes, especially in the second half of the 20th century. Due to the climate change-related shift in precipitation with increasing spring droughts and due to the increasingly negative water balance, many ditches are now cut too deeply into the landscape and drain the precipitation water of the winter months too quickly. Since there is often no significant precipitation following spring tillage, in many places even the existing crop dams cannot hold back enough water. Therefore, inland ditches today contribute significantly to the drying out of the land and thus to the drought stress of the crops.

When constructing retaining sills, the effective depth of the ditch is reduced (Patt & Gonsowski, 2011; Landgraf et al., 2004; Lange et al., 1993). A sill is therefore installed across the ditch. This can, for example, consist of several oak planks lying on top of each other and secured by posts (»pilots«). In order to avoid deepening behind the threshold, it may be useful to secure it with armourstone. In many cases, it makes sense to use retaining sleepers and riprap in combination.

With the support sills, the draining effect of the ditch is reduced throughout the year. The distance between the ground level and the upper edge of the supporting threshold should be 0.8 m for arable land, 0.5 m for grassland or forest and 0.3 m for neighbouring peatland. Adjustments to the sleeper height may be appropriate depending on the soil conditions and terrain relief of the adjacent land. The number of supporting sleepers depends on the existing relief, so that after a slope of more than 0.20 m the next sleeper should be realized. The ditch thus retains its function of draining excess water from the area. The trafficability ´and usability of the areas is not generally restricted by this measure, provided that it is implemented professionally.

Sediment accumulates behind the sleepers, which can be left on site in the sense of a deliberate raising of the bottom. The supporting sills will thus foreseeably become bottom sills.

The measure is intended for artificially created watercourses, i.e. ditches. In contrast to natural watercourses, the aspects of reduced bedload transport or passability for watercourse organisms (construction of bed slides instead of supporting sills, Patt & Gonsowski, 2011; Lange et al., 1993) play only a subordinate role here and are therefore not considered further.

The installation of retaining sills does not constitute a watercourse development and, according to §87 BbgWG, as part of watercourse maintenance, does not require a permit (Ministerium für Landliche Entwicklung, Umwelt und Landwirtschaft des Landes Brandenburg, 2019).

#### 5.3.3 Expected effectiveness

The measure is particularly effective in lowland areas with low relief, where a few sills can already achieve an extensive backwater or a rise in the groundwater level. The effect is aimed at improving the water supply of the plants by reducing the groundwater flow distance. Especially in dry periods, plant growth and the cooling of the landscape can be maintained for longer.

#### 5.3.4 Costs

Opportunity, investment and management costs are calculated according to the procedure described in the measure W-I-2, chapter 5.2.

#### 5.3.5 Synergy effects

The measure contributes to safeguarding agricultural yields. Wetland biotopes located in the catchment area of the inland ditches are protected from drying out in periods of drought for longer due to the lower ditch water runoff and the higher groundwater levels. Since the thresholds should also keep the ditches themselves in water for longer, the fauna and flora in the ditches also benefit.

#### 5.3.6 Obstacles

Improper implementation can lead to waterlogging of adjacent areas, which is why detailed planning on site with the participation of all affected land users is absolutely necessary. In general, acceptance problems can occur if the necessity of the measure is not recognized due to a lack of awareness of the changed climatic regime. In contrast to culture dams, dynamic regulation of the ditch water level is not possible in the case of retaining sills, which means that rapid removal of larger quantities of water in times of water surplus is not possible.

Supporting sills can only be installed in inland ditches that do not have subsurface drains discharging into them.

#### 5.3.7 Stakeholders

Water maintenance associations, agricultural enterprises

# 6 Land use category: Nature conservation

## 6.1 N-I-1: Restoration of wet meadows

### 6.1.1 Aim of the measure

The goal of the measure is the re-wetting of former drained wet meadows to cool the surrounding area through the evapotranspiration of plants and evaporation of water surfaces. This can be

*Figure 28: Wet meadows have a positive effect on the microclimate.*

achieved by rising the groundwater level and therby restoring natural site conditions.

### 6.1.2 Implementation

Wet meadows are moist to wet biotopes largely free of woody plants and characterized by a cover of grasses, sedges, rushes and other herbaceous plants. To restore near-natural water levels within drained grasslands, closure or impoundment of drainage ditches is implemented. To determine the exact type or points of closure of the ditches, hydrological studies and mapping of the ditches are necessary, as well as a review of existing data on the area.

For smaller ditches complete or sectional backfilling will be performed. The earth material to be used will be placed in the ditch using a mini-excavator. In the case of sectional backfilling, an approx. 1 m wide ditch backwater is created every 20-50 m, depending on the slope of the terrain, and compacted with the excavator shovel. Thus, the water is impounded at many points within the meadow.

In order to maintain some degree of control over the re-wetting process and to prevent flooding of surrounding cropland, impoundments will be constructed at larger ditches or existing impoundments will be replaced and managed. By overdamming the ditches, the groundwater level can even be raised above ground level, at least on a small scale. An alternative to the dams is the implementation of a bed raising in deeper ditches to reduce the run-off.

In the course of re-wetting, a natural recolonization with site-appropriate plant communities (sedges, rushes, etc.) now occurs in the wet meadow, which increases the cooling of the surrounding area via transpiration. Keeping the areas free of successively growing woody plants and thus preserving the wet meadow must be ensured by extensive use (e.g. extensive mowing or grazing with low livestock density) or regular bush cutting.

### 6.1.3 Expected effectiveness

The cooling effect of wetlands can extend up to 400 m into the surrounding area (site-specific) (Simsek & Ödül, 2018). Intact wetlands can evaporate 34 % more water than heavily drained areas (Wu et al., 2016). Surface run-off is attenuated on meadows compared to cropland.

### 6.1.4 Costs

**Cost calculation in nature conservation** The cost data in nature conservation are broadly based on calculations for Bavaria (Beiersdorf & Ullmann, 2012). These are adjusted according to current data for material costs as per local advertisements, machine costs as per the KTBL calculator (KTBL, 2022) and labour costs as per the federal collective agreement for landscape conservation (Bundesverband Garten-, Landschafts- und Sportplatzbau e. V., 2021).

**Opportunity costs:** For this measure, opportunity costs arise from the conversion of land used for agriculture to wet meadows. They result from the difference between the profit of the old use and the profit of the wet meadows. It is assumed that the drainage ditches cannot be used for agricultural purposes, but that costs are incurred due to their maintenance. The profit generated on the land previously used for agriculture is calculated according to the measures in agriculture. The potential profit for the wetland meadows is determined according to the usual cost assessment for contractual nature conservation. It amounts to the site-specific profit resulting from the potential agricultural use, as applicable.

**Investment costs:** During the implementation of the measure, there are costs associated with the sealing of the drainage ditches. These are composed of the costs for filling material, the costs for the machinery and the labour costs (Beiersdorf & Ullmann, 2022b).

**Management costs:** With economically unusable wet meadows, costs arise as regular maintenance mowing is required to prevent brush encroachment. This also applies to the surfaces of the former drainage ditches.

### 6.1.5 Synergy effects

Wet meadows serve as retention zones for flood events by delaying the release of water to streams and rivers (water storage and retention). There are significantly lower nutrient discharges than with other forms of cultivation (drinking water protection). Furthermore, wet meadows promote groundwater recharge. In addition to the importance of wet meadows as an important part of the traditional cultural landscape, they are above all a habitat worth protecting for numerous endangered plant and animal species.

### 6.1.6 Obstacles

Management of the meadows needs to be adjusted due to higher groundwater level. The importance of the wet meadow as an agricultural production area (e.g. for livestock feed production) has continuously decreased due to the lower yield and the higher price of the hay. Therefore, the measure will only be economically attractive in connection with contract nature conservation.

### 6.1.7 Stakeholders

Farmers, nature conservation organizations, municipalities

## 6.2 N-I-2: Peatland restoration

### 6.2.1 Aim of the measure

Re-wetting degraded peatlands with unfavourable conservation status by raising the groundwater level increases water retention in the landscape and increases the area of an ecosystem with high evapotranspiration capacity. In addition, the climate-damaging effect of drained peatlands (release of large quantities of climate-damaging gases) is prevented.

### 6.2.2 Implementation

Growing, peat-accumulating peatlands in Germany only exist on 1 % of their former area (Couwenberg & Joosten, 2001) and mainly represent small-scale peatlands or partial areas of formerly large-scale peatlands. Comprehensive peatland restoration (peatland revitalization) requires a variety of measures to restore growing and vital peatlands (Succow, 2001). However, since the primary goal of the measure described here is the cooling of the landscape achieved through re-wetting, the work steps required to implement the measure are limited to restoring the natural water balance. With reference to the respective situation on site (identification of the re-wetting potential, ditch system, slope inclination, etc.), each peatland area requires a differentiated consideration and the development of an overall concept.

*Figure 29: To preserve the fens, the existing drainage ditches must be closed again.*

Water levels in degraded peatlands often lack elevation and stability due to increased run-off from drainage, accelerated surface run-off, and/or groundwater extraction. Therefore, rapid and direct run-off of rainwater via drainage ditches must be prevented.

To achieve this, smaller ditches are completely backfilled. The material used for this purpose may be resident material or non-resident material (sandy loam). An alternative is to backfill the ditches with sawdust according to the Zug method (Staubli, 2004). This has proven to be a suitable substitute material because it is easy to transport, inexpensive, usually locally available, and purely organic. To carry it out, wooden stakes are inserted into the ditch at intervals of 2 to 15 meters, depending on the slope of the terrain, and the ditch sections are backfilled with the material of choice (Grosvernier & Staubli, 2009).

To maintain some degree of control over the re-wetting process and prevent flooding of surrounding farmland, weirs are constructed on larger ditches or existing weirs are renewed and managed, which is also an effective measure for raising the marsh water table (Edom et al., 2007; Brooks & Stoneman, 1997; Dietrich et al., 2001; Schuch, 1994).

### 6.2.3 Expected effectiveness

It has been demonstrated that re-naturalized peatlands can serve as cool, moist islands within the landscape, protecting it from overheating (Worrall et al., 2019).

### 6.2.4 Costs

**Opportunity costs:** Under this measure, opportunity costs arise from the conversion of land used for agriculture or forestry to peatland. These arise from the foregone profits of the previous use.

**Investment costs:** As with the creation of wet meadows, costs are incurred for the closure of the drainage ditches when the measure is implemented. These consist of the costs for the filling material, the costs for machinery and the labour costs.

**Management costs:** None.

### 6.2.5 Synergy effects

Intact peatlands remove 150-250 million tons of $CO_2$ (carbon sink and carbon sink) from the atmosphere worldwide each year by sequestering the CO2 absorbed by plants during their growth in peat after they die.

Peatlands perform an important water retention function during flood events by creating large areas of peatlands capable of overdraft and expansion as temporary water storage. In addition, peatlands serve as habitats for many rare and protected animal and plant species and specialized communities. Further, they are pollutant sinks.

### 6.2.6 Obstacles

Conflicts of use may arise if the re-wetting measures affect e.g. adjacent agricultural or forestry areas (periodic flooding, adjustments of use or even abandonment of use). Despite the re-wetting concept to be developed for each peatland site, there is a rather large forecast uncertainty. In the meantime, suboptimal stages (methane outgassing) may have to be accepted.

### 6.2.7 Stakeholders

Nature conservation organizations, farmers and foresters, municipalities

## 6.3 N-II-1: Creation of small water bodies

### 6.3.1 Aim of the measure

When creating artificial small water bodies such as ponds or pools, a hollow form is created which is permanently or periodically filled with water. The increased water retention and evaporation through the newly created water surface as well as the riparian vegetation results in a cooling of the surrounding landscape.

### 6.3.2 Implementation

Before construction can begin, preliminary explorations are necessary to select the optimal site (see below). The most common method of creating small water bodies is to create a hollow form in a natural depression or trough, which is filled with surface water (precipitation, surface runoff). For this purpose, an excavator is used to create an excavation about 2 m deep in the centre and about 200 m$^2$ in total. The shape should be based on natural wetland biotopes (flattened watercourse edge: 0.2 m deep, 0.50 m wide) to enhance the watercourse as a habitat for animals (Stolz & Riedel, 2014). Due to the sandy soils prevailing in the Elbe-Elster district, the bottom and the sides of the newly created small water body need to be compacted with a 0.5 m thick clay layer (application in several, individually compacted layers). On top of the clay layer, an additional 0.1 m thick layer of wash mud (pressed mud) is applied, which additionally seals the subsoil. Thus, the completed small water body is now approx. 1.40 m deep. On areas with clay soil, the bottom and sides of the water body can be compacted with an excavator shovel instead of sealing with a clay/wash mud layer. In this case, only an excavation of 1.5 m depth is necessary.

Depending on the intensity of precipitation, it may take several weeks for the hollow form to fill with water. Detailed planning for the creation of the small water body, which takes into account the particular characteristics of the site, is appropriate.

The advantage of this measure is that it can be carried out relatively quickly and inexpensively, as the construction measures only have to be carried out on a very small scale. Successional vegetation typical of the banks also forms quite quickly, often already in the year following the creation of the small water body (Stolz & Riedel, 2014). The excavated material can be used to build earth banks near the small water body as habitat for lizards, for example.

### 6.3.3 Expected effectiveness

Evapotranspiration is increased by the newly created water surface and riparian vegetation. However, the effect is often only temporary, as many small water bodies carry water only periodically or silt up after a few years if no maintenance measures are carried out.

### 6.3.4 Costs

**Opportunity costs:** The sites on which small water bodies may be created strongly differ from each other. Accordingly, the opportunity costs are calculated depending on the location and par-

*Figure 30: A newly created small water body with shallow banks for amphibians.*

allel to the cost calculation on comparable areas for the measures in the settlement sector and the agricultural sector.

**Investment costs:** The costs associated with the creation of these small water bodies consist of the costs for digging a depression and (on sandy soils) the costs for layering clay within the depression. The resulting hollow then fills up with water on its own. The vegetation likewise emerges of its own accord.

**Management costs:** Since small water bodies are particularly prone to siltation, they require regular desedimentation. Any surplus vegetation in the water body should also be removed during this process. The costs are calculated according to standard landscape management costs (Beiersdorf & Ullmann, 2022b).

### 6.3.5 Synergy effects

The implementation of the measure counteracts the strong decrease of small water bodies in Germany since the end of the 19th century (Drews & Ziemek, 1995). Habitats for endangered species are created, optimized and connected. For example, small water bodies serve as stepping stones for amphibian migration and are habitats for about 1000 animal and 200 plant species (Drews & Ziemek, 1995), including protected dragonfly and bird species. Furthermore, the water body provides a water supply for animals living in the surrounding area and enhances the aesthetic appeal of the landscape.

### 6.3.6 Obstacles

The creation of small water bodies can lead to conflicts of use, e.g. with agriculture or forestry by reducing the manageable area. Other points of criticism could be the (anthropogenic) encroachment on the landscape itself, or in the settlement area disturbing odours and mosquito populations (Stolz & Riedel, 2014). Annual drying during the summer months, but during which cooling by evaporation is most likely to be needed, is possible. In addition, especially in shallow, eutrophic small water bodies with reed canopy cover and lack of inflow, complete siltation is likely after about 5-20 years, depending on the site. This process is accelerated by nutrient input from adjacent agricultural areas or leaf fall. Thus, regular maintenance is necessary for most small water bodies, e.g. desilting/dredging or removal of vegetation if the pond is overgrown. These maintenance activities, as well as the creation of the small water body, must be carefully planned to minimize the risk of injury or death to occurring wildlife species (e.g., hibernating amphibians in the pond mud and breeding birds in the reeds). It is recommended that maintenance work be carried out on the small water body every five years.

### 6.3.7 Stakeholders

Nature conservation associations, local authorities, farmers, foresters, landowners

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GEFÖRDERT VOM

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## 8 Glossary

**Opportunity costs** forgone profit or benefit of the best alternative use of resources that are deployed to implement the described measure.

**Discounting** Discounting calculates the present value of future costs or benefits. Cost and benefits in the future are considered to be of less value for human beings than costs and benefits that occur in the present. A reason for that is that the future is in contrast to the present uncertain. Human beings value resources that are available to them in the present more than resources that are available to them in the future. Therefore, future costs and benefits need to be discounted with a discount rate r.

**Present value** The present value expresses the value human beings assign in the present to payments that occur in the future. Future payments need to be discounted as human beings value the future less than the present (see also Discounting).

**Investment costs** Investment costs are costs that are incurred at the beginning to implement the described measure

**Management costs** Management costs are costs that periodically accrue for maintenance, once the described measure has been implemented.

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