

Costs and benefits of landscape-based water retention measures as nature-based solutions to mitigating climate impacts in eastern Germany, Czech Republic, and Slovakia

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Abstract

In eastern Germany, the Czech Republic, and Slovakia, historic policies led to large, monocropped agricultural landscapes resulting in degradation of traditional landscapes. In the last 20 years, the expansion of urban and industrial areas has added to this degradation. The growing interest in nature-based solutions, including water-retention measures, is a response to reversing landscape degradation, rejuvenating ecosystem services, and mitigating the impacts of large-scale commercial agriculture and climate change. In this study, the costs and benefits of water-retention measures in east Germany, the Czech Republic, and Slovakia are assessed. Results indicate that water-retention measures offer increased water availability over all land use classes assessed, help increase crop productivity, and aid in landscape cooling. Croplands are suggested as being the best value for money, offering the greatest volume potentials (mean = 88 million m³), cooling effects (mean = -1.6°C), and productivity gains (mean = €66 million yr⁻¹), while also being the cheapest to implement per unit area. Differing policies in the three states will likely result in non-uniform selection or implementation of measures. Future work should focus on local-level studies offering greater practical messages beyond the regional-level analysis conducted here. This work contributes to the growing body of literature assessing the costs and benefits of water-retention measures, including the potential for landscape cooling, lowering temperature gradients, and ecosystem restoration. As the world urbanises, and as more land is converted to homogeneous cropland, such measures may prove critical in mitigating climate change, landscape drying, flood runoff, and soil and nutrient loss.

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Keywords

Climate mitigation; landcover; Germany, Czech Republic, Slovakia; nature-based solutions; water-retention measures.

Introduction

Extensive drainage and the loss of native functional vegetation has resulted in landscapes becoming degraded and subject to desertification (Ripl, 1995, 2003). Degraded landscapes have lower buffering capacity against natural hazards including floods and droughts, as well as reducing nutrient cycling and erosion control, leading to lower land productivity and increased displacement of soil (Khan and Hanjra, 2008; Borelli et al. 2017). For example, in Slovakia the loss of soil through water erosion averages 0.01-0.03 mm yr⁻¹ in (mountainous) forested regions, 0.06 mm yr⁻¹ on grasslands, 1.8 mm yr⁻¹ on cereal fields, 3.4 mm yr⁻¹ over bare ground, and 3.6 mm yr⁻¹ on root crop fields (Midriak, 2004). Similarly, Belete et al. (2020) show the impacts of land cover change and climate variability on local water supply in the Blue Nile Basin, and suggest that ecosystem-based strategies should be adopted to mitigate against future impacts. Currently, about 52% of global agricultural lands are classified as moderately to severely degraded and at risk of abandonment (Iseman and Miralles-Wilhelm, 2021) with unavoidable impacts to both the environment (nutrient leakage, soil erosion) and humans (food yield losses, financial losses). To restore ecosystem functionality, it is important to improve the sustainable use of landscapes, for which a range of nature-based solutions (NBS) are available. Indeed, *“nature-based solutions aim to protect, sustainably manage, and restore natural and modified ecosystems to address societal challenges effectively, and to provide human well-being and biodiversity benefits. They are underpinned by benefits that flow from healthy ecosystems and contribute to addressing major challenges including climate change, disaster risk reduction, food and water security, health, and are critical to economic development”* (www.iucn.org). The use of NBS to address climate challenges is increasing, with nature-based water retention methods being identified as solutions for water management challenges (Khan and Hanjra, 2008; Burek et al. 2012; Grimaldi et al. 2013; Belete et al. 2020; Balden et al. 2021; Staccione et al. 2021). Compared to engineered solutions, NBS can be cost-effective, offering multiple co-benefits (EEA, 2015; Cohen-Sachman et al., 2016; EC, 2015; Hodgson et al., 2016; Masi et al., 2017), including supplying additional water resources, nutrient management, flood and drought mitigation, decreasing local sediment transport, as well as aesthetic and recreational functionality (Burek et al. 2012; IPBES, 2019; Okruszko and Bokal, 2020; Balden et al. 2021).

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Some central aims of water retention measures (WRM) are to retain rainwater and stormwater and gradually return it to the local water cycle, to replenish soil and groundwater reserves, feed springs, reduce erosion, and contribute to mitigating flood and drought risk. Such measures can lead to restoring biodiversity, increasing soil fertility, creating additional water resources, and rehabilitating the local climate (Brouwer and Fournier, 2017; Sušnik and Masia, 2020; Program Obnovy Krajiny, 2021). They can increase ecosystems' capacity to deal with stress (i.e. enhanced resilience and adaptability), a crucial sustainability objective (Lodemann et al., 2010). WRMs address water and landscape issues while enhancing environmental quality and contributing to improving agricultural productivity (Staccione et al. 2021), promoting local economies. They contribute to priorities of the European Green Deal (EU, 2019), the 2030 Agenda for sustainable development (UN SDGs; UN, 2015), the Common Agricultural Policy (CAP; Magaudda et al., 2020) and the Water Framework Directive (WFD; Okruszko and Bokal, 2020). WRMs also contribute to habitat preservation, recreational and social benefits, and local climate regulation (Kravčík et al., 2007; EC, 2013; Program Obnovy Krajiny, 2021). Their value can be assessed in terms of ecological contributions and/or in monetary terms (Häyhä and Franzese, 2014; Barth and Döll, 2016). WRMs can be divided into technological, biotechnical, and technological-preventative/economic in nature (Kravčík et al. 2007). Technological measures include absorption ditches, depressions, improvement of land surfaces to enhance infiltration, small dams and reservoirs, and anti-erosion measures. Biotechnological measures are similar, but with a focus on the use of natural vegetation rather than engineered solutions. Examples of technological-preventive and economic measures include the application of optimal approaches for protecting soil, ensuring the replenishment of excess water runoff, the limiting of non-vegetated hard surfaces in built-up areas, replacing impermeable surfaces, preventing the clear-cutting of forests, improved land-use planning, integrated land management, and more sensitive uses of the land with a view towards conservation.

Evapotranspiration, along with non-utilised outflows, are often deemed “lost” components of the hydrological cycle. Rising ‘overheated’ air draws moisture from surroundings, transporting water vapour to the upper atmosphere. This results in an open water cycle. As warm air accommodates more water vapour, greater levels of landscape drying can result as a consequence. Over crops and other degraded landscapes, such vertical temperature profiles are often found. The ascending warm, moist air transports higher volumes of water, drying the soil surface and causing crop water losses. Such surface drying due to ‘overheated’ surfaces, especially over drylands due to land-atmosphere feedbacks, has recently been reported by Schumacher et al. (2022) who observed that strong evaporation over hot land surfaces can exacerbate surface and soil drying, and can lead dryland drought propagation. On the other hand, native vegetation is able to dampen such vertical

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temperature extremes, reducing surface temperatures. Stands with well-developed vertical structure differ in vertical temperature distribution from monocultures. An inverse temperature gradient is created during warm days in forests and beneath trees. High humidity is maintained in lower vegetation, often in the form of dew. Because the temperature of canopies approaches the air temperature, there is little sensible heat to ascend. Water vapour-saturated air slowly rises and reaches the dew point, creating local afternoon/evening rainfall, returning some of the evaporated water to the surface. A (partially) closed water cycle is formed (Makarieva and Gorshkov, 2007). It is important to distinguish between drying of the landscape caused by overheated air, and evapotranspiration with a local cooling effect which “recycles” water locally (Huryna et al. 2014; Pokorný et al. 2016; Hesslerová et al. 2019; Pokorný 2019). It is the latter situation which water retention measures aim to partially restore in the transboundary region considered in this study, where large swathes of landscape have been degraded.

There is guidance on the selection and implementation of nature-based WRMs (Strosser et al. 2015, EEA, 2015; Okruszko and Bokal, 2020), including defining WRMs, selection and implementation criteria, policy coordination, and cost-analysis. Liu et al. (2017) offer a detailed review of NBS, including WRMs, and their effectiveness. It is shown that many studies focus on quantifying water availability increases or flood decreases, or changes in pollutant, nutrient and/or sediment loads. Little mention is made of cost-benefit analyses, nor of local climate modulation. Sejak et al. (2018) added to the quantification of ecosystem services the thermodynamic aspect and regulatory services of ecosystems (climate services, water retention, oxygen production, biodiversity). Keestra et al. (2018) describe the beneficial impacts of NBS on ecosystem services, but do not consider the benefits to local hydrological cycles or temperature regulation, or consider the costs of implementation. Therefore, in the literature, there are a lack of locally relevant studies considering the costs and benefits of WRMs, especially in the context of climate and hydrological modulation. Okruszko and Bokal (2020) present a concept for the selection and implementation of WRMs, rather than detailing their post-implementation impacts, although for some select cases, the relative change in river flows is assessed. Strosser et al. (2015) present examples from five case studies, with a focus on impacts to peak flow reduction, pollutant/nutrient control, and the benefits on biodiversity, but do not consider local climate impacts or cost-benefit analysis. Staccione et al. (2021) characterise the effectiveness of retention ponds in the Lamone River catchment, Italy. It is shown that such ponds increase the water available for irrigation and could contribute to ecological improvements. Based on a cost-benefit analysis, it is suggested that the ponds are financially sustainable in the long-run, yet they do not consider the local climate regulation of the WRMs. Mayor and Bautista (2012) focus on the improvement of soil properties resulting from water and soil retention, showing potential for improvement especially on dry or

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parched landscapes. Balden et al. (2021) use a modelling approach to simulate the effectiveness of WRMs in reducing fine bed material load in rivers. Khan and Hanjra (2008) describe a study modelling the hydrological impacts on land and water management measures in the Murray-Darling basin, Australia, but do not assess productivity changes, nor climate regulatory impacts. Grimaldi et al. (2013) assess the monetary sustainability of soil and water conservation measures in the Sahelian area of Burkina Faso. It is shown that small-scale, locally-suitable measures can be monetarily sustainable in the long run, as well as offering soil retention benefits. However, it is also indicated that other, more extensive land-use changes may also be needed. Also in Burkina Faso, Nyamekye et al. (2020) use satellite-derived MODIS data to assess the impacts of implemented soil and water conservation measures. Based on measurements on the normalised difference vegetation index (NDVI), it was shown that such measures have resulted in landscape restoration by improving overall greening. However, impacts to hydrology, productivity, and climate regulation could not be assessed. Sejkál et al. (2022) suggest that the Želivka River Basin, Czech Republic, does not contribute fully to society (e.g. GDP, recreational value) due to long-term poor landscape management, and that improving landscape-based water retention would aid in restoring full ecosystem functioning and services. However, no quantification of these potential benefits was carried out. Therefore, while studies have started to consider WRMs, including locally in the Czech Republic, the selection, implementation, and impacts, mostly focus on hydrological and/or soil-related impacts. Few consider the costs and benefits of implementing WRMs, and even fewer consider the effect on local climate regulation potentially resulting from WRM implementation. In addition, few studies consider locally-relevant case studies in extensively degraded regions.

This article addresses these shortcomings by describing the assessment of the potential impacts of landscape-based WRMs in a transboundary Eastern Germany-Czech Republic-Slovak case study. The study considers locally-relevant hydrological, agricultural, and climate-regulation impacts resulting from the implementation of landscape-based WRMs. It outlines a cost-benefit analysis for potential measures, thereby adding to the growing literature on water retention measures in particular, and NBS in general. In the study region, the role of extensively drained fields and their impact on the distribution of solar energy and the effects of water-related landscape restoration measures on local climate and the water cycle are explored. Due to the level and extent of degradation, restoring landscapes to reduce land and climate impacts is increasingly urgent, and evidence to support the implementation of NBS and WRMs from a number of viewpoints is necessary. In this regard, a main focus of water retention measures in the region is to rehabilitate local water cycling to mitigate floods and droughts, enhance soil water conditions, lower temperature extremes, and act to cool an increasingly overheated landscape. This study considers the potential impacts of WRMs to contribute

to these challenges, and considers the costs and productivity benefits of such measures being considered, adding to the existing literature on such water retention measures as well as being locally-relevant for decision makers.

Case study description

The study area covers the whole territories of the Czech Republic (78,871 km²) and Slovakia (49,035 km²). The German part of this transboundary case study covers the former German Democratic Republic (108,944 km²). The study region was divided into 15 sub-regions based on NUTS-2 unit divisions (Figure 1).

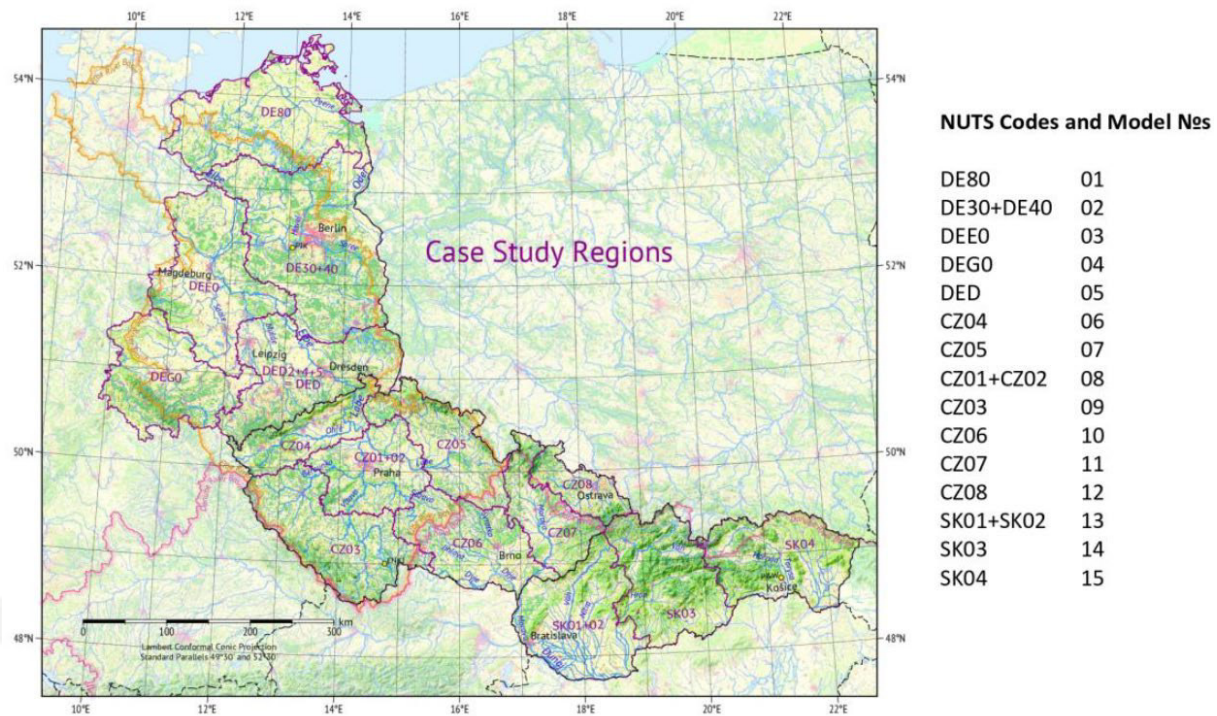


Figure 1: Map showing the case study region and the separation into the 15 modelling units based on NUTS-2 level regions. Key on the right indicates region numbering used in the text and figures.

The study area shares a common history of socialist rule which helped shape the landscape. There were very large field blocks generated through collectivisation in 1949 – 1960 and 1970 - 1989 that are still present as uniform agricultural monocultures despite the original (pre-1940s), splintered property rights being re-established. In the past 30 years, there has been no significant landscape structural change in the case study, which could have improved the retention and accumulation of water, reduced nutrient losses from fields, and decreased the local surface temperature. Associated

phenomena resulting from historical developments include losses in agricultural yields and both quantitative (floods and droughts) and qualitative (higher nutrient and matter losses from catchments) water-related problems (Hesslerová et al. 2013, 2019; Ellison et al. 2017; Huryňa and Pokorný 2016; Ripl, 2003). The situation has deteriorated in recent years despite the EU's efforts to introduce various agro-environmental measures along with various proposed measures to mitigate climate change.

This study envisions water as a natural hub between nexus sectors (cf. Hoff, 2011), being related to the water–land–climate nexus based on landscape energetics (Ripl, 1995; Ellison et al. 2017; Hesslerová et al. 2013, 2019). Water connects all parts of the hydrological cycle, which is driven by solar energy input (Figure 2). The aim of the study is to determine the role of WRMs in the landscape. In terms of the local climate, the study addresses the issue of the relationship between vegetation and the near-surface temperature, which is one of the key characteristics of the solar-driven energy balance of the landscape. The hydrological aspect focuses on the importance of evapotranspiration, which is not interpreted as a loss of water, but as an important process of closing the water cycle and cooling the landscape. In the study, there is a distinction between evapotranspiration as a cooling process and the upward flow of heated air from overheated drained surfaces, which cause rapid landscape drainage. The “water rotor” concept (Kravčík et al. 2007; Figure 2) gives an illustration of this concept.

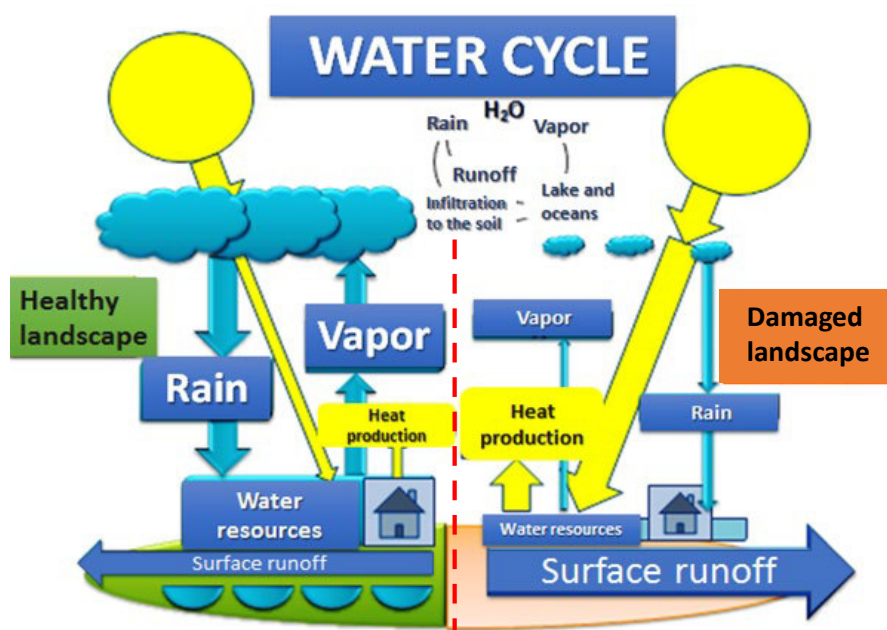


Figure 2: The Water Rotor concept, illustrating the differences in local hydrological cycles between healthy landscapes (left) and damaged landscapes (right). Adapted from Kravčík et al. (2007).

In the study area, WRMs are being considered for a number of reasons, and have been implemented in various initiatives (Figure 3). Increasing water availability in the landscape would help reverse structural drought generation processes of current land management approaches, referring to the dominance of “empty” agricultural landscapes (i.e. monocultures) in lowlands that generate dry surfaces, especially after harvest, leading to elevated surface temperatures and convection of dry, hot air, in turn further drying the landscape. Such measures contribute to water quality improvement, which is generally not sufficient in any water body in the region. There are challenges surrounding food production, including soil degradation (loss of organic matter, compaction, erosion) and the increase of biomass production for bioenergy generation (rape for biodiesel and maize for biogas). Increasing the diversity of cultural landscapes including reducing the size of field blocks, interspersing hedges, shelterbelts, and other woody (forest) structures, plus introducing or rehabilitating watercourses, ponds, and wetlands aim to mitigate these challenges.

(a)



(b)



(c)

(d)



(e)

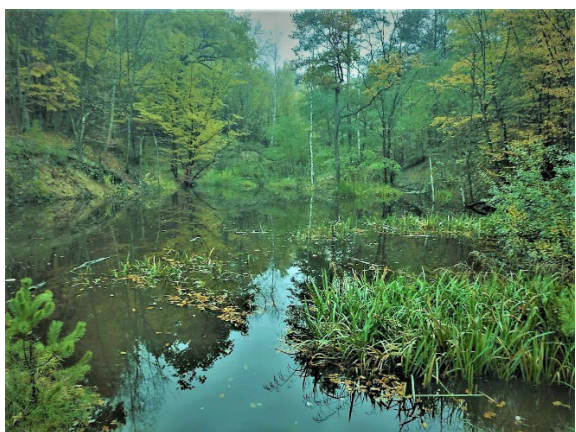


Figure 3: nature-based water-retention measures currently installed throughout the study region. A bioretention approach for water retention on a former logging road in Ťahanovce, Slovakia, in (a) 2011 and (b) 2020. Rejuvenation of a previously degraded landscape in Slovakia, showing the same site in (c) 2012, (d) 2014, and (e) 2020. Photographs courtesy of Michal Kravčík.

Methodology and data

Methodological process

The approach is based on Kravčík (2021) for which the benefits of investing in water retention measures are estimated. Water retention in the landscape creates new reserves of water resources. Through evapotranspiration thermoregulation of the landscape, sensible heat loss and temperature reduction is enabled, with potential increases in crop yields and carbon sequestration. This study assesses a number of metrics: 1) the volume of water transported from the ground in the form of water vapour, representing an evaporative cooling potential; 2) investments required for new water retention measures; 3) the volume of water from measures available for atmospheric cooling and; 4) the decrease in 'hot day' temperature over different land covers. Surface and air temperature are used

to calculate the velocity of ascending air. Combined with absolute humidity, this is converted into the volume of water released to the atmosphere. The cost per 1 m³ of new WRMs over different land use types is multiplied by the volume of potential water retention measures to estimate the investments required to realise new landscape-based WRMs. Via water retention measures, evapotranspiration is increased, and using this information, the additional water released to the atmosphere (i.e. additional cooling) is calculated. This is translated into the solar energy transferred to evaporation, and thus to the assessment of near-surface temperature reduction on 'hot days' over different land uses. To assess the impacts of WRMs on the local climate and hydrology, and to estimate costs and benefits of the measures, a series of calculation steps were required, outlined below. Numerous data were required to perform the calculations, summarised below.

The first part of the method estimates the volume of water transported from surfaces to the atmosphere. It aims to reflect water that is 'lost' from surfaces due to overheating as a result from being altered from their natural state. The area of land covered by different land classes was determined in each sub-region (Figure 1). The land classes (m²) are: forests, agricultural land, wetlands and meadows, bare ground, water, vineyards, pastures and permanent grasslands, urban areas, and roads, which were obtained from the SWIM and CAPRI models (next section). The air temperature (T_a ; °C) was assessed for a range of values from 18°C to 40°C, corresponding to an emphasis on the growing season. T_a was related to the surface temperature (T_s ; °C) via a T_a - T_s lookup table (based on long term data collection, see Hesslerová et al. 2013, 2019, 2021; Ellison et al. 2017; Supplementary Information). As an example, at a T_a of 20°C, the T_s is 25°C for bare ground and urban areas and 18.5°C for forests. Relative humidity (Rh; %) is a variable that together with T_a , yields values of absolute water humidity (A_{wh} ; g m⁻³) via another lookup table (based on a h-x diagram; Supplementary Information). For each T_a between 18 and 40°C, Rh was varied from 10-100%, giving 230 combinations of T_a and Rh. From the above, the velocity of ascending air, i.e. vertical acceleration of an air particle due to temperature difference (V_a ; m s⁻¹) is ascertained:

$$V_a = -g * ((T_a - T_s) / T_a) \quad (1)$$

where g is the acceleration under gravity (9.81 m s⁻²). This is a simplification of the principle, not considering the change in the velocity of the emerging particle with height. V_a is multiplied by 3600 to obtain the volume of hot air released from 1 m² of heated surface in one hour (V_m ; m³ hr⁻¹). This is subsequently converted to the volume of water transported (V_t ; l m⁻² hr⁻¹) using:

$$V_t = (A_{wh} * V_m) / 1000 \quad (2)$$

This is converted again into the volume of water transported (V_{wt} ; m^3) from each land class in each sub-area in one hour:

$$V_{wt} = (\text{land class area} * V_t) / 1000 \quad (3)$$

The second part of the method is concerned with the potential impacts of landscape-based water retention measures in storing water in the landscape, reducing near-surface air temperatures. For the remaining calculations, a number of assumptions are made regarding the volume of water stored in water retention measures in different land use classes, the investments required to construct the measures, the intensity of new water 'created', the increase in evapotranspiration (E_t), the potential increase in agroforestry production, sensible heat reduction, and the potential temperature reduction (Table 1).

Table 1: assumptions for parameters used in the estimation of the impact of water retention measures.

Land use	Water retention potential ($m^3 \text{ ha}^{-1}$) ^{1,2}	Investment (€ m^{-3})	Increase of evapotranspiration ($\text{mm ha}^{-1} \text{ day}^{-1}$)	Agroforestry production (€ ha^{-1}) ³	Sensible heat reduction ($\text{GWh ha}^{-1} \text{ day}^{-1}$) ⁴	Temperature reduction ($^{\circ}\text{C}$) ⁵
Urban ⁶	300	20	6	0	0.042	4.8
Agriculture ⁷	100	5	4	75	0.028	3.2
Forest	40	5	2	75	0.014	1.6

¹Defined for an average rainfall of 35 mm. The retention potential is based on Kravčik (2021).

²Assumed that each 5000 m^3 of water retention creates water sources at an intensity of 1 l s^{-1}

³Assuming that 1.5 t increase in production = €75

⁴Evaporation of 1 l requires 700 Wh (rounded value used in calculations. The specific heat of water vaporization depends on the temperature at which vaporization takes place. At normal air pressure the values are as follows: 0 $^{\circ}\text{C}$ ~ 2500 kJ kg^{-1} (695 Wh); 25 $^{\circ}\text{C}$ ~ 2450 kJ kg^{-1} (680 Wh); 100 $^{\circ}\text{C}$ ~ 2250 kJ kg^{-1} (627 Wh).

⁵Evaporation of 80000 m^3 water at a height of 100 m decreases temperature by 1 $^{\circ}\text{C}$

⁶Includes built up areas and road infrastructure

⁷Includes agriculture land, grasslands, gardens, and vineyards

The volume potential of water retention measures ($\times 10^6 \text{ m}^3$) is estimated by multiplying the area of the land use class by the water retention potential and dividing by 1000000. The investment requirement is estimated by multiplying the volume potential by the investment required per 1 m^3 .

The increase in (agricultural) production is the product of area and agroforestry production. Total sensible heat reduction (GWh) is the area multiplied by the values in Table 1. The decrease of the local temperature (T_{drop}) during hot days is calculated using:

$$T_{\text{drop}} = \text{area of the land use class} * (\text{temperature reduction} / \text{total land area}) \quad (4)$$

where the temperature reduction is given in Table 1.

Data

The Soil and Water Integrated Model (SWIM; www.pik-potsdam.de/en/institute/departments/climate-resilience/models/swim), an eco-hydrological semi-distributed model, was a data source for this study. Relevant data from SWIM include spatially distributed monthly-aggregated values for runoff and evapotranspiration. Land use and crop data were provided by the European Corine Land Cover database (<https://land.copernicus.eu/pan-european/corine-land-cover>) and Common Agricultural Policy Regionalised Impact Modelling System (CAPRI; www.capri-model.org/dokuwiki/doku.php) model. The data were aggregated to the 15 sub-regions for this study (Figure 1). CAPRI data are used at NUTS-2 level, and no further processing was required. Local data were needed for specific landscape climatic effects (represented by degrees of cooling and air velocities) typically induced by different types of land cover in the region. This was based on long-term monitoring of temperature effects of different types of land cover (20-year research and monitoring of ENKI) under local meteorological conditions and at different times of the year, with emphasis placed on the growing season. Table 2 summarises the data used in the study. Table 3 details the land class areas in each of the 15 sub-regions.

Table 2: data sources and units

Data	Units	Source
Area data – non-agricultural	ha; m ²	SWIM
Area data – agricultural	ha; m ²	CAPRI
Precipitation	mm	SWIM
Evaporation/evapotranspiration	mm	SWIM
Temperature	°C	SWIM
Solar radiation	W m ⁻²	SWIM

Table 3: land class areal coverages (ha) in each of the 15 study sub-regions (see Figure 1 for sub-region map). Data from CORINE, SWIM and CAPRI.

Sub-region	Forests	Agriculture	Wetlands	Bare ground	Water	Vineyards	Pastures	Urban	Roads
1	509214	1446220	27330	3037	75122	0	395032	66130	3404
2	1116435	1410830	25082	16418	68124	30	441232	186863	7629
3	463271	1422650	9425	8388	20357	720	239523	105793	2551
4	545912	1007550	7486	3718	5734	0	215183	90651	1328
5	504483	1085960	5114	10516	27462	390	267356	169278	4046
6	293455	397060	10927	15396	7267	210	136305	32616	1780
7	406062	729300	3279	1811	4452	0	150698	68590	1472
8	317190	709970	2651	2093	7890	300	46748	76894	3566
9	679720	922780	12787	1814	22481	0	259298	48576	1467
10	406218	881470	1511	1334	9305	20450	55104	65296	1351
11	342746	485680	4544	651	2455	380	89364	52764	1381
12	185030	297060	603	2030	3784	0	74355	39614	1645
13	457454	941050	4267	2076	17672	1010	33770	110747	2768
14	852302	471370	20213	2113	7703	400	136812	54418	1315
15	690841	581810	7020	7096	6952	1070	97938	68874	2330

For the costs and benefits of water retention measures, the costs associated with forest restoration and loss of climate ecosystem functions are in the order of €1.5 million ha⁻¹ year⁻¹ (Sejak et al. 2018), costs that exceed the cost of restoration of agricultural landscapes. It is estimated that the construction of one cubic meter of bioretention volume in a developed, urbanized area will amount to €28 m⁻³. In other land types (forest, farming land, pastures, orchards, gardens, vineyards), water retaining projects cost €5 m⁻³; <https://www.waterholistic.com/wp-content/uploads/2021/05/KSK-EN.pdf>. It is estimated that arable land will increase crop production by c. €80 ha⁻¹ if water-retaining measures are implemented. The expected increased yield on permanent grasslands is c. €40 ha⁻¹. The projected benefit due to enhanced wood production is €20 ha⁻¹ (Program Obnovy Krajiny, 2021). It is important to note that the cost assessment of nature-based and local water-retention measures is case specific, and as such costs reported here should not be directly transferred to other locations. Costs can be

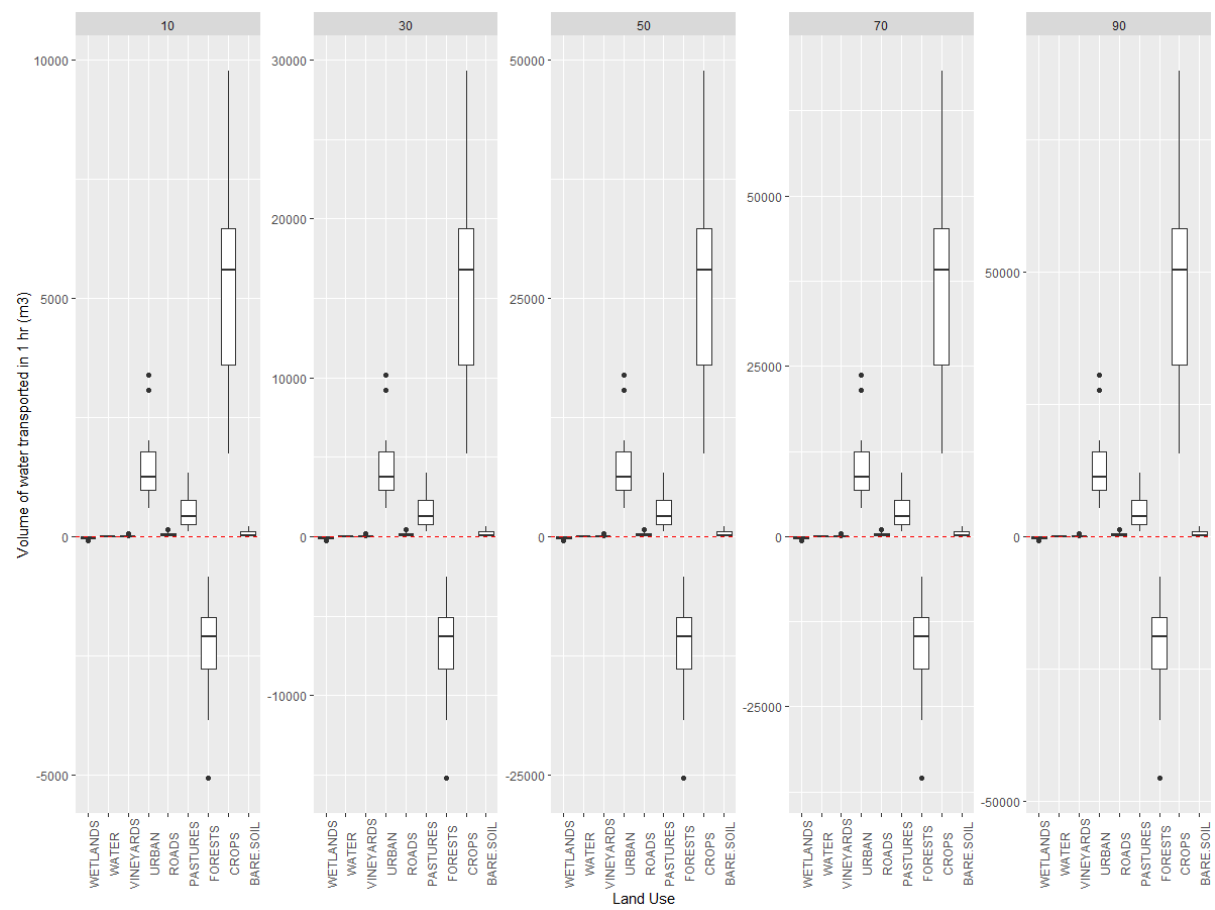
affected by the type, complexity, location, and size of proposed measures, as well as landscape typology (Okruszko and Bokal, 2020). As an example, Staccione et al. (2021) report water retention measure costs in Italy of €12-14 m⁻³.

Results

Water transported from land surfaces

Results demonstrate how different land cover types lose water through water vapour transport caused by an overheated landscape (Figure 4). The volume of transported water gives a potential expressing how much water, depending on the difference between $T_a - T_s$ and R_h , can be held in a unit volume of air above a given surface. Positive differences means no water loss, i.e. there is no ascending air, and water stays within the vegetation. Negative values (larger than 5°C) cause movement of hot air that is able to draw water from the surroundings and drain the landscape. The volume of water transported from landscapes at 18°C and 40°C, and for R_h from 10 - 90%, is shown in Figure 4. The trend for all land classes is that the water volume transported increases significantly as the surface temperature increasingly exceeds the air temperature. Croplands are shown to transport the largest volumes of water from land surfaces with significant variation between the 15 regions indicated by the height of the bars in Figure 4, supporting the suggestion that extensive monocultured croplands can lead to surface drying. Urban areas and pastures show the next largest volumes of water transport. Forests show negative values of water transport, implying that forests act of local moisture storage areas, retaining water in the landscape, contributing to local hydrological cycle closure by evapotranspiration.

(a)



(b)

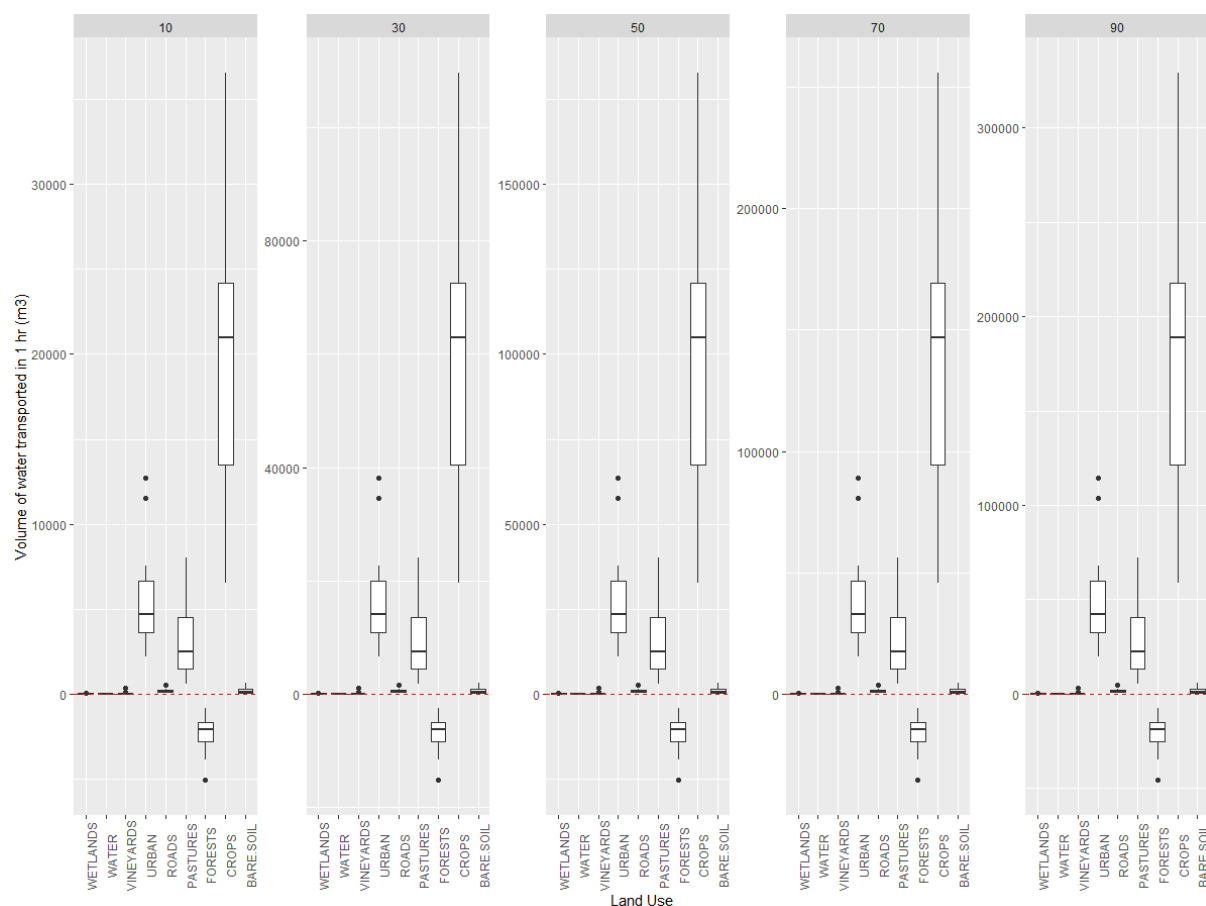


Figure 4: volume of water transported from different land types (Table 3) in one hour for (a) $T_a = 18^\circ\text{C}$ and; (b) 40°C . Each column refers to different values of R_h , from 10 to 90%. Note the difference in y-axis scale between (a) and (b). Boxes show the ranges across the 15 case study regions in each land use class. Dots indicate statistical outliers.

Water retention measure volume potentials

Croplands offer the highest water volume potential regarding water retention measures (Figure 5; mean = 88 million m^3), followed by urban areas, forests, and pastures. These land uses, if appropriately managed, show large potential to store water, helping mitigate flood runoff during wet periods and water shortages in drought periods. Roads and vineyards show limited potential for water storage due to their small areas.

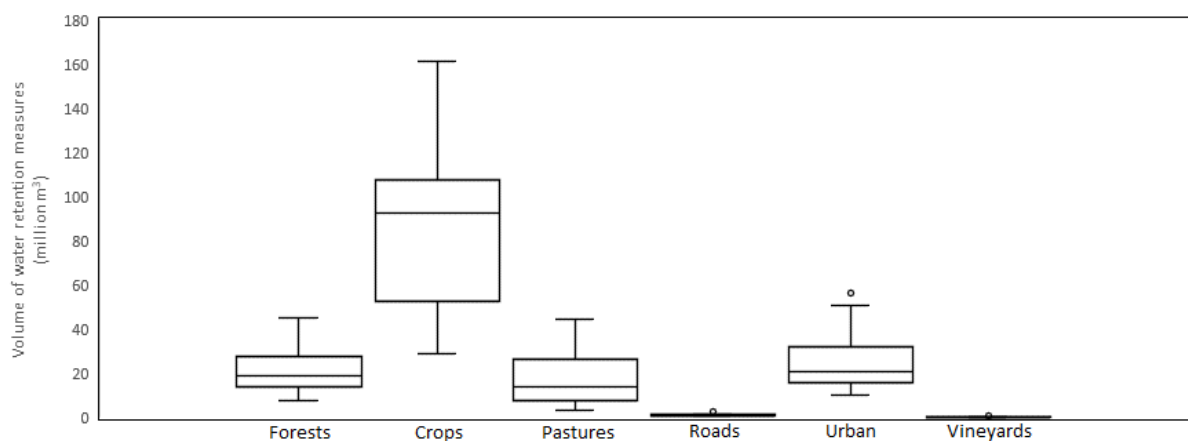


Figure 5: the potential volume of water retention measures on different land uses (Table 3). Boxes show the ranges across the 15 case study regions. Dots represent statistical outliers.

Water retention measure investments

The investments needed to finance the development of WRM varies greatly among the land use types (Figure 6). Urban (mean = € 490 million) and croplands (mean = € 440 million) require the largest investments, though croplands offer a far greater volume potential for water retention measures than urban areas (Figure 5). The high cost for measures in urban areas is due to higher land values in urban areas relative to croplands. This is due to greater infrastructure and service disruption, as well as to higher land prices in urban areas associated with new developments. Other land uses require considerably less investment to meet WRM volume potentials. Cropland offers good value for money in terms of Euros per volume of water retention, especially when compared with urban areas.

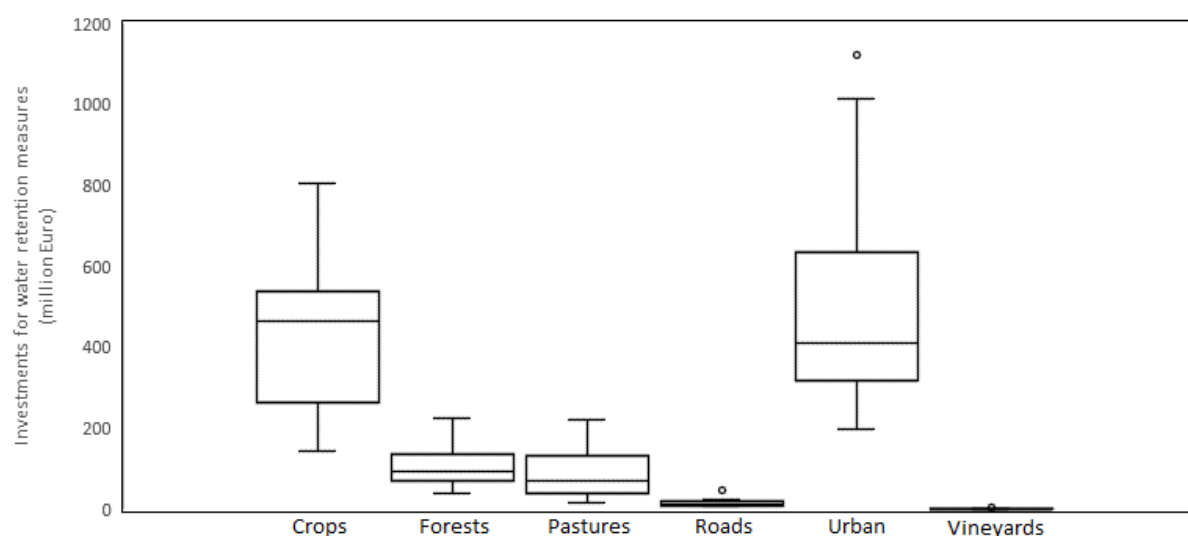


Figure 6: investments needed to finance water retention measures on different land uses (Table 3). Boxes show the ranges across the 15 case study regions. Dots represent statistical outliers.

Water retention measure benefits: crop production increases and landscape cooling potential

The estimated increase in production from productive land uses suggests that the greatest gains are expected on croplands and forest lands (Figure 7). Croplands show the greatest potential improvements in production that could result from increased water stored in retention measures assuming the water would be beneficially utilised. Pastures and vineyards offer lower production increase potentials due to their lower productivity and extension respectively.

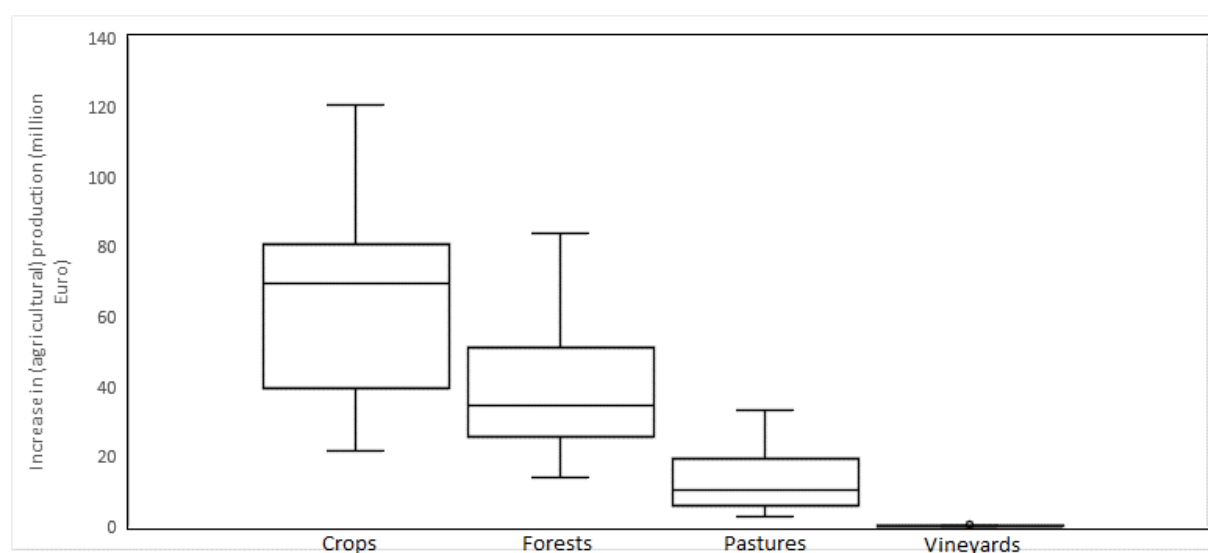


Figure 7: estimated production increases on productive land uses. Boxes show the ranges across the 15 case study regions. Dots represent statistical outliers.

The implementation of WRMs is expected to lead to local landscape cooling, in particular lowering the local temperature during hot days (Figure 8). The greatest temperature decreases are expected over croplands (mean = -1.6°C). Forests, pastures, and urban areas may also experience temperature reductions resulting from the implementation of water retention measures. These temperature reductions could lead to lower irrigation water demand (on cropland), air conditioning requirements (in urban areas), and a more comfortable urban environment. The values for forests depend on the health of the stands.

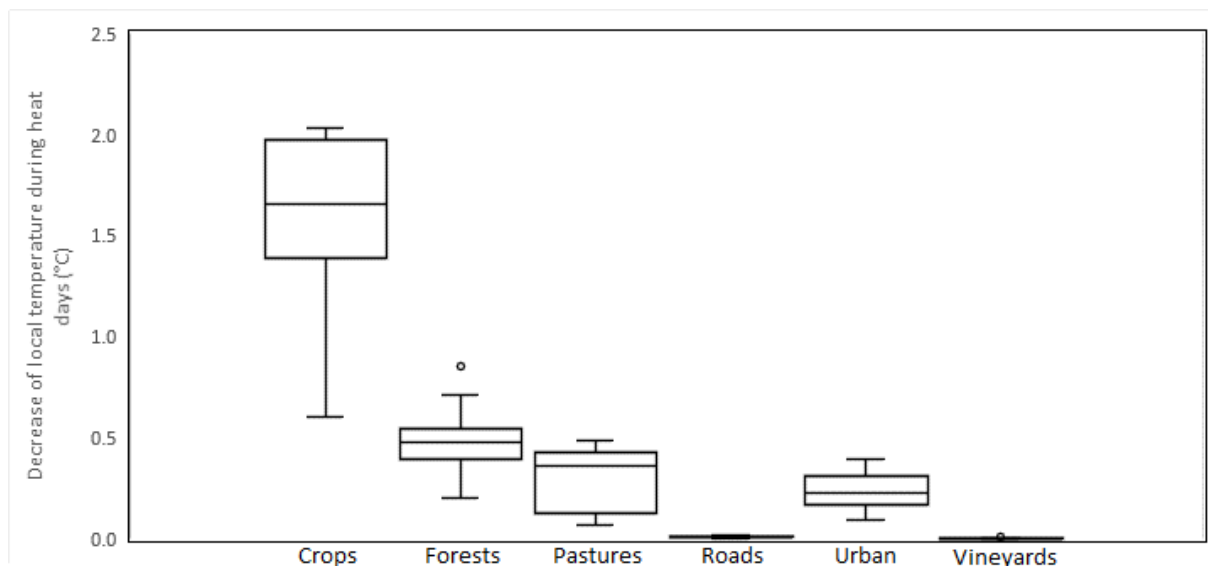


Figure 8: decrease in local temperature on different land uses during hot days in the study area. Boxes show the ranges across the 15 case study regions. Dots represent statistical outliers.

Discussion

Results demonstrate that altered and degraded landscapes, especially croplands and urban areas, contribute to excessive water being transported from the surface to the atmosphere (Figure 4), leading to surface drying, heating, and elevated crop water requirements, in line with the idea that lifting of hot, moist air contributes to heating and drying of those landscapes, leading to a positive feedback effect (Hesslerová et al. 2019; Pokorný 2019; Seják et al. 2022). Results demonstrate that forest areas are ‘water sinks’, leading to a locally-closed water cycle. Detrimental impacts of landscape degradation (excessive temperatures, water transfer away from the surface, soil nutrient losses, loss of agricultural income) have been reported in other studies (Burek et al. 2012; Mchunu and Chaplot, 2012; Salvati and Carlucci, 2013; Montanarella, 2015; Sutton et al. 2016; Právělie, 2021). Rejuvenation of the landscape through the implementation of WRMs can counter-act this effect, especially when done alongside other nature-based regeneration methods (e.g. Burek et al. 2012; EC, 2013). The values of local temperature reduction calculated in this study for forest stands are not negligible (c. 0.5°C), however this depends on their health status. In the case of deterioration of forest health or complete decay of the stands, their ability for local temperature reduction can substantially decrease (Hesslerová et al. 2018). To counteract the historical impacts of widespread land degradation, this study suggests that croplands and urban areas offer the greatest potential for WRMs in the study area in terms of water retention (Figure 5) and local landscape cooling (Figure 8). However, siting water-retention measures in urban areas is significantly costlier than on croplands due to the elevated land prices and

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enhanced service disruption (Figure 6). Croplands would be cheaper regarding the implementation of such measures, offering greater return on investment opportunity. This finding is given further support by results showing that croplands offer the greatest agricultural potential for production increases (expressed in €; Figure 7) due to their large extent and high levels of production. Mitigating reductions in agricultural income from landscape degradation through the implementation of landscape restoration measures has been reported elsewhere (Salvati and Carlucci, 2013; Právělie, 2021), suggesting that monetary benefits can be realised. This is important, as global financial losses from degraded arable landscapes are considerable (US\$400 billion from water-related soil erosion alone; Montanarella, 2015). As an additional benefit, restoring WRMs on croplands leads to the greatest degree of local atmospheric cooling (0.5 – 2°C; Figure 8). Based on empirical experience, there are discrepancies with the values reported for urban areas, which are probably underestimated here. Although these areas often occupy a small area in the landscape, their impact on the local climate and runoff is crucial. When implementing water retention measures in urban areas, a reduction in temperature of up to 4°C can be expected (0.2°C from study results), as well as flood management, biodiversity protection, climate change adaptation, and improved urban planning (Zeľňáková et al. 2017). Other studies report significant landscape cooling effects over non-degraded landscapes (Lewis et al. 2015; De Frenne et al., 2021), supporting the findings in this work which suggest that restoring the landscape to a natural state will bring local climate regulation benefits (cf. Belete et al. 2020). Despite this, it has been shown that even when landscape-based restoration attempts are made, long-term improvements in biodiversity metrics are not guaranteed, especially on fragile peat lands (Krejčová et al. 2021).

It is suggested that in this transboundary case study, the implementation of nature-based WRMs on predominantly monocultured agricultural land offer the cheapest, and most effective contributions regarding the rejuvenation of local landscape ecosystem functioning, as well as potentially offering significant returns on investment via enhanced production opportunities. A recent scoping study in the Košice Region, Slovakia, suggested that due to potential productivity increases resulting from water-retention measures on arable lands, vineyards, orchards and gardens, grasslands, and forests, the medium-term investment required for these measures (c. €400 million over 10 years) will be returned in about 13 years (Kravčík, 2021). Similarly, Kravčík et al. (2021) describe the impacts of local scale landscape restoration measures in Jarabina village, Slovakia. Potential water retention measures are expected to increase water availability, improve crop yields, and lead to moderate temperature regulation. The work of Kravčík et al. (2021) demonstrates the locally-relevant impact of such measures, while the work presented in this paper extends the range of analysis from a village to a large transboundary setting, highlighting the wider economic and social benefits of water retention

measures. As global arable land financial losses on degraded lands (Montanarella, 2015) are significant, aside from any yield-related declines, any measures to reduce such losses, financial and food-related, should be adopted, especially when it is shown that implementing these measures is financially sustainable in the short to medium term (cf. Grimaldi et al 2013; Salvati and Carlucci, 2013; Kravčik, 2021; Staccione et al. 2021).

While agreeing with other studies showing that NBS, and water-retention measures in particular offer opportunity for enhancing local water availability (Keestra et al. 2008; Strosser et al. 2015; Staccione et al. 2021), this study goes further by offering quantitative estimates for potential productivity gains, as well as quantifying the local atmospheric cooling potential. This cooling, leading to less water being transported from surfaces (cf. Lewis et al. 2015; De Frenne et al., 2021; Seják et al. 2022), can contribute to lower crop water requirements, and can lead to lower air conditioning requirements in urban areas. Additionally, WRMs can improve local biodiversity, especially in urban areas (Zeleňáková et al. 2017), and other ecosystem services including controlling soil and nutrient runoff (cf. Sutton et al. 2016; van den Heuvel et al. 2020; Právělie, 2021). This study offers further support for the cost-effectiveness, as well as the wider beneficial impacts of NBS, and in particular, water-retention measures. A final additional benefit that such measures can bring is to decrease diurnal temperature fluctuations. Such reductions in temperature swings can help prevent damage to young plants, especially in spring and early summer, potentially contributing to improved crop yields.

This study made a number of assumptions that could be improved upon with further research. The land coverage and climatological/hydrological data provided by the SWIM and CAPRI models were aggregated to NUTS-II level regions. This leads to important features not being captured in this analysis, for example the contrast between mountainous and lowland regions, identifying smaller towns and villages, or being able to resolve locally-specific features such as woodlands, lakes, and ponds. Local drought-impacted regions in lowlands with extensive agricultural land are not explicitly captured. Likewise, local detail regarding erosion losses or water balances are not assessed here. Very local (i.e. field-scale) level analyses would be required in order to resolve such features, and to plan accordingly, including selecting the most appropriate type of water retention measure (following guidelines set out in EEA, 2015 and Okruszko and Bokál, 2020). Similarly, the values in Table 1 are averages applied over the study domain. Future work should seek to refine these for each country, for regions, or even individual fields, making the results more locally applicable. Despite this, these results give order of magnitude estimates of the costs and benefits of water-retention NBS in the study area, demonstrating their effectiveness in restoring landscape functionality and mitigating climate impacts (cf. Burek et al. 2012; EEA, 2015; Zeleňáková et al. 2017; Nyameke et al. 2020). It is hoped that together with local efforts such as those described in Kravčik (2021), this study will contribute to incentivising action

towards practical support for water-retention initiatives contributing to landscape recovery programmes throughout the east German-Czech-Slovak region and beyond.

Conclusions

Historical policies from the middle of 20th century leading to increasingly large, monocropped agricultural landscapes and expanding urban area in last 25 years, has led to degradation of traditional landscapes in eastern Germany, the Czech Republic, and Slovakia. The recent and growing interest in nature-based solutions, including water-retention measures, is a response to reversing landscape degradation, rejuvenating ecosystem services, and mitigating the impacts of both large-scale commercial agriculture and climate change. Dry surfaces (agriculture, urban), overheated by solar radiation and sensible heat, draw water from the surroundings and drives warm, moist air high into atmosphere. In this study, the potential costs and benefits of water-retention measures in east Germany, the Czech Republic, and Slovakia are estimated. Results indicate that water-retention measures offer increased water storage over all land use classes, can increase crop productivity, and can aid in landscape cooling. Croplands are suggested as being the best 'value for money', offering the greatest volume potentials, cooling effects, and productivity gains, while also being the cheapest to implement per unit area. Local studies in a local region in the east of Slovakia indicate an approximately 13 year return on investment, with similar potential across the wider region studied here. However, differing policies in the three states mean non-uniform selection or implementation of measures. As a result, local-level research within each country is required to refine the values presented here, and to offer locally-relevant guidance. This work contributes to the growing body of literature assessing the costs and benefits of nature-based solutions, and particularly of water-retention measures, including the potential for landscape cooling. As the world urbanises, and as more land is given over to large, homogeneous cropland, such measures may prove critical in mitigating climate change, landscape drying, flood runoff, and soil and nutrient loss from soils. This research adds to the evidence base for natural water-retention measures and can serve as an entry point for further analyses.

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