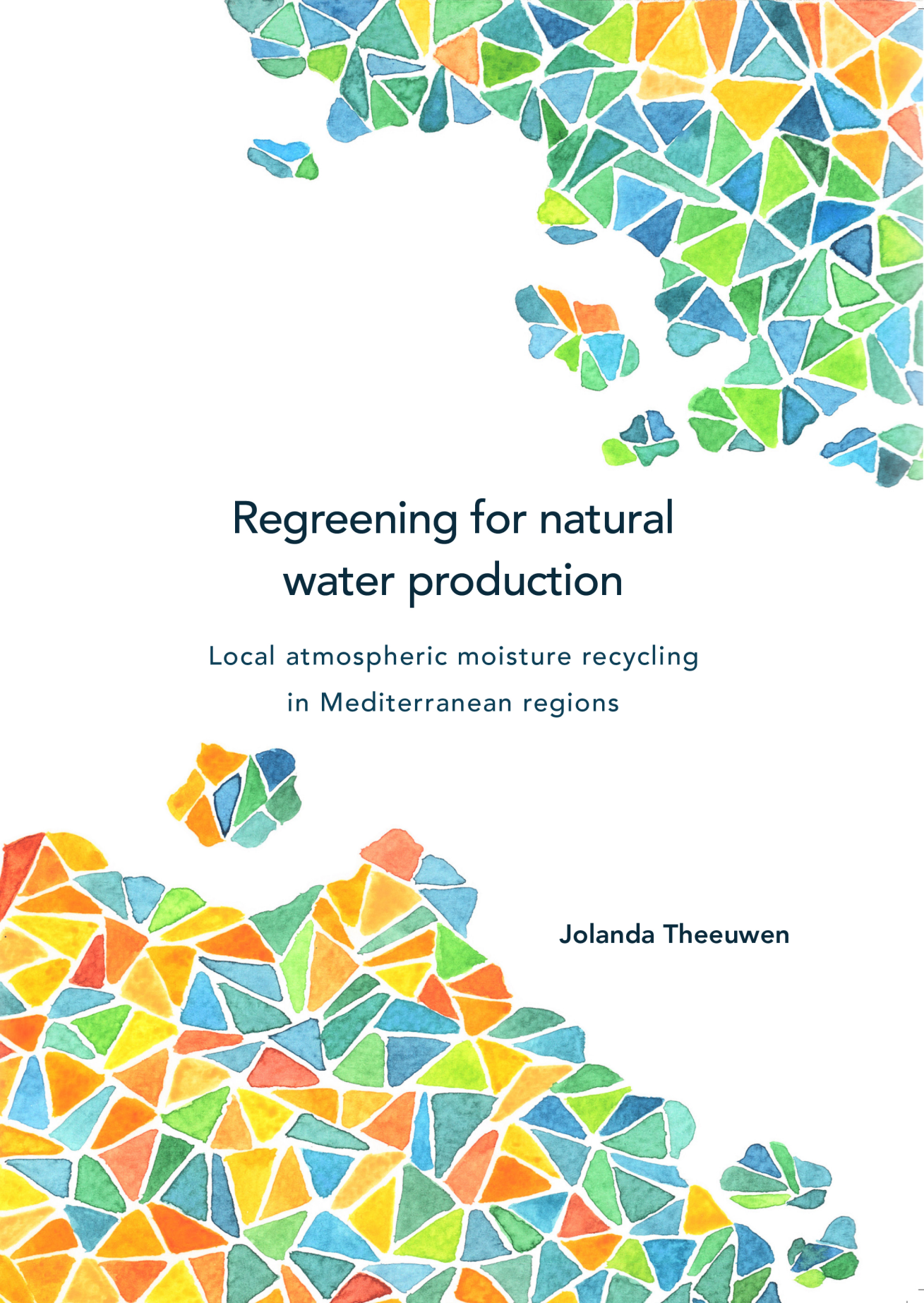


A stylized map of Europe composed of numerous small, irregular triangles in various shades of blue, green, yellow, and orange. The map is positioned in the upper right and lower left corners of the cover, leaving a white central area for the text.

Regreening for natural water production

Local atmospheric moisture recycling
in Mediterranean regions

Jolanda Theeuwes

Regreening for natural water production

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Jolanda Juliana Elisabeth Theeuwen

Regreening for natural water production

Local atmospheric moisture recycling in Mediterranean regions

Vergroenen voor natuurlijke waterproductie
Lokale atmosferische vochtrecycling in mediterrane gebieden

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de
Universiteit Utrecht
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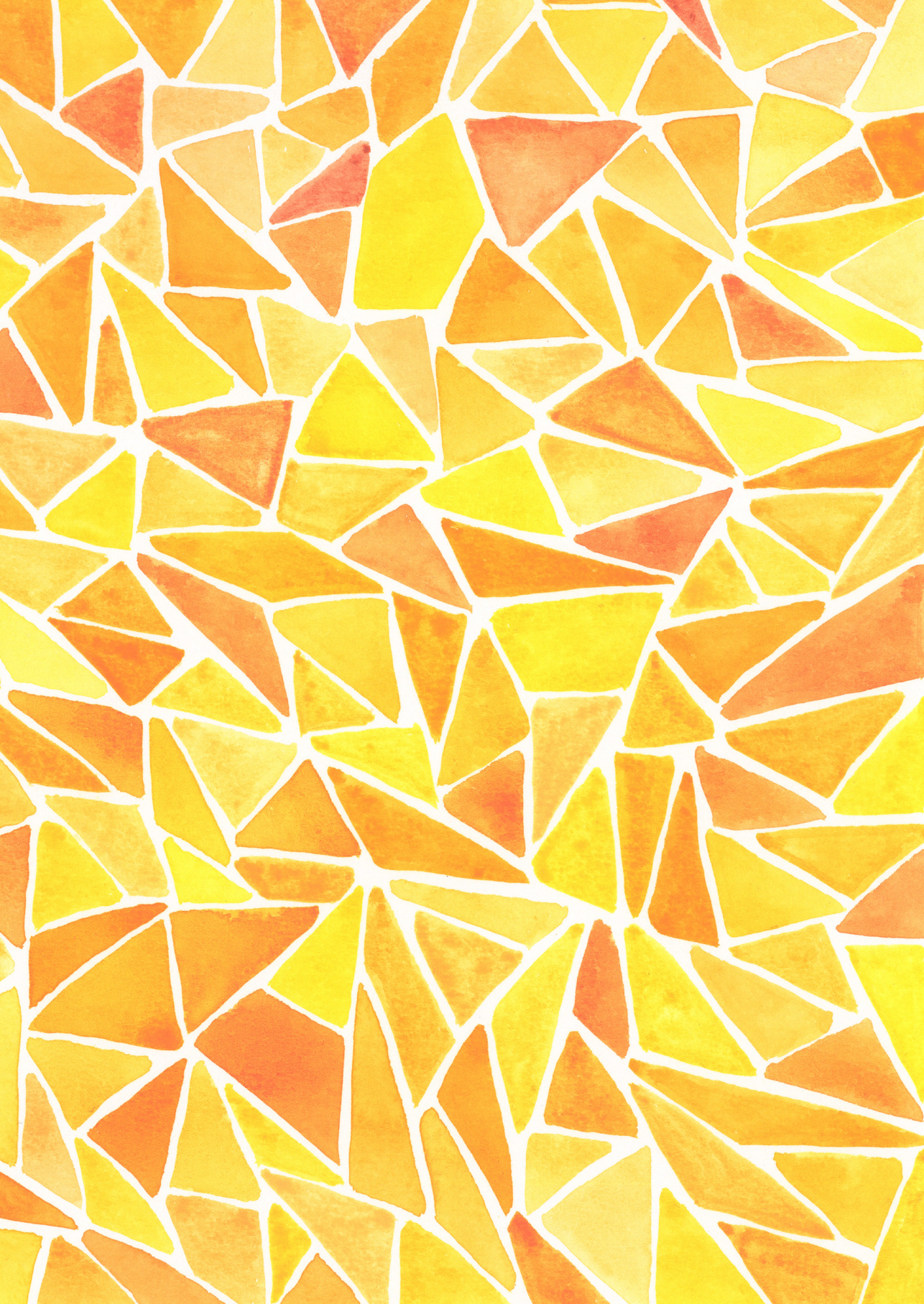
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TABLE OF CONTENTS

CHAPTER ONE	7
<i>General introduction</i>	
CHAPTER TWO	25
<i>Local moisture recycling across the globe</i>	
CHAPTER THREE	47
<i>Ecohydrological variables underlie local moisture recycling in Mediterranean-type climates</i>	
CHAPTER FOUR	71
<i>Forestation tends to create favourable conditions for convective precipitation in the Mediterranean Basin</i>	
CHAPTER FIVE	93
<i>Targeted rainfall enhancement as an objective of forestation</i>	
CHAPTER SIX	109
<i>Towards greening for natural water production: a transdisciplinary model for impact</i>	
CHAPTER SEVEN	131
<i>General discussion</i>	
APPENDIX	145
<i>References</i>	
<i>Summary/Samenvatting</i>	
<i>Acknowledgements</i>	
<i>About the author</i>	
<i>List of publications</i>	





General introduction

Chapter 1 | General introduction

1.1 Background

1.1.1 *Global change driving water scarcity*

Human activities have been altering the Earth's land surface throughout the Holocene (Klein Goldewijk et al. 2011) and discussions on how land-use changes affect the climate date back more than two millennia (Bonan 2016). Historical observations noted that deforestation exposed the ground, causing daytime warming and reduced rainfall. However, such observations lacked robust documentation and often relied on anecdotal evidence (Bonan 2016). Modern sciences allow us to study changes in climate and land use using model simulations and isotope data (e.g., Dermody et al., 2012; Klein Goldewijk et al., 2011).

The onset of the Industrial Revolution in the 1800s marked a significant increase in human influence on the climate, as fossil fuel combustion led to a drastic increase in CO₂ emissions (Steffen et al. 2011). Alongside these carbon emissions, deforestation had been well established (Kaplan et al. 2009), jointly driving climatic changes. However, the role of CO₂ in global warming was mostly emphasized in the late 20th century (National Research Council 1979). The focus on carbon emissions shaped the future of climate science and policy in the decades that followed (Bony et al. 2013). As a result, the role of land-use management in climate mitigation beyond carbon sequestration received less attention (Donatti et al. 2022), not fully addressing the problem.

Climate change is one of the underlying drivers of water scarcity. Global warming has led to shifts in atmospheric temperatures and precipitation patterns, and contributes to more frequent and severe extreme weather events such as droughts and floods (e.g., X. Huang & Swain, 2022; Meehl & Tebaldi, 2004). These changes affect water resources and enhance water scarcity across the globe, affecting ecosystems, food productivity, industry, and the living environment (Schewe et al. 2014). A second driver of water scarcity is unsustainable land use. Land-use practices such as intensive agriculture enhance erosion and drying (Yang et al. 2024). In addition to drying, the projected population growth will increase water demands (Seckler et al. 1999), resulting in a growing water gap (Leijnse et al. 2024). Solutions to fill this water gap are needed.

1.1.2 *Solutions to water scarcity?*

There are different technical and nature-based solutions to enhance freshwater availability on a small scale, i.e., for industry or agriculture (Intergovernmental Panel on Climate Change (IPCC) 2023a; van Woesik et al. 2023). Although these solutions

can help to increase water availability, they do not solve the underlying issues that drive drying and global warming. To solve the global problem of water scarcity and increase water availability for large ecosystems, additional solutions are necessary.

Agroforestry and greening are nature-based solutions that promote infiltration to enhance soil moisture (Octavia et al. 2023). Some studies show that greening may also contribute to regional precipitation (e.g., Cao et al., 2024; Tian et al., 2022), suggesting that it may be a solution to water scarcity on a regional scale. Regreening is defined here as ecosystem restoration, including but not limited to forest restoration (Box 1.1). In addition to enhancing carbon sequestration, improving biodiversity, food productivity and livelihoods, and building resilience for climate change (unep.org/interactive/flagship-initiatives-boosting-nature-livelihoods/), large scale greening efforts may also enable natural water production to address water scarcity worldwide. However, some studies report local drying due to enhanced evapotranspiration following greening efforts (e.g., Brown et al., 2005; Zhang et al., 2001). This thesis explores the potential of greening to enhance rainfall. Achieving this requires a deeper understanding of the interactions and feedbacks between climate and vegetation.

Box 1.1 Regreening and forestation

This thesis uses the concept of greening as well as forestation. **Regreening** is defined here as ecosystem restoration and includes, but is not limited to, forest restoration. **Forestation** is defined as an increase in forest cover and includes both reforestation, which is the restoration of forests, and afforestation, which describes the planting of trees in regions without previous tree cover.

The overall aim of this thesis focusses on greening. However, some chapters focus specifically on forests. Chapter 4 focuses solely on forests to simplify the model set-up. The context of Chapter 5 is the large amount of forestation efforts that aim to mitigate climate change, and therefore, focusses solely on forests.

Forests and other types of vegetation can affect climate through similar processes. However, the outcomes of these processes can vary due to differences in vegetation characteristics. Due to the large rooting depth of trees, it is expected that forests have access to more soil moisture compared to grasses and shrubs, which is beneficial for rainfall enhancement. Therefore, Section 1.2 focusses on the climatic effects of forests.

1.2 Climatic effects of forests

1.2.1 Local cooling or warming?

Vegetation helps to compensate for the anthropogenic carbon emissions by capturing CO₂ for photosynthesis and storing it as biomass in vegetation and soil (Lewis et al. 2019; Panchal et al. 2022). Doing so, vegetation contributes to mitigating global warming. Forests, grasslands, and wetlands are particularly effective at reducing atmospheric CO₂, and stabilizing the climate (Bonan 2016;

Leifeld and Menichetti 2018). As a result, the restoration and preservation of natural ecosystems globally can have a cooling effect.

On a local scale, vegetation influences atmospheric temperature by altering the surface radiation budget, which describes the incoming and outgoing shortwave (solar) and longwave radiation at the Earth's surface (Wallace and Hobbs 2006). Incoming radiation is partially absorbed and partially reflected back to space by clouds, aerosols, atmospheric gases, and the Earth's surface (Wallace and Hobbs 2006). Vegetation can affect all components of the energy balance. First, by transpiring water and emitting chemicals, vegetation promotes cloud formation (Wallace and Hobbs 2006; Duveiller et al. 2021). These clouds and particles can capture or reflect solar radiation. Whether clouds contribute to cooling or warming depends on the type of cloud (Facchini et al. 1999; Chen et al. 2000; Duveiller et al. 2021; Noual et al. 2023). Second, the darkness of the land cover affects the amount of solar radiation that is reflected back to space and absorbed by the Earth's surface (Wallace and Hobbs 2006). In general, vegetation has a darker colour than degraded landscapes and reflects less radiation back to space (Bonan 2016). As a result, more radiation is absorbed by the surface, which can enhance local temperatures (Rohatyn et al. 2022).

The energy that is captured by the Earth's surface from incoming solar radiation is partly emitted back to space as longwave radiation. Additionally, this energy is used to transfer heat through three processes: evaporation, convection, and conduction. These heat fluxes are defined as the latent heat flux, sensible heat flux, and ground heat flux, respectively (Bonan 2016).

- *The latent heat flux represents the energy that is used to evaporate water. This energy can be released into the atmosphere when the water vapor condenses.*
- *The sensible heat flux transfers heat from the surface to the atmosphere through convection, directly raising local atmospheric temperatures.*
- *The ground heat flux transfers heat into deeper soil layers via conduction.*

The balance between the sensible and latent heat flux affects the atmospheric temperature locally. Whereas the sensible heat flux contributes to warming, the latent heat flux has a cooling effect. By sustaining evapotranspiration (including both evaporation and transpiration), vegetation increases the latent heat flux and reduces the energy that is available to directly warm the atmosphere (Bonan 2016). Therefore, through evapotranspiration, vegetation has a cooling effect.

The combination of these different factors determines whether forests contribute to warming or cooling. In boreal regions, between 50° and 70° N, forests have a net warming effect as the warming, due to the dark colour of the land surface, is

stronger than the cooling effect (Bonan 2008). In the tropics forests have a net cooling effect due to the large rates of evapotranspiration (Bonan 2008). Between the tropics and the boreal regions, the cooling effect is weaker than in the tropics and the warming effect is weaker than in the boreal regions (Bonan et al. 2024). For these temperate regions there is an intermediary effect that is dependent on soil moisture availability (Teuling et al. 2010) and forest type (Naudts et al. 2016).

1.2.2 Local drying or wetting?

Evapotranspiration links the surface energy budget to the hydrological cycle and plays a crucial role in the distribution of water between the soil and the atmosphere. The cycling of water between land and atmosphere can be referred to as the small water cycle, which takes place within a period of days or weeks (Van der Ent and Savenije 2011). This is much shorter compared to the global water cycle that can span thousands of years (Oki and Kanae 2006). In the small water cycle, the fraction of precipitation that is stored in the soil and used by vegetation for evapotranspiration is called the green water flux (Wang-Erlandsson et al. 2022). This flux plays a crucial role in many Earth system processes (Gleeson et al. 2020).

Evapotranspiration is dependent on the available amount of energy and water. In dry regions evapotranspiration may be limited by water availability and in very wet regions evapotranspiration may be limited by energy availability (Seneviratne et al. 2010). In these wet regions, the darkening of the land surface due to regreening may enhance evapotranspiration (Bonan 2008). Furthermore, in densely vegetated regions energy may be limited due the shading effect that reduces the exposure of the soil to sunlight (Bonan 2016). In dry regions, deep roots can access deep soil layers and enhance infiltration, preserving evapotranspiration (Pierret et al. 2016). In regions where evapotranspiration is soil water-limited, changes in vegetation have a larger hydrological impact than in more humid environments where evapotranspiration is energy-limited (Hou et al. 2023).

Furthermore, vegetation contributes to the infiltration of rainwater as it improves soil structure, texture, and permeability, both through physical and chemical processes (Pingping et al. 2013). Additionally, part of the rainwater is intercepted by leaves, where it can reevaporate (Bonan 2016). Through infiltration and interception water availability increases, which is beneficial for evapotranspiration in water-limited regions (Seneviratne et al. 2010). Rainwater that does not infiltrate or does not get intercepted runs off to infiltrate elsewhere or ends up in open water where it is no longer available for vegetation (Falkenmark and Rockström 2006). Unsustainable land use negatively affects soil quality and infiltration (Pingping et al. 2013), and therefore, reduces green water availability (Wang-Erlandsson et al. 2022). Restoring

degraded landscapes can reduce runoff and improve infiltration (Pingping et al. 2013), and therefore, water availability.

Regreening can also contribute to local drying due to enhanced evapotranspiration (e.g., Brown et al., 2005; Zhang et al., 2001). However, vegetation and precipitation are strongly coupled (Lotsch et al. 2003) and due to atmospheric feedbacks and moisture transport it is not straightforward whether an increase in evapotranspiration contributes to drying (Ellison et al. 2012; Wang-Erlandsson et al. 2018). As vegetation drives evapotranspiration, the local atmospheric humidity increases, promoting the formation of clouds and rainfall. Under the right atmospheric conditions, this water vapor can return as precipitation (Findell and Eltahir 2003a; Findell and Eltahir 2003b) and minimize drying. Therefore, to prevent local drying regreening initiatives should be conducted in regions where evaporated water returns as precipitation locally.

These interlinked processes, related to the energy balance and hydrological cycle, introduce the complexity of the Earth system. To fully understand how regreening may contribute to rainfall enhancement and increased water availability, its impact on many different processes must be explored. By investigating how much water that is lost through evapotranspiration returns as rainfall, it may be possible to determine whether regreening contributes to enhanced freshwater or causes drying. This can be studied, without explicitly studying all of the interlinked processes, using atmospheric moisture recycling.

1.3 Atmospheric moisture recycling

1.3.1 *Terrestrial moisture recycling*

Water evaporates from its source and gets transported through the atmosphere to eventually return to earth. The return of evaporated water as precipitation downwind is called atmospheric moisture recycling (Keys et al. 2016). On average, about 40% of global precipitation comes from evaporation over land (Van der Ent et al. 2014), and 70% of terrestrial evaporation returns as precipitation over land (Tuinenburg et al. 2020b). The return of evaporated water as rainfall over land is called terrestrial moisture recycling and varies significantly, over space and time (Van der Ent and Savenije 2011; Tuinenburg et al. 2020b).

Terrestrial moisture recycling is influenced by the distribution of landmass and the atmospheric circulation, which is illustrated by high terrestrial precipitation recycling ratios in western Eurasia (Van der Ent and Savenije 2011; Tuinenburg et al. 2020b). Due to the large landmasses in the Northern Hemisphere and dominant westerly winds (from west to east), in Eurasia, evaporated water needs to travel long

distances before it reaches the Pacific ocean. This long pathway over land increases the chances of evaporated water to return as precipitation over land and boosts terrestrial moisture recycling. In addition, terrestrial recycling is affected by elevation in the land surface (orography) and convective processes (Tuinenburg et al. 2020b). Convection refers to the vertical transfer of air through the atmosphere, driven by temperature gradients, arising from solar heating of the land surface. Both convection and orography contribute to the rising of air, and as the air rises, it cools, contributing to condensation, cloud formation, and precipitation (Wallace and Hobbs 2006).

1.3.2 Zooming in on moisture recycling

For greening initiatives to contribute to freshwater availability, they need to be conducted in regions where, potentially, a large fraction of evapotranspiration recycles over land. Evaporated water can contribute to rainfall within the region, however, evaporated water can also travel thousands of kilometres before returning as precipitation over land. Regional recycling describes the return of evaporated water as rainfall within the same region and typically increases with the size of the region (Van der Ent and Savenije 2011).

An example of a region with high regional recycling is the Amazon river basin, which has the largest regional moisture recycling of all major river basins globally (Tuinenburg et al. 2020b). In this region, 63% of evaporated water returns as rainfall within the basin itself, and 36% of total precipitation originates from within this region (Tuinenburg et al. 2020b). These high recycling rates seem to be crucial to enhance freshwater availability through tree restoration (Hoek van Dijke et al. 2022). This would make greening initiatives that aim to enhance rainfall particularly effective in regions with high regional recycling ratios. Furthermore, vegetation may have a positive influence on regional recycling as was illustrated in the Chinese Loess plateau. Here, large scale afforestation activities that took place at the end of the previous century seem to have enhanced regional moisture recycling and precipitation (Tian et al. 2022).

Although greening contributes to enhanced precipitation in the wider region, an increase in vegetation may still contribute to drying when the water does not return as precipitation locally but elsewhere within the region (Filoso et al. 2017). To understand where greening may contribute to local drying atmospheric moisture recycling needs to be studied at a smaller spatial scale. Previous research efforts have mainly focused on the role of vegetation in the recycling of moisture on a spatial scale of several hundreds of kilometres or more (Keys et al. 2016; Staal et al. 2018; Wang-Erlandsson et al. 2018; Te Wierik et al. 2022). Similar to regional moisture recycling, it is possible to calculate the amount of evaporated water that recycles locally, i.e., within several tens of kilometres (Figure 1.1).

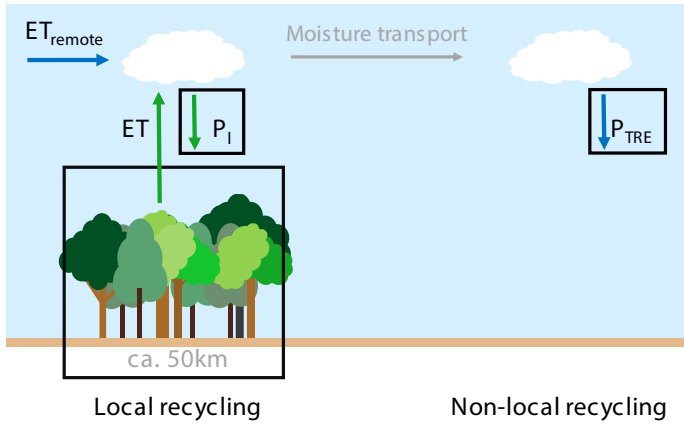


Figure 1.1. A schematic overview of terrestrial moisture recycling, including local moisture recycling (P_I). Evaporated water that does not return as rainfall locally, yet returns as precipitation over land can be considered targeted rainfall enhancement (P_{TRE}). ET: evapotranspiration

1.3.3 Atmospheric moisture tracking

Atmospheric moisture recycling can be calculated from atmospheric moisture connections, which describe the pathways that water vapor follows between evaporation sources and precipitation sinks. These connections can be used to study the variability of moisture sources over time (Keys et al. 2014), the impact of land-use changes on precipitation (Wang-Erlandsson et al. 2018; Hoek van Dijke et al. 2022; Tuinenburg et al. 2022), the moisture sources for terrestrial precipitation (Van der Ent and Savenije 2013) the moisture sources for important agricultural areas (Bagley et al. 2012), and more. Atmospheric moisture connections are typically calculated using an analytical model (e.g., Dominguez et al., 2020; Van der Ent and Savenije, 2011), an offline atmospheric moisture-tracking model (Sodemann et al. 2008; Van der Ent et al. 2013; Holgate et al. 2020; Tuinenburg and Staal 2020; Keune et al. 2022) or water vapor tracers in a regional weather model or climate model (e.g., Dominguez et al., 2016; Liu et al., 2023).

Analytical moisture recycling models provide a simple description of the budget of moisture sources and sinks (Dominguez et al. 2020). While these models are simple, they are valuable for identifying general patterns in moisture recycling. Regional weather models or climate models can be used to simulate atmospheric processes at a high-resolution. Detailed inputs like terrain, land use, and weather observations can be included in such a model to study finer-scale phenomena, enabling to study complex processes that may affect moisture transport (Dominguez et al. 2016). By including water vapor tracers that follow the atmospheric flow, these models can track water between source and sink. These models can simulate condensation, evaporation, and their effects on atmospheric dynamics (Dominguez

et al. 2020), and therefore, they can be used to study the impact of changes in land cover on atmospheric moisture pathways. However, the computational costs of such models are relatively high compared to other methods that can be used for moisture tracking.

An offline moisture-tracking model calculates the transport of atmospheric moisture by analysing pre-computed atmospheric data, which makes it less computationally costly compared to using regional weather models and global climate models (Van der Ent et al. 2013; Tuinenburg and Staal 2020). Using these offline models, water vapor can be traced backward or forward in time, which means that it is possible to study where evaporated water rains out, as well as trace back where precipitation originated from. The original atmospheric dynamics cannot be altered in these models.

There are various offline moisture-tracking models. These models can be divided into Eulerian and Lagrangian models. First, Eulerian models track moisture transport by dividing the atmosphere into a fixed grid, each representing a specific area. For each time step, the model calculates how much moisture enters or leaves each cell, based on factors like wind speed, direction, evaporation, and precipitation (Van der Ent et al. 2013). The wind moves moisture from one grid cell to another, and the model uses data on humidity, evaporation, and rainfall to track how moisture accumulates or is lost in each area over time (Van der Ent et al. 2013). Eulerian models are good at resolving large-scale patterns and are efficient to calculate moisture flows on a global or regional scale. However, due to the sometimes large grid sizes, these models might be less accurate on a local scale (Tuinenburg and Staal 2020).

The atmospheric moisture connections that are used in this thesis were calculated with a Lagrangian moisture-tracking model (Figure 1.2). This Lagrangian model tracks individual air parcels that hold water vapor from a specific evaporation source (Tuinenburg and Staal 2020). The locations of these parcels are not bound to a grid, and therefore, a Lagrangian model is better suited to study moisture recycling on a local scale as the parcels can move within a grid cell. These air parcels are released from an evaporation source and follow the atmospheric flow, with their movement determined by wind speed and direction. A parcel releases water vapor when there is a precipitation event in its location. The total amount of evaporated water at the source is distributed among a set number of air parcels. While using more parcels increases computational time, using fewer parcels may reduce accuracy (Tuinenburg and Staal 2020). As the air parcels that hold the evaporation from the source location travel, they release water as precipitation. The amount of evaporated water that rains out at each location is determined by the ratio of precipitation to atmospheric humidity at that time and place (Tuinenburg and Staal 2020).

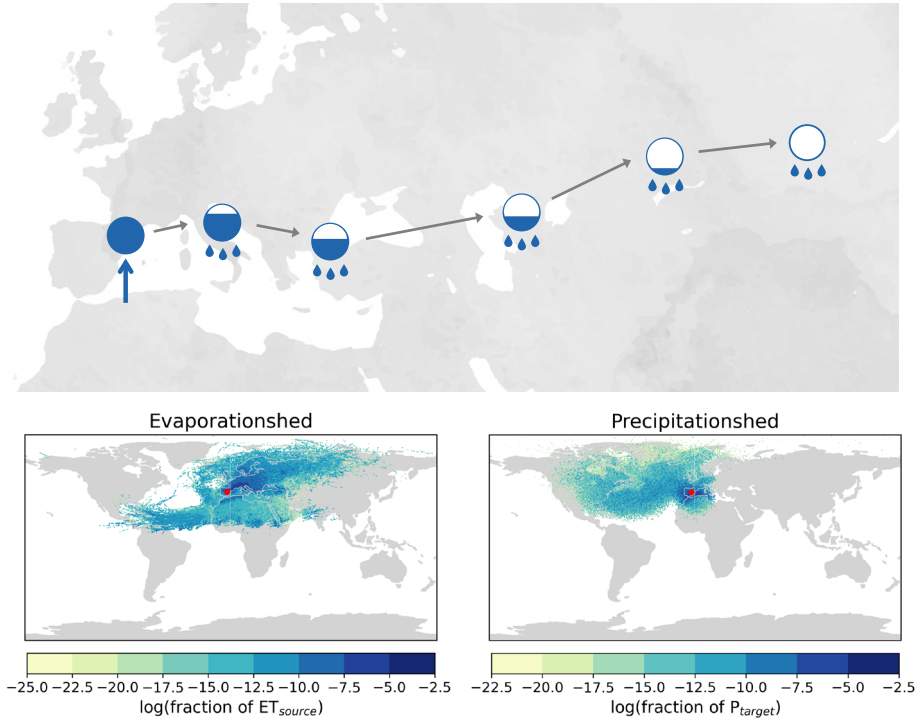


Figure 1.2. Method and output of a Lagrangian moisture-tracking model. Top: in a Lagrangian moisture tracking model air parcels are released at the evaporation source. These parcels are tracked through the atmosphere using information on wind speed and direction, precipitation, evaporation and atmospheric humidity. Along their trajectories, parcels release moisture in the form of precipitation. All the parcel trajectories are combined in the evaporationshed or precipitationshed. Bottom left: the evaporationshed describes where the evaporated water from below the red dot precipitates. Bottom right: the precipitationshed describes where the precipitation in the location below the red dot originated from as evaporation. The evaporationshed and precipitationshed are the multi-year (2008-2017) average for the month July.

When evaporated water from a specific source is tracked, this results in an evaporation footprint, or evaporationshed (Van der Ent and Savenije 2013). This evaporationshed describes where the evaporated water from this specific source rains out (Figure 1.2). Using this evaporationshed it is possible to calculate the fraction of the evaporated water that rains out over land, or over one specific country or region. When a moisture-tracking model is used to track backward, this results in the precipitation footprint, or precipitationshed (Keys et al. 2014). This precipitationshed describes where precipitation for one specific location originated from (Figure 1.2). The precipitationshed can be used to calculate the fraction of precipitation that originated as evaporation over land or within a specific region.

Whereas the evaporation- and precipitation sheds allow to study the climatology and spatial patterns of atmospheric moisture recycling, they cannot be used to experiment with changes in land cover or climate as the atmospheric dynamics are not explicitly simulated. Hence, evaporation- and precipitation sheds alone are not sufficient to fully understand the hydrological effects of greening.

1.4 The underlying dynamics of summer precipitation

Process-based models can be used to study the impact of greening on the underlying dynamics of precipitation. One important driver of local precipitation is convection, which is the vertical transfer of air through the atmosphere driven by temperature gradients. Convection is an important driver of summer precipitation. Due to strong heating at the earth's surface the thin layer of air above the surface warms up and starts to rise. When the rising air contains sufficient water vapor convection may drive convective rainfall, which is often seen at the end of the afternoon on a warm summer's day (Wallace and Hobbs 2006). Convection can trigger the formation of very tall clouds that develop within a short period of time and on a very local scale. The development of these clouds is strongly dependent on land surface characteristics and affected by land-use changes (Nair et al. 2011; Xu et al. 2022).

The underlying processes of convective rainfall take place within the atmospheric boundary layer. The atmospheric boundary layer is the lowest part of the Earth's atmosphere, directly influenced by its contact with the Earth's surface. As the sun heats the land surface, the surface warms the air above it, resulting in convection that drives the deepening of the boundary layer (Stull 1988). The atmospheric boundary layer can grow up to several kilometres depending on different factors, such as the intensity of heating at the surface and how easily an air parcel can rise, which depends on the stability of the atmosphere (Stull 1988). The type of land cover, amount of soil moisture, and roughness of the land surface influence the exchange of heat and moisture between the land and atmosphere, and therefore, the development of the atmospheric boundary layer and deep convective clouds that can generate convective rainfall (Stull 1988; Konings et al. 2011; Van Heerwaarden and Teuling 2014; Vilà-Guerau de Arellano et al. 2015). Simulating the underlying processes of the atmospheric boundary layer development provides insight into how land cover changes affect the development of deep convective clouds that can trigger convective precipitation locally.

1.5 Mediterranean-type climate regions

This thesis focusses on Mediterranean-type climate regions specifically as atmospheric warming has been especially strong here, with temperature changes well above the global average (Huang et al. 2012). These regions have been identified as climate

change hotspots (Ali et al. 2022). Here, soil moisture is highly variable due to the contrasting wet and dry conditions in winter and summer (Mimeau et al. 2021). During summer, the soil moisture availability is the limiting factor for evapotranspiration (Seneviratne et al. 2010). Soil moisture may increase through enhanced infiltration due to regreening. It remains unclear if forests can improve local climate conditions and freshwater availability in Mediterranean-type climate regions.

There are five major Mediterranean-type climate regions across the globe according to the Köppen-Geiger climate classification (Peel et al. 2007). These regions are located in south-west Australia, in central Chile, in south-west US, in the Cape region of South Africa and around the Mediterranean Sea, the latter being referred to as the Mediterranean Basin. These regions are found between 30° and 45° latitude both on the Northern and Southern Hemisphere. All five regions are located on the Western side of continents (Figure 1.3).

Mediterranean regions are characterized by their dry and warm summers and wet and temperate winters (Esler et al. 2018). These climatic conditions are the direct result of their geographical location. During winter, westerly winds transport mild ocean air inland, blocking cold continental air from reaching these regions, resulting in mild temperatures. In addition, there is frequent rainfall because these areas lie within the tracks of extratropical storms that are fuelled by warm sea surface temperatures and bring in oceanic moisture (Seager et al. 2019). During summer, subtropical high-pressure systems form over the region. In these systems, dry and warm air descends, resulting in the dry and warm weather conditions (Seager et al. 2019). These dry conditions have a negative impact on water resources and enhance water stress (Miller et al. 1983; Essa et al. 2023).



Figure 1.3. The Mediterranean-type climate regions across the globe as studied in this thesis: south-west US, the Mediterranean Basin, central Chile, the Cape region of South Africa, and south-west Australia. The Mediterranean-type climate regions are based on the Köppen-Geiger climate classification (Peel et al., 2007). To obtain five consecutive areas some additional small terrestrial areas with a semi-arid climate are included.

In various Mediterranean-type climate regions groundwater resources are being depleted faster than they can be replenished (United Nations 2019) and the water demand is larger than the availability, resulting in a water gap (Leijnse et al. 2024). The Mediterranean regions are already facing problems of water scarcity and for some regions these problems are expected to worsen (Mekonnen and Hoekstra 2016; He et al. 2021). Due to global warming, the Mediterranean-type climate regions face an increasing risk of shifting toward arid conditions, specifically in areas with limited vegetation (Kéfi et al. 2007). As a result of drying and higher atmospheric temperatures, the risk of wildfires is also likely to increase in these regions that are already prone to wildfires (Keeley et al. 2011; Ali et al. 2022).

All Mediterranean-type climate regions demonstrate potential for tree restoration under current climate conditions, meaning that there is space available to plant trees outside of areas with existing tree cover, urban zones, and agricultural lands (Bastin et al. 2019). This does not necessarily mean that all this area should be covered in trees, as part of this area may include other well-functioning ecosystems such as grasslands (Veldman et al. 2019). However, despite the potential for tree restoration in Mediterranean-type climate regions, the number of studies on the effects of land-use changes on precipitation is limited here (te Wierik et al. 2021).

1.6 This thesis

1.6.1 Knowledge gaps

The climatic effects of greening activities in Mediterranean-type climate regions remain unclear. It is unclear if greening consistently leads to increased precipitation or drying, or whether the effects vary spatially and temporally across and within the different regions. Finally, it is unclear under what specific conditions greening could contribute to rainfall enhancement in Mediterranean-type climate regions. Specifically the latter is relevant to design an engineering-driven greening strategy aimed at enhancing rainfall.

The local return of evaporated water as precipitation may provide insight into whether greening contributes to enhanced precipitation or drying locally. Various metrics describe the recycling of moisture over land and within regions, however, it remains unclear how much water recycles within several tens of kilometres. Additionally, it is unclear if vegetation has a significant influence on this recycling of moisture.

It is known that greening affects precipitation downwind. Insights into where greening may contribute to precipitation downwind contribute to an engineering-driven greening strategy aiming at targeted rainfall enhancement (Figure 1.1).

However, it remains unclear whether sufficient knowledge and tools are available to project the hydrological effects of greening to adopt such an engineering approach.

Finally, solely understanding the hydrological effects of greening is not sufficient to realize successful greening initiatives. To realize greening projects that enhance rainfall, it is necessary to integrate knowledge from various scientific disciplines with knowledge from stakeholders, which can be established by adopting a transdisciplinary research approach. It is unclear if adopting such an approach effectively enhances the societal impact of scientific research that aims to study rainfall enhancement through greening.

1.6.2 Research aim, objectives and thesis outline

The aim of this thesis is to understand how greening can contribute to local rainfall enhancement. Specifically, I study where it could be possible to enhance local rainfall in Mediterranean-type climate regions. Five research objectives were formulated to investigate this aim:

1. *Quantify local moisture recycling for Mediterranean-type climate regions globally.*
2. *Assess which atmospheric and land surface characteristics link to local moisture recycling in Mediterranean-type climate regions globally.*
3. *Determine the impact of forestation on the development of the atmospheric boundary layer and deep convective clouds in the Mediterranean Basin.*
4. *Discuss how targeted rainfall enhancement can be an objective of forestation globally.*
5. *Evaluate the societal impact of the research conducted for this thesis.*

In Chapter 2, the local evaporation recycling ratio is quantified using global atmospheric moisture connections at the highest spatial resolution currently available. In Chapter 3, using the same high-resolution moisture connections, local precipitation recycling is quantified. Following the resolution of the atmospheric moisture connections, for the Mediterranean-type climate regions, the local evaporation recycling ratio is defined as the fraction of evaporated water that returns as precipitation within ca. 50km from its source; the local precipitation recycling is defined as the amount of precipitation that originated within ca. 50km from where it rains out.

In Chapters 2 and 3, statistical models are used to analyse and discuss the correlations between local evaporation and precipitation recycling and various atmospheric and land surface characteristics. These analyses provide insights into the links between local moisture recycling and land-atmosphere interactions, their strength, and their variability across the five major Mediterranean-type climate regions. The results show which atmospheric and landscape characteristics promote high local moisture recycling and how this varies across the five Mediterranean-type climate regions.

These chapters help to narrow down where in these Mediterranean-type climate regions regreening may enhance precipitation and where it may enhance drying.

In **Chapter 4** a process-based modelling approach is used to simulate the impact of a land cover change from bare soil to forest on the development of the atmospheric boundary layer and deep convective clouds in the Mediterranean Basin. This chapter provides insights into how part of the atmospheric dynamics could be affected by forestation and how this translates to changes in convective precipitation.

Chapter 5 dives deeper into the potential of forests to contribute to rainfall downwind. Whereas Chapters 2-4 focus on local recycling, Chapter 5 focusses on non-local recycling. This chapter explores the state-of-the-art tools and knowledge that allow to integrate targeted rainfall enhancement in forestation initiatives.

The research outputs from Chapters 2-5 are evaluated in **Chapter 6**, which discusses if the transdisciplinary research approach that was adopted in this PhD research is beneficial to generate societal impact and the development of an early career scientist.

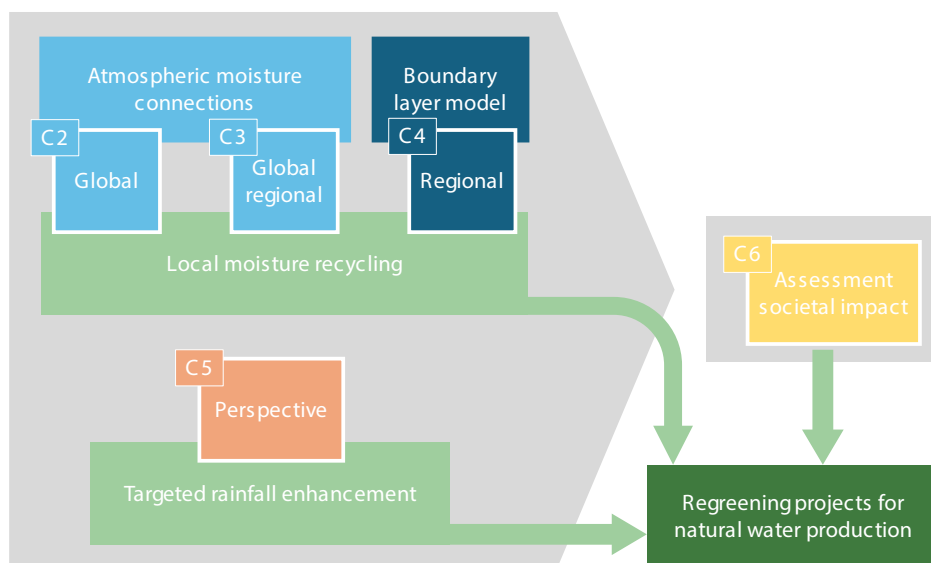


Figure 1.4. Schematic overview of how each of the chapters (CX) in this thesis contribute to the realization of the strategic planning of regreening projects for natural water production (green arrows). The content of Chapters 2-5 is used to assess the societal impact of the research activities that relate to this thesis (grey shapes). The blue colours indicate the chapters that study atmospheric moisture recycling on various scales, with the colour intensity indicating different methods. Chapter 1 provides a general introduction for this research and Chapter 7 discusses how the main findings contribute to realizing regreening projects that contribute to natural water production.

The focus of this thesis narrows from Chapter 2 to Chapter 4 as Chapter 2 adopts a global perspective, Chapter 3 examines Mediterranean-type climate regions across the globe, and Chapter 4 centres the Mediterranean Basin. In Chapters 5 and 6 the focus of this thesis expands again. Chapter 5 adopts a global perspective as it discusses the non-local hydrological effect of forestation and Chapter 6 puts the research findings into perspective by evaluating how they contribute to generate societal impact. Finally, **Chapter 7** synthesizes the overall findings of this research, describes how the outputs may be used to strategically plan regreening initiatives that aim for rainfall enhancement, and discusses opportunities for future research. A schematic overview of how each chapter contributes to the realization of the strategic planning of regreening initiatives for natural water production is shown in Figure 1.4.



2

Local moisture recycling
across the globe

Chapter 2 | Local moisture recycling across the globe

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Abstract

Changes in evaporation over land affect terrestrial precipitation via atmospheric moisture recycling and consequently freshwater availability. Although global moisture recycling at regional and continental scales are relatively well understood, the patterns of local moisture recycling and the main variables that impact it remain unknown. We calculate the local moisture recycling ratio (LMR) as the fraction of evaporated moisture that precipitates within a distance of 0.5° (typically 50km) from its source, identify variables that correlate with it over land globally and study its model dependency. We derive seasonal and annual LMR using a 10-year climatology (2008–2017) of monthly averaged atmospheric moisture connections at a scale of 0.5° obtained from a Lagrangian atmospheric moisture-tracking model. We find that, annually, on average 1.7% (st.dev. = 1.1%) of evaporated moisture returns as precipitation locally, but with large temporal and spatial variability, where LMR peaks in summer and over wet and mountainous regions. Our results show that wetness, orography, latitude, convective available potential energy, wind speed, and total cloud cover correlate clearly with LMR, indicating that especially wet regions with little wind and strong ascending air are favourable for high LMR. Finally, we find that spatial patterns of local recycling are consistent between different models, yet the magnitude of recycling varies. Our results can be used to study impacts of evaporation changes on local precipitation, with implications for, for example, greening and water management.

In this chapter, supplementary tables and figures are referenced using an 'S' (e.g., Table S1, Figure S2). These supplementary materials are not included in the thesis itself but can be accessed via the following link and QR-code: [Supplement to Chapter 2](#).



2.1 Introduction

Atmospheric moisture connections redistribute water from evaporation sources to precipitation sinks, affecting climates globally, regionally, and locally. These connections are key in the global hydrological cycle and are used to understand the importance of terrestrial evaporation for water availability. As evaporated moisture can travel up to thousands of kilometres in the atmosphere, changes in evaporation can affect precipitation in a large area. An evaporation shed (Van der Ent and Savenije 2013) describes where evaporated moisture from a specific source region precipitates and therefore, can be used to study (1) the changes in precipitation on a global scale following a change in evaporation in the source region and (2) atmospheric moisture recycling. Globally, more than half of terrestrial evaporated moisture precipitates over land (Van der Ent et al. 2010; Tuinenburg et al. 2020b), which is a process called terrestrial moisture recycling. Additionally, about half of terrestrial precipitation originates from land (Tuinenburg et al. 2020b). Hence, terrestrial moisture recycling has an important contribution to water availability. For example, 80% of China's water resources originates from evaporation over Eurasia (Van der Ent et al. 2010). Furthermore, areas can also feed precipitation to themselves through regional moisture recycling. In the Amazon basin, 63% of the evaporated moisture precipitates within the basin itself (Tuinenburg et al. 2020b). Terrestrial moisture recycling is considered an ecosystem service (Keys et al. 2016; Falkenmark et al. 2019) as globally, almost 20% of terrestrial precipitation originates from vegetation-regulated moisture recycling (Keys et al. 2016). How this ecosystem service is affected by, for instance, deforestation, can be studied using atmospheric moisture connections.

Moisture recycling has been used to study downwind impacts of land-use changes (Bagley et al. 2012; Keys et al. 2012; Wang-Erlandsson et al. 2018), which can affect both the magnitude and pattern of moisture recycling (Van der Ent et al. 2014), and the impact of ecosystems on other ecosystems (O'Connor et al. 2021a). Hence, atmospheric moisture connections can be used for freshwater governance to understand and manage the impacts of land-use changes downwind such as changes in freshwater availability for irrigation and natural ecosystems (Te Wierik et al. 2020; te Wierik et al. 2021). For example, previous research showed that for 45% of the Earth's land surface, an increase in vegetation is beneficial for downwind water availability (Cui et al. 2022).

So far, analytical recycling models and moisture-tracking models have been used to study terrestrial recycling and downwind impacts of land cover change on global and regional levels (Burde and Zangvil 2001; Van der Ent et al. 2010). Multiple studies focus on the regional recycling for specific regions, with a spatial scale ranging from 500km up to several thousands of kilometres (e.g., Lettau et al. 1979; Trenberth

1999; Burde 2006b; Dominguez et al. 2006; Staal et al. 2018). Furthermore, regional recycling on a spatial scale of 1.5° has been studied globally using a Eulerian moisture-tracking model, assuming a well-mixed atmosphere (Van der Ent and Savenije 2011). It was debated that regional recycling ratios are difficult to compare due to differences in the shape and size of the studied regions (Van der Ent and Savenije 2011). Therefore, van der Ent and Savenije (2011) defined the typical length scale of evaporation recycling, which can be used to compare between different regions as it is independent of the region's size and shape. This length scale decreases with increasing regional recycling and, therefore, is a proxy for an area's regional recycling. However, it does not allow for the quantification of the amount of water that recycles within the defined region and therefore does not provide quantitative insight into the regional impacts of evaporation changes induced by land-cover changes.

In regions with high regional recycling, forestation can enhance freshwater availability and for regions with low regional recycling, forestation may cause local drying (Hoek van Dijke et al. 2022) due to reductions in streamflow as a result of enhanced evaporation locally (Brown et al. 2005; Jackson et al. 2005). To physically understand, for instance, the role of local wetting or drying due to reforestation, deforestation, or the use of groundwater or surface water for irrigation, local moisture recycling is key. We argue that local impacts need to be studied explicitly as they may have a crucial role in future water governance, e.g., to prevent tree restoration projects causing local drying.

The state-of-the-art high-resolution atmospheric moisture connections obtained with the Lagrangian atmospheric moisture-tracking model "UTrack" allow us to calculate the evaporation recycling ratio at higher spatial resolution (0.5°) (Tuinenburg et al. 2020b; Tuinenburg and Staal 2020). We define this as the local moisture recycling ratio (LMR) as this high resolution allows us to study local-scale land-atmosphere feedbacks, which will help us better understand hydrological impacts of land-use change. LMR describes which fraction of evaporated moisture recycles within its source grid cell and its eight surrounding grid cells. Moisture recycling has not been studied before on this high-resolution scale globally. To get a better physical understanding of this metric we identify which factors correlate with it. We analyse this for different latitude classes to account for different cell sizes across latitude. Factors included in this analysis are: orography, precipitation, precipitation type, evaporation, shear, convective available potential energy, atmospheric moisture flux, wind speed, total cloud cover, boundary layer height and surface net solar radiation. These variables relate to either convection, local wetness, or moisture transport away from the source location, which we identified as important factors for local moisture recycling. Furthermore, we study how LMR varies over the globe and throughout the year for a 10-year climatology (2008-2017), as well as its scaling and model dependency.

2.2 Methods

We use global atmospheric moisture connections obtained from Tuinenburg et al. (2020b) to calculate LMR worldwide. These moisture connections are a 10-year climatology (2008–2017) of monthly averages and have a spatial resolution of 0.5° . These UTrack-atmospheric-moisture data are derived using a Lagrangian atmospheric moisture-tracking model by Tuinenburg and Staal (2020) that tracks evaporated moisture at a spatial scale of 0.25° . The data are stored at a spatial resolution of 0.5° . In this model, for each grid cell of 0.25° , each mm of evaporation is represented by one hundred released moisture parcels. The wind transports these parcels horizontally and vertically through the atmosphere. Additionally, a probabilistic scheme describes the vertical movement of the moisture parcels over 25 atmospheric layers. In this scheme, the parcels are randomly distributed across the vertical moisture profile of each grid cell. At each time step (0.1 h), the moisture budget is made using evaporation, precipitation and total precipitable water. Parcels are tracked for up to 30 days or up to the point at which only 1% of their original moisture is still present. On average, the lifetime of atmospheric moisture is 8–10 days (Sodemann 2020). After 30 days for most of the parcels all of the original moisture has rained out (Tuinenburg and Staal 2020). Input data for UTrack consist of evaporation, precipitation, precipitable water, and wind speed in each direction and are obtained from the ERA5 dataset (Hersbach et al. 2020). We refer to Tuinenburg and Staal (2020) for a complete description of the model settings and the tests and assumptions underlying them.

LMR is the fraction of evaporated moisture that precipitates locally. To study the scale dependency of local moisture recycling, we examine three definitions of LMR (Figure S1): the fraction of evaporated moisture that precipitates in (1) its source grid cell, i.e., r_1 , (2) its source grid cell and its eight neighbouring grid cells, i.e., r_9 , and (3) its source grid cell and its 24 neighbouring grid cells, i.e., r_{25} . Equations 2.1–2.3 describe the three definitions of LMR, in which $E_{i,j}$ is the amount of moisture evaporated from source grid cell i,j . The fraction of $E_{i,j}$ that precipitates within its source grid cell and its (8 or 24) neighbouring grid cells is indicated by $P_{E,i+l,j+k}$ ($i+l,j+k$, with $l = 0$ and $k = 0$ for r_1 , $l = -1,0,1$ and $k = -1,0,1$ for r_9 and $l = -2,-1,0,1,2$ and $k = -2,-1,0,1,2$ for r_{25}).

$$r_1 = \frac{P_{E,i,j}}{E_{i,j}} \quad (2.1)$$

$$r_9 = \frac{\sum_{l=-1}^1 \sum_{k=-1}^1 P_{E,i+l,j+k}}{E_{i,j}} \quad (2.2)$$

$$r_{25} = \frac{\sum_{l=-2}^2 \sum_{k=-2}^2 P_{E,i+l,j+k}}{E_{i,j}} \quad (2.3)$$

r_1 , r_9 , and r_{25} result in different local moisture recycling ratios across the globe (Figure S2). r_1 peaks over the oceans where precipitation is relatively low and evaporation is relatively large, which results in relatively large recycling ratios. In addition, we find exceptionally low values over mountain peaks, yet not over all elevated terrain. This result is inconsistent with the patterns found for r_9 and r_{25} , as these patterns include peaks over mountainous and low recycling over the oceans. These patterns can be explained by enhanced convection over mountains due to orographic lift and strong winds over the ocean that carry moisture away from its source. The patterns found for r_9 and r_{25} seem to capture multiple physical processes that are important for moisture transport and the formation of precipitation better than the pattern of r_1 . In our study we do not focus on r_1 , as r_1 does not include all small-scale flows of $<50\text{km}$. This is because moisture can evaporate from cell i,j , and precipitate in the adjacent cell, while transport length is $<50\text{km}$. Furthermore, as the patterns of r_9 and r_{25} are similar and agree with our understanding of relevant processes, we decided to define the local moisture recycling ratio (LMR) as r_9 to keep the spatial scale as small as possible.

For r_9 , the distance between the centre of the source grid cell and its surrounding grid cells describes the typical length of the local moisture flow, which is approximately 0.5° . We calculated this typical length across the globe by calculating the average of the zonal length, meridional length, and diagonal length of all terrestrial grid cells. The total average equals 50.1km (st.dev. = 15.5km), so, the average moisture flow length is approximately 50km .

Furthermore, the LMR derived with the Lagrangian approach using output from UTrack is compared with the output from the Eulerian moisture-tracking model WAM2-layers (Link et al. 2020), to study the model dependency of LMR. For this comparison, the resolution of the UTrack data is reduced to 1.5° to match the output of the WAM2-layers model. To do so, all evaporationsheds over land were multiplied with their source evaporation. Then, the recycling within cells of 1.5° was calculated for all terrestrial surfaces. A detailed description of the atmospheric moisture connections obtained with WAM2-layers and the model itself are provided by Link et al. (2020) and Van der Ent et al. (2013).

We study the relations between multiple variables and the 10-year climatology (2008-2017) of local moisture recycling to identify factors that relate to and may affect recycling. To calculate this 10-year climatology of LMR, for each month, we weighted the multi-year (2008-2017) monthly LMR by multi-year monthly evaporation in the same period:

$$LMR_{\text{annual average}} = \sum_{i=\text{jan}}^{\text{dec}} LMR \frac{E_{\text{month } i}}{E_{\text{year}}} \quad (2.4)$$

Here, E_{year} is the sum of the evaporation of the 12 months. To identify factors that might affect LMR, variables that relate to atmospheric moisture and vertical displacement of air are selected, as both higher atmospheric moisture content and ascending air promote precipitation. All these variables are obtained, either directly or indirectly from ERA5 reanalysis data (Hersbach et al. 2020). We downscaled the original resolution from 0.25° to 0.5° by centrally averaging the data. For all variables we calculated the climatological mean for the years 2008-2017.

In total 13 variables are selected (Figure S3): (1) elevation (z) which we expect to enhance LMR through orographic lift. (2) Precipitation, which we expect to correlate positively with LMR given that in Lagrangian moisture-tracking models, the amount of moisture that leaves the parcel (i.e., precipitates) scales with precipitation. (3) Total evaporation as it enhances the atmospheric moisture content and we therefore expect it to promote precipitation locally. (4) Wetness (precipitation minus evaporation), as with increasing wetness the downward flux of moisture increases and evaporated water becomes more likely to precipitate possibly promoting LMR. (4) Convective precipitation and (5) large-scale precipitation, as they scale with precipitation by definition. Both are included to study whether the type of precipitation is an important factor explaining LMR. (6) Latitude, which is a proxy for processes related to the Hadley cell circulation, which is characterized by the ascent and descent of air at specific latitudes, which we expect to have an important contribution to LMR, because they respectively enhance and reduce the formation of precipitation (Wang and Yang 2022). (7) The vertical integral of the atmospheric moisture flux (in northward and eastward directions and the total flux) as it carries the moisture away from its source and could thus reduce LMR. (8) Convective available potential energy (CAPE), which feeds convection and therefore promotes precipitation locally, which could enhance LMR. (9) Vertical wind shear between 650 and 750 hPa of both meridional and zonal winds, as it affects moisture transport in multiple directions and, therefore, we expect it to impact LMR. (10) Total wind speed, as it carries the wind, and therefore, we expect it to correlate negatively with LMR. (11) Total cloud cover as a proxy for condensation processes which possibly enhance LMR (Richards and Arkin 1998). (12) Boundary layer height, because thinner boundaries need less evaporation to reach saturation of air, and therefore, we expect it will promote precipitation locally. Finally, (13) net surface solar radiation as a proxy for the energy source of convection, and other processes, which we expect to be important for LMR. We calculate shear (τ) using Equation (2.5).

$$\tau = \frac{\ln \frac{v_2}{v_1}}{\ln \frac{z_2}{z_1}} \quad (2.5)$$

In this equation, v_1 and v_2 are the wind speed (in zonal and meridional directions) at two different heights (z_1 and z_2). We identified significant correlations using Spearman rank correlations. It should be noted that a correlation does not imply causality. We exclude oceans, seas and Antarctica from this analysis using the land-sea mask from ERA5. We classify the data based on latitude to account for decreasing grid cell size with increasing latitude. Each class has a range of 15° and includes the grid cells on both the Northern and Southern Hemispheres (see Table S1). Between 60° and 90° south, the grid cells do not contain land besides Antarctica, and are therefore not included in the classes. Additionally, we used the Ecoregions 2017 data (<https://ecoregions.appspot.com/>) to study the spatially averaged local moisture recycling of 14 biomes across the globe (Figure S4). We study variation amongst biomes, as biomes include information on both biotic factors such as vegetation type, and abiotic factors such as climate.

2.3 Results

2.3.1 LMR obtained from output of UTrack

Annually, on average about 1.7% (st. dev. = 1.1%) of terrestrial evaporated moisture recycles locally. LMR shows spatiotemporal variation (Figure 2.1) with peaks over elevated (e.g., the Atlas Mountains and Ethiopian Highlands) and wet areas (e.g., Congo Basin and Southeast Asia) and minima over arid regions (e.g., Australia and the Sahara Desert). Additionally, we find peaks in LMR during summer (i.e., during DJF for the Southern Hemisphere and during JJA for the Northern Hemisphere).

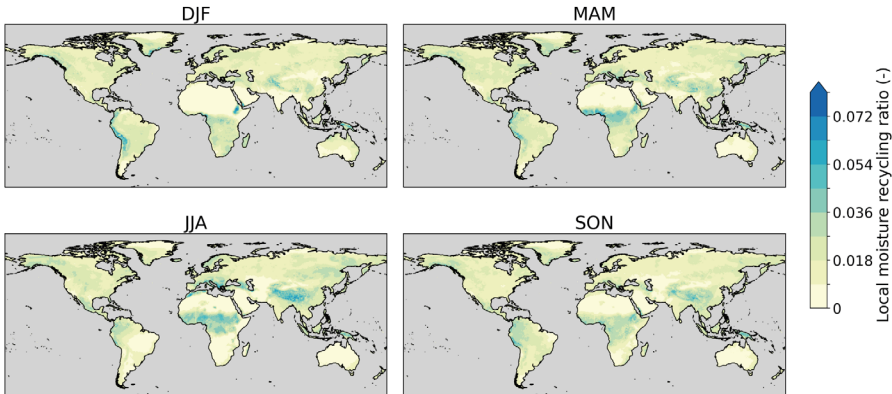


Figure 2.1. 10-year climatology (2008–2017) of the seasonal averages of local moisture recycling across the global land surface. Here, local moisture recycling is defined as the fraction of evaporated moisture that precipitates in its source grid cell and its eight neighbouring grid cells (r_g). Different seasons are DJF: December–February, MAM: March–May, JJA: June–August, and SON: September–November.

This seasonality is especially strong over mountainous and wet areas. In the mid-latitudes, especially the Mediterranean Basin, LMR shows seasonality with peaks in summer (JJA). However, seasonality is largest at low latitudes. Within the tropics we find some spatial differences. First, LMR in the Congo Basin and Southeast Asia exceed LMR in the Amazon Basin. Second, recycling in the Congo Basin and Southeast Asia peaks in JJA and recycling in the Amazon Basin peaks in DJF, which is the wet season for a large part of the Amazon.

We calculated recycling on a 1.5° grid using both the dataset by Link et al. (2020), which we refer to as $r_{\text{WAM2-layers}}$ and the dataset by Tuinenburg et al. (2020b) (upscaled to 1.5°), which we refer to as r_{UTrack} to study the model dependency of local recycling (Figure 2.2). We find that the global spatial patterns of r_{UTrack} and $r_{\text{WAM2-layers}}$ agree (Figure 2.2 & Figure S5). However, the magnitude of $r_{\text{WAM2-Layers}}$ is larger than r_{UTrack} over mountains, the tropics, and the high latitudes. r_{UTrack} is larger than $r_{\text{WAM2-layers}}$ over drylands and deserts (e.g., the Sahel region and Western Asia) (Figure 2.2). However, over drylands and deserts recycling ratios are relatively small and therefore, the relative difference as presented in Figure 2.2 has less meaning here. Globally, the difference between r_{UTrack} and $r_{\text{WAM2-layers}}$ and its variation is largest around the equator (Figure S6). On average, the relative difference between UTrack and WAM2-Layers $((\text{UTrack} - \text{WAM2-Layers}) / \text{UTrack})$ equals -1.5 (st.dev. = 3.4).

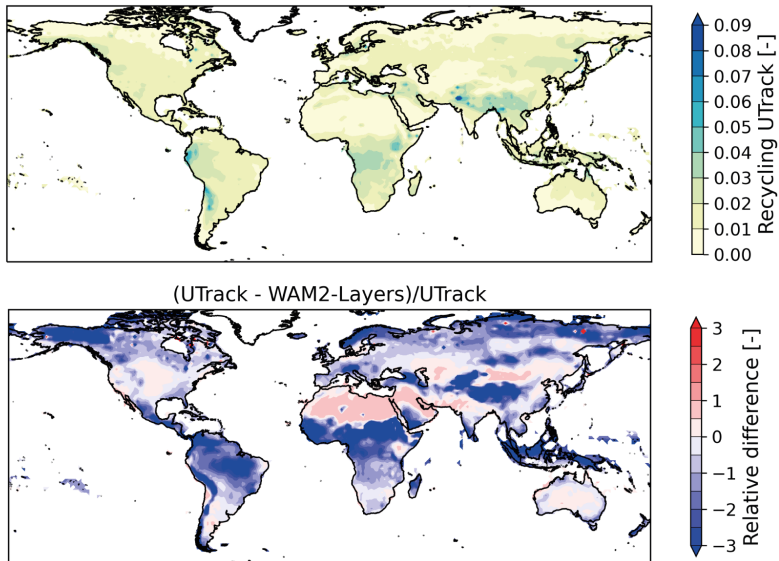


Figure 2.2. r_{UTrack} , the fraction of evaporated moisture that recycles within its source grid cell of 1.5° (top). The relative deviation between r_{UTrack} and $r_{\text{WAM2-layers}}$ (bottom). This deviation is calculated using the fraction of moisture recycling within one grid cell at a resolution of 1.5° obtained from the datasets by Tuinenburg et al. (2020b) and Link et al. (2020).

2.3.2 Factors underlying LMR

For each latitude class we calculated the Spearman rank correlation coefficient (ρ) (Table 2.1). Below we discuss only statistically significant ($p < 0.05$) correlations with $\rho \geq 0.4$, that indicate a moderate correlation. These correlations are emboldened in Table 2.1. We find that LMR correlates positively with total precipitation and wetness for all classes between 15° and 75° . In addition, between 15° and 30° , LMR correlates strongly with total precipitation ($\rho = 0.80$). In addition to total precipitation, large scale precipitation (between 15° and 45° and between 60° and 75°) and convective precipitation (between 15° and 45°) correlate positively with LMR. Overall, there is a moderate correlation between precipitation and LMR for the mid-latitudes. The highest correlation between LMR and convective precipitation is found between 15° and 30° latitude. For this latitude class, LMR also correlates positively with evaporation and CAPE. Despite the low correlation between LMR and CAPE for most of the latitude classes, high CAPE clearly relates to LMR, as the skewed profile in the scatter density plot indicates that only a small amount of the grid cells with a relatively high CAPE have a low LMR (Figure 2.3). Furthermore, the presence of clouds also correlates with LMR. Between LMR and total cloud cover, a positive correlation holds between 15° and 45° , and a negative correlation holds between 60° and 75° . Furthermore, the vertical integrals of the eastward and northward moisture fluxes correlate less with LMR compared to the vertical fluxes (e.g., precipitation). For the higher latitudes, the northward moisture flux correlates positively with LMR (between 60° and 75°) and the eastward moisture flux correlates negatively with LMR (between 75° and 90°). The moisture flux depends on wind speed, yet, wind speed correlates negatively with LMR for the lower latitudes (between 0° and 45°). Furthermore, LMR correlates positively with orography between 30° and 75° . We find that for high elevation, LMR is always relatively high (Figure S7). Additionally, LMR correlates negatively with boundary layer height between 45° and 60° . Finally, LMR correlates negatively with wind shear at 650 hPa in the meridional direction (between 75° and 90°) and with latitude (between 60° and 75°). However, we find an oscillating relation between LMR and latitude (Figure 2.4), which is not captured by the Spearman rank correlation coefficients. This pattern indicates high LMR over the equator (0°) and 60° north, and low LMR around 30° north and south. Orography seems to disrupt the relation between latitude and LMR causing peaks in LMR around 35° north and 20° south (Figure 2.4). LMR does not correlate to surface net solar radiation for any latitude. However, for low surface net solar radiation ($< 0.75 \times 10^6 \text{ J/m}^2$) holds that LMR increases with increasing surface net solar radiation (Figure 2.3).

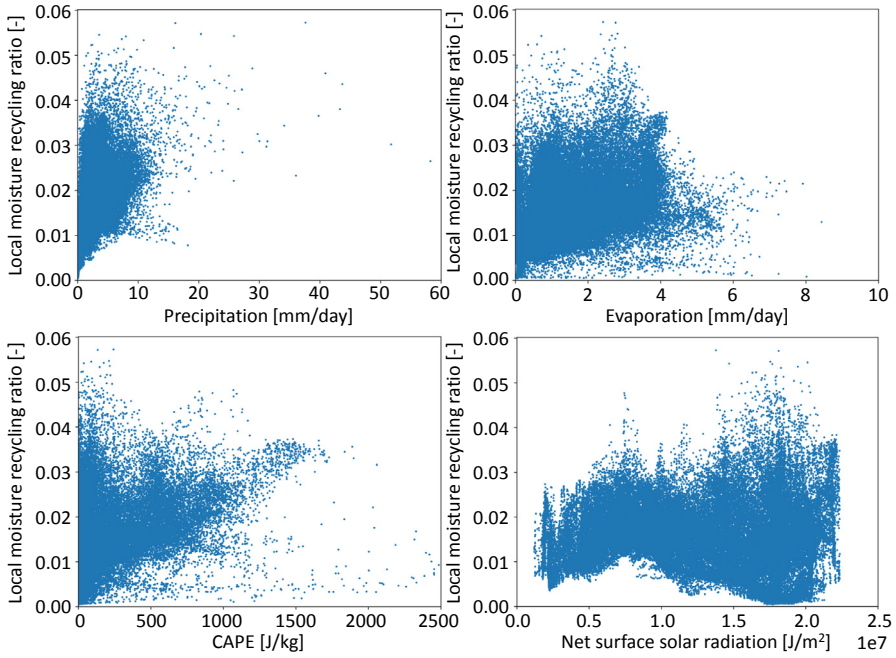


Figure 2.3. Scatter plots of the 10-year climatology (2008–2017) of the local moisture recycling ratio over land and precipitation (top left), evaporation (top right), convective available potential energy (CAPE) (bottom left), and solar net surface radiation (bottom right). Each dot represents a 0.5° resolution grid cell over land.

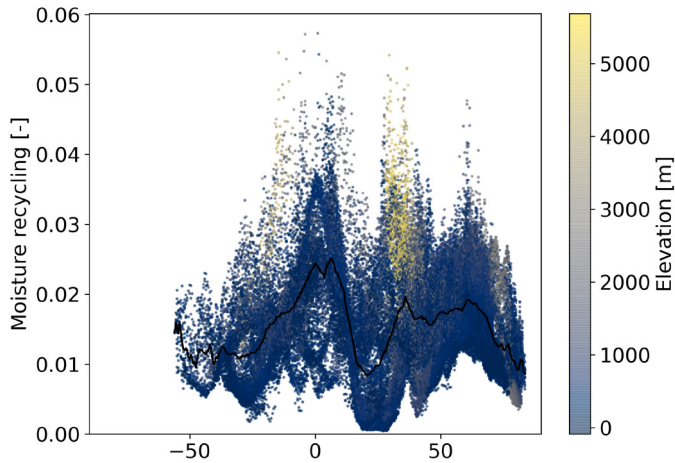


Figure 2.4. Scatter plot of the 10-year climatology (2008–2017) of LMR and latitude. The colour scale indicates elevation, with blue being low elevation and yellow being high elevation. The black line represents the zonal average of LMR. Each dot represents a 0.5° resolution grid cell over land.

Table 2.1. Spearman rank correlation coefficients between LMR and all tested variables. ‘**’ indicates a significant correlation ($p < 0.05$) and moderate and strong correlations ($\rho > 0.4$) are emboldened. The classes including latitudes between 0° and 60° include grid cells of the Northern Hemisphere and Southern Hemisphere. The classes including latitudes exceeding 60° include grid cells of the Northern Hemisphere only.

Variable	Spearman rank correlation coefficients for different latitudes					
	$0^\circ\text{-}15^\circ$	$15^\circ\text{-}30^\circ$	$30^\circ\text{-}45^\circ$	$45^\circ\text{-}60^\circ$	$60^\circ\text{-}75^\circ$	$75^\circ\text{-}90^\circ$
Total precipitation (P)	0.15*	0.80*	0.47*	0.40*	0.45*	0.37*
Total evaporation (E)	-0.05*	0.63*	0.19*	-0.12*	0.19*	0.20*
Wetness (P-E)	0.18*	0.59*	0.52*	0.48*	0.43*	0.27*
Convective precipitation	0.20*	0.79*	0.46*	0.29*	0.35*	0.33*
Large scale precipitation	-0.06*	0.75*	0.46*	0.38*	0.40*	0.36*
Fraction of cp	0.36*	-0.35*	-0.13*	-0.14*	0.19*	0.28*
Latitude	0.24*	-0.18*	0.22*	0.14*	-0.40*	-0.18*
Eastward moisture flux	0.15*	0.00	-0.30*	-0.38*	-0.20*	-0.49*
Northward moisture flux	-0.03*	0.22*	0.29*	-0.03*	0.48*	0.23*
Total moisture flux	-0.28*	0.30*	-0.29*	-0.33*	-0.03	-0.16*
CAPE	0.31*	0.58*	0.37*	0.06*	0.12*	-0.02
Zonal shear	0.15*	-0.12*	0.02	-0.31*	0.00	0.24*
Meridional shear	-0.22*	0.15*	-0.08*	-0.01	0.05*	-0.46*
Orography	0.31*	0.29*	0.49*	0.54*	0.68*	-0.13*
Total cloud cover	0.28*	0.78*	0.43*	0.09*	-0.56*	0.08*
Surface net solar radiation	-0.16*	0.10*	-0.30*	-0.08*	0.28*	0.21*
Boundary layer height	-0.31*	-0.32*	-0.39*	-0.53*	-0.18*	-0.06*
Total wind speed	-0.46*	-0.55*	-0.47*	-0.26*	-0.26*	-0.30*

2.4 Discussion

2.4.1 Factors underlying LMR

Moisture recycling affects humankind by influencing water security, agriculture, forestry, regional climate stability and Earth system resilience (Keys et al. 2019; Wang-Erlandsson et al. 2022). Different types of moisture recycling were subject to research and used for different applications (Van der Ent et al. 2010; Bagley et al. 2012; Pranindita et al. 2022). We analysed the local moisture recycling ratio (LMR) (of evaporated moisture) across the globe at 0.5° resolution, and which factors might

affect it. We find that LMR, defined as the fraction of evaporated moisture that precipitates within a distance of 0.5° (typically 50km) from its source, varies over time and space, peaking in summer and over elevated and wet regions. First, latitude, elevation, and Convective Available Potential Energy (CAPE) seem to be important factors influencing LMR (Figure 2.5). Some of these variables promote convection (Roe 2005; Wallace and Hobbs 2006; Scheff and Frierson 2012), strongly suggesting the dependency of LMR on convection. Convective storms develop due to unstable conditions resulting in precipitation locally (Eltahir 1998) and a higher CAPE may result in more rainfall (Williams and Renno 1993; Eltahir and Pal 1996). The pattern of LMR across orographic features and latitudes coincides with updraft and downdraft of air caused by orographic lift or the Hadley cell circulation (Wallace and Hobbs 2006), promoting condensation. Resulting from the Hadley cell circulation, around the equator and 60° north and south, air ascends, resulting in a high LMR. Around 30° north and south, air descends, resulting in a low LMR. Deviations from this pattern correspond to orographic features which promote LMR through orographic lift. Overall, our results suggest a positive relation between ascending air flow and LMR.

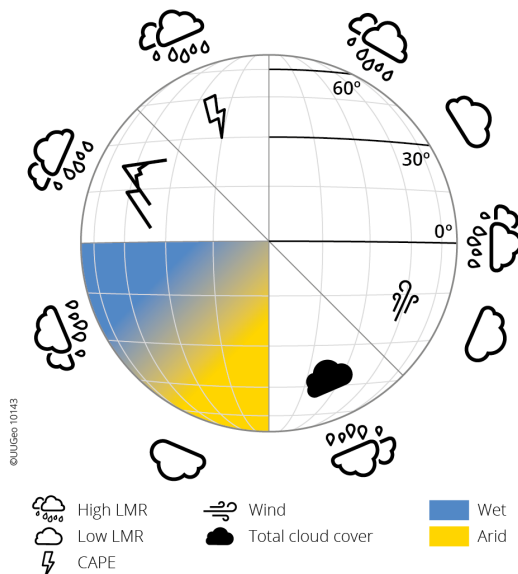


Figure 2.5. Conceptual model of the most important factors influencing local moisture recycling around the globe. Rainy clouds indicate variables that increase LMR and clouds without raindrops indicate variables that decrease LMR. Blue indicates wet regions, yellow indicates arid regions.

Second, wetness seems to be an important factor underlying LMR as LMR significantly correlates with precipitation and P-E (precipitation minus evaporation). Furthermore, both large-scale and convective precipitation significantly correlate with LMR. This is surprising, as convection promotes precipitation locally (Eltahir 1998); therefore, we expected a stronger correlation between LMR and convective precipitation than between LMR and large-scale precipitation. As both correlations are similar, this suggests that the type of precipitation might not affect LMR. Although convection is a local-scale process (i.e., having a spatial scale below 100km) (Miyamoto et al. 2013), remotely evaporated moisture can be transported to a region with high convective activity and then precipitate as convective precipitation (Liberato et al. 2012; Jana et al. 2018). In that way, the precipitation type is independent of the distance between moisture source and target location and therefore does not relate to LMR.

Total cloud cover correlates both positively (between 15° and 45°) and negatively (between 60° and 75°) with LMR. Total cloud cover correlates with precipitation, convective precipitation, and large-scale precipitation for all latitudes except between 60° and 75° (Table S2). Due to the positive correlation between LMR and precipitation and the absence of a correlation between precipitation and total cloud cover at these latitudes we can statistically explain the negative correlation between total cloud cover and LMR. Physically, this result is harder to explain. Our results describe the importance of convection underlying LMR at lower latitudes, where total cloud cover correlates with convective precipitation. For higher latitudes, the importance of convection underlying LMR decreases, and therefore, we expected also the correlation between total cloud cover and LMR to decrease and not to become negative. Likely, another process that we cannot identify with our analysis causes the correlation between total cloud cover and LMR to be negative. Overall, we find that wetness enhances LMR independent of the precipitation type.

Unexpectedly, we do not find a clear correlation between the vertical integral of the atmospheric moisture flux and LMR. However, for the lower latitudes (between 0° and 45° latitude), LMR correlates to wind speed (at 10 and 100 m), which carries evaporated moisture away from its source location, enhancing the moisture flux. Therefore, horizontal moisture fluxes at specific altitudes are better for our analysis than the vertical integral of the moisture flux. However, since wind carries moisture away from its source, we expected that wind speed and LMR would also correlate at higher latitudes (latitude above 45°). It could be that here a more significant amount of moisture is present at higher altitudes, explaining why LMR and wind at 10m do not correlate. However, wind speeds at 650 hPa and 750 hPa also do not correlate to LMR for these latitudes (Table S2).

Despite the importance of vertical shear in atmospheric moisture-tracking models (Van der Ent et al. 2013), we do not find a correlation between local moisture recycling and vertical shear between 650 and 750 hPa. Shear is the friction between air layers that minimizes complete mixing and for some regions around the world is strongest between 650 hPa and 750 hPa (Dominguez et al. 2016). A possible explanation is that due to its small spatial scale, the temporal scale of LMR is also small, which may prevent the air reaching 700 hPa within the spatial scale of LMR. Furthermore, it is possible that our study design is insufficient to capture the relation between LMR and shear throughout the year over the globe. We aimed for a general analysis to identify the main factors that might influence LMR. A more detailed study that distinguishes between different seasons and isolates different climate zones is necessary to identify more factors that influence LMR as some factors might be more important during a specific season. For example, convection occurs more during summer than during winter, and therefore, might have a stronger correlation with LMR during summer. Besides, some factors are shape and size dependent similar to LMR, while other factors are not dependent on grid cell size and shape. This might cause a bias in the results of the Spearman analysis. Furthermore, due to the many interactions within the Earth system and, consequently, between the variables included in our study, it is impossible to determine the true drivers of LMR. However, the correlations do indicate how changes in the environment may affect LMR.

2.4.2 Regional patterns

To zoom in on the importance of each of the different factors underlying LMR for various areas across the globe, we determined LMR for the major global biomes (Figure S8). LMR is highest for the wet tropics (between 0° and 15° north and south) and montane grasslands and lowest for desert-like biomes in both the Northern and Southern Hemisphere (between 30° and 45° north and south), confirming the importance of wetness, orography, and latitude. However, in the tropics (between 0° and 15° latitude), we do not find any correlation between LMR and precipitation, evaporation, wetness, or orography. Possibly, due to the abundance of water and energy for evaporation, moisture recycles locally under all circumstances, except for when wind speed is high.

Comparing LMR for each biome between both hemispheres indicates that some of the factors underlying LMR are more robust across the globe than others. In the Mediterranean biomes, located between 30°–40° north and south, air generally descends due to the Hadley cell circulation. As a result, these biomes are expected to have low LMR. Although we find a low LMR for the Mediterranean biomes in the Southern Hemisphere, we find a relatively high LMR for the Mediterranean biomes

in the Northern Hemisphere. The Spearman rank analysis indicates that at these latitudes, wind speed correlates with LMR. Diverging wind patterns may explain the difference between both hemispheres.

Although LMR is the highest in the wet tropics, we find different results among the various tropical regions (Amazon Basin, Congo Basin & Southeast Asia). LMR in the Congo Basin exceeds LMR in the Amazon Basin (Figure 2.1), despite larger amounts of precipitation in the Amazon Basin (Hersbach et al. 2020). In the tropics, current deforestation results in drying (Bagley et al. 2014; Staal et al. 2020b), reducing evaporation. As LMR in the Congo Basin exceeds LMR in the Amazon Basin, deforestation has a relatively large impact on local precipitation in the Congo Basin, suggesting a larger impact on droughts locally. This is further exacerbated by the fact that the Congo Basin, in comparison with the Amazon Basin, has many small-scale moisture feedback loops (Wunderling et al. 2022b). Unlike LMR, basin recycling is similar for both basins (Tuinenburg et al. 2020b). Suggesting, the impact of deforestation on precipitation in the entire basin is similar for both basins, indicating both basins would experience similar overall drying. However, drought conditions can also enhance recycling ratios (Bagley et al. 2014), possibly promoting LMR. Further research is necessary to understand the impact of deforestation on LMR in the tropics in more detail.

2.4.3 *The spatial scale of the local moisture recycling ratio*

We study local moisture recycling on a spatial scale of 0.5° , which is approximately 55km around the equator and 50km on average for all land cells across the globe. Instead of recycling within one grid cell (r_1), we studied the recycling of evaporated moisture within its source grid cell and its 8 surrounding grid cells. Compared to r_1 , r_9 includes all moisture flows with a length scale of typically 50km (0.5°). For r_1 , moisture flows with a length smaller than 50km to neighbouring cells are not included and, therefore, r_1 by definition underestimates the actual recycling. These moisture flows are accounted for in r_9 .

Defining LMR on a grid scale gives complications. First, the longitudinal distance for a grid cell size decreases with latitude, resulting in different sizes and shapes, which makes it difficult to compare LMR among all grid cells. For the low- and mid-latitudes, the variation in grid cell size affects LMR only slightly, as confirmed when LMR for each grid cell was scaled to a single area (Figure S9). Therefore, we believe that the variation in grid size causes only a small bias in the statistical analysis, as the largest fraction of the land surface is at the low- and mid-latitudes, and moisture recycling is less important for the higher latitudes. However, it should be noted that for similar wind speed, LMR will be lower in smaller grid cells than larger grid cells. Second, the spatial scale of recycling is strongly dependent on

regional differences such as biome type, the dominating winds, and the proximity to mountains. For instance, with increasing distance to the Andes mountains the median travelling distance of transpired moisture from the Amazon forest increases (Staal et al. 2018) and for the Ganges basin, evaporated moisture is blocked by the Himalayas, limiting upward moisture flow and inducing precipitation (Tuinenburg et al. 2012). Further, precipitation can be triggered by micrometeorological processes (e.g., Knox et al. 2011; Taylor et al. 2012) making it unknown at what spatial scale moisture recycling is the dominant process for precipitation. Therefore, we believe that a grid-based approach to systematically study LMR globally is a solid approach to define and study the physical processes at a spatial scale $>50\text{km}$ through, for instance, the Spearman analysis to study the underlying processes. However, our definition of LMR is not sufficient to identify processes on a spatial scale smaller than 50km that might be relevant.

2.4.4 Model and definition dependencies

It is important to note that the typical length scale of moisture recycling, as defined by Van der Ent and Savenije (2011), allows for a comparison of regional moisture recycling for different regions around the world due to its independence of the region's size and shape (Figure S10). The typical length scale of evaporated moisture recycling decreases with increasing recycling. It peaks over deserts and is small over the tropics and mountainous regions (Figure S9), overlapping with the spatial pattern of LMR. However, this typical length scale does not allow for the quantification of the amount of recycled moisture and therefore, it is difficult to apply this metric to study the impact of evaporation changes due to land-use change. Therefore, studies that aim to quantify moisture recycling locally may best use recycling ratios. However, studies that aim to compare recycling among different regions can best use the typical length scale of recycling.

In this article, we explore the model dependency of local recycling as we calculated the differences in magnitude of recycling within one grid cell of 1.5° obtained from output of the UTrack and WAM2-layers models (Link et al. 2020; Tuinenburg et al. 2020b). The spatial patterns are similar, yet the different magnitudes indicate a large model dependency, and, therefore, an uncertainty in moisture recycling. Furthermore, Van der Ent et al. (2010) calculated recycling within a grid cell of 1.5° for the years 1999–2008 using WAM2-layers and found a similar spatial pattern with high recycling over mountainous and tropical regions and low recycling over desert-like regions. These recycling ratios also have a larger magnitude than LMR. However, it is not straightforward to interpret the differences in recycling ratios as both models use different input data (i.e., ERA5 and ERA-Interim). To assess the possible role of the models in causing the difference in moisture recycling, we describe the main

differences between the models. First, WAM2-layers calculates atmospheric moisture recycling on a larger temporal and spatial scale than UTrack. A larger grid cell size and time step increases the likelihood of evaporation and precipitation taking place within the same small amount of time, which might result in an overestimation of recycling within one grid cell. Second, WAM2-layers generates moisture flows using two vertical layers; therefore, strong winds at specific vertical levels will be described in less detail, reducing estimated moisture transport and enhancing estimated moisture recycling within a single grid cell. Differences between r_{UTrack} and $r_{WAM2-layers}$ are highly visible over mountainous regions where wind experiences relatively strong friction, highly impacting the wind. Finally, different approaches are used to include vertical mixing in the two models. Vertical mixing causes the greatest error in moisture-tracking models, but it is unknown to what extent vertical mixing is underestimated (Stohl et al. 2005; Tuinenburg and Staal 2020).

Besides studies using atmospheric moisture-tracking (Van der Ent et al. 2010; Bagley et al. 2014; Keys et al. 2014), some previous studies used different methods to calculate regional moisture recycling for a specific area, such as isotope measurements (An et al. 2017) and bulk recycling models (Burde and Zangvil 2001). The most common recycling models are modifications of Budyko's model (Budyko 1974; Burde and Zangvil 2001), which are 1D or 2D analytical models. These models assume that the atmosphere is completely mixed, meaning that evaporated water mixes directly and perfectly with advected water throughout the entire water column. Because of this assumption, first, these models overlook fast recycling, which describes local showers that yield precipitation before the evaporated water is fully mixed. Excluding fast recycling causes models to underestimate terrestrial moisture recycling for some regions (e.g., Amazon Basin) (Burde 2006b). Second, these models ignore the influence of vertical shear, which causes a significant error (Dominguez et al. 2020). Our method minimises these errors because of two model aspects. First, at each time step, each parcel has a small chance of getting mixed, causing each parcel to move approximately once in the vertical direction every 24 hours, in addition to the displacement based on reanalysis data of vertical winds. This process minimizes complete mixing and reduces the error due to shear and fast recycling. Second, the error due to fast recycling also becomes smaller because lower atmospheric levels contribute more to the total precipitation than higher levels due to the skewed vertical moisture profile. WAM2-layers accounts for vertical shear as it models two vertical atmospheric layers of which the interface is located at the height at which shear typically occurs. These two layers are both completely mixed and therefore, compared to bulk models, WAM2-layers better represents the distribution of moisture throughout the atmospheric column. As an alternative method, moisture flows can be calculated on a smaller time step to

increase the interactions between different wind components, resulting in a better representation of turbulence (Keune et al. 2022). Despite the error reduction, the representation of fast recycling in UTrack should be studied in more detail, as fast recycling is expected to influence LMR significantly.

LMR is calculated as a ten-year average. This period of ten years might miss multi-year climate variability such as the El Niño Southern Oscillation and the North Atlantic Oscillation. The time series of atmospheric moisture connections provided by Link et al. (2020) allowed to study inter-annual variation in relatively local recycling. This shows that recycling is dependent on multi-year atmospheric phenomena. During the major El Niño event of 2015-2016, the northeast of South Africa had a lower-than-average local recycling ratio for 2015 (Figure S11). This pattern coincides with the impact of wetness during El Niño years, consistent with the hypothesis that wetness enhances LMR. Furthermore, extreme events such as heat waves and droughts might affect the multi-year annual mean. For example, we clearly find lower recycling over Russia during 2010, which may relate to the 2010 heatwave in eastern Europe and Russia. Overall, for these multi-year and extreme events we find that, for regions that face wetter-than-normal conditions, LMR is enhanced, and for regions that face drier-than-normal conditions, LMR is reduced. Hence, drought events might result in a decrease in LMR as seen for the 2010 heat wave event in Europe and Russia. However, not for all inter-annual climate variability modes we find a clear impact on moisture recycling. It may be that these phenomena do not affect wetness throughout the entire year, and therefore, annual means might not represent them well.

2.4.5 Implications/applications of LMR

LMR could be applied in the field of water management. The spatial pattern of LMR shows some overlap with global agricultural water management (Molden 2007; Salmon et al. 2015). Generally, the tropics have a high LMR and here agriculture is mainly rainfed (Salmon et al. 2015; Costa et al. 2019), indicating that these agricultural regions are self-dependent to some extent regarding precipitation. Also, agriculture in the Mediterranean Basin and South Australia is mainly rainfed. For semi-arid regions that depend on rainfed agriculture, changes in precipitation may have a significant impact (Keys et al. 2016). LMR in the Mediterranean Basin exceeds LMR in southern Australia, indicating that a larger fraction of evaporated moisture returns locally. Thus, when evaporation is maintained in the Mediterranean Basin, part of the precipitation will sustain here, which holds to a lesser extent for southern Australia. Besides LMR (i.e., local evaporation recycling), local precipitation recycling can help to understand the precipitation dependence on local evaporation for each region. Irrigated agriculture is important in India and

China (Döll and Siebert 2002; Salmon et al. 2015), which are regions with a relatively low LMR, indicating that only a small amount of the evaporated moisture returns as precipitation locally. For irrigated agriculture in regions that are characterized by a high LMR, a relatively large amount of the evaporated water returns to its source, which reduces the amount of water that is necessary for irrigation. Terrestrial evaporation is an important source for precipitation and freshwater availability (Keune and Miralles 2019). Therefore, spatial planning using LMR might improve agricultural water management.

Global climate change likely affects atmospheric moisture connections due to changes in atmospheric dynamics. For example, due to global warming, the tropical atmospheric circulation may weaken (Vecchi et al. 2006), and the Hadley cells may move poleward (Shaw 2019). This will affect the updraft and downdraft of air around the globe, which we found to be important processes underlying LMR. Furthermore, climate change has different opposing impacts on storm tracks which have an important role in moisture transport by transporting latent heat poleward (Shaw et al. 2016). Additionally, in a warmer climate continental recycling is predicted to decrease and precipitation over land would be more dependent on evaporation over the ocean (Findell et al. 2019). However, our study does not account for any impacts of climate change. As our results indicate that wetness and convection enhance LMR, LMR may change due to, for example, drying and wetting of regions, changes in Hadley cell circulation, and circulation in the tropics. Furthermore, climate change enhances the risk of droughts (Rasmijn et al. 2018; Teuling 2018). LMR may be used to study drought resilience globally as for a high LMR a local drought might drastically impact the local water cycle.

We expect that LMR can also be helpful in other ways. Specifically, we expect the concept of LMR can be used to study how changes in evaporation, due to for example afforestation, affect the local water cycle beyond merely a loss of moisture due to enhanced evaporation. However, besides evaporation, land-use changes also influence the energy balance, which may alter the atmospheric moisture connections and thus, LMR. Using future land-use scenarios as input for moisture-tracking models, it will be possible to study the impact of land-use changes on atmospheric moisture connections. However, future scenarios often include other changes besides land use, which makes it difficult to study the changes of land use specifically. However, LMR can help us to better predict the impact of land cover changes on the local water cycle. It might help us to identify regions where reforestation would not cause local drying due to enhanced evaporation (Hoek van Dijke et al. 2022; Tuinenburg et al. 2022). Overall, LMR gives us a better insight into the atmospheric part of the local water cycle and terrestrial evaporation as a source for local freshwater availability.

2.5 Conclusions

We calculated the local moisture recycling ratio (LMR) from atmospheric moisture connections at a spatial scale of 0.5° . LMR is the fraction of evaporated moisture that precipitates within a distance of 0.5° (typically 50km) from its source. On average, 1.7% (st.dev. = 1.1%) of global terrestrial evaporation returns as precipitation locally, with peaks of approximately 6%. LMR peaks in summer and in wet and elevated regions. LMR correlates with orography, precipitation, wetness, convective available potential energy, and wind suggesting these variables might affect LMR. In addition, latitude correlates with LMR, which likely indicates the importance of the ascending and descending air related to the Hadley cell circulation. Furthermore, by comparing LMR obtained from different models we found that the spatial pattern of LMR is not model-dependent, yet, the magnitude of LMR is strongly dependent on the model. LMR defines the local impacts of evaporation on precipitation, and thus, the role of enhanced evaporation as a source for local freshwater availability. Therefore, LMR can be used to evaluate which locations may be suitable for greening without largely disrupting the local water cycle.



3

Ecohydrological variables
underlie local moisture recycling
in Mediterranean-type climates

Chapter 3 | Ecohydrological variables underlie local moisture recycling in Mediterranean-type climates

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Abstract

Mediterranean areas are projected to face increased water scarcity due to global changes. Because a relatively large fraction of the precipitation in Mediterranean areas originates locally, changes at the land surface may further dampen local precipitation. Here, we study the contribution of evaporation to local precipitation for the first time on a scale of approximately 50km using local evaporation recycling (ELMR) and local precipitation recycling (PLMR), and make a comparison among five Mediterranean-type climate regions: south-west Australia, south-west US, central Chile, the Mediterranean Basin, and the Cape region of South Africa. Specifically, this study aims to understand the effects of ecohydrological (dependent on vegetation or the hydrological cycle) and non-ecohydrological variables on ELMR and PLMR. We find that (1) on average, ecohydrological variables correlate more frequently and more strongly to ELMR and PLMR than non-ecohydrological variables; (2) ELMR is large over wet areas and PLMR is large over dry areas; and (3) there are differences in underlying factors of ELMR and PLMR among the regions due to differences in wetness, topography, and land cover. The results suggest that in Mediterranean regions, changes in vegetation cover or the hydrological cycle may strengthen the local water cycle through enhancing ELMR. Finally, ELMR and PLMR help to identify where in Mediterranean regions we might enhance the local water cycle through land cover changes.

In this chapter, supplementary text, tables and figures are referenced using an 'S' (e.g., Table S1, Figure S2). These supplementary materials are not included in the thesis itself but can be accessed via the following link and QR-code: [Supplement to Chapter 3](#).



3.1 Introduction

Water scarcity is expected to increase across Mediterranean-type climate regions during the 21st century due to atmospheric warming (Lu et al. 2019). Globally, there are five major Mediterranean-type climate regions: south-west Australia (SWA), south-west US (SWUS), central Chile (CC), the Mediterranean Basin (MB), and the Cape region of South Africa (CSA). These regions are characterized by mild wet winters and warm dry summers (Lionello et al. 2006) and here, atmospheric warming exceeds global average rates, making them climate change hotspots (Ali et al. 2022). Previous studies on land-atmosphere feedbacks suggest that land cover changes, specifically greening, could be used to mitigate the intensification of extreme droughts and heatwaves and thus serve as a climate adaptation measure (e.g., Bonan, 2008; Miralles et al., 2019). For example, in the Mediterranean Basin, greening could compensate drying under future climate scenarios by increasing precipitation (Tuinenburg et al. 2022), but increased forest cover could also reduce streamflow due to increased evapotranspiration (Galleguillos et al. 2021), which we refer to as evaporation. Before we will be able to predict whether land cover changes could minimize drying locally, we first need to better understand the impacts of land cover on local precipitation.

Increased vegetation may contribute to precipitation (Spracklen et al. 2018; Baker 2021; Cui et al. 2022) and atmospheric moisture recycling (Ellison et al., 2019.; Layton & Ellison, 2016; Spracklen et al., 2012). Atmospheric moisture recycling is the return of evaporated water as precipitation over land (Van der Ent et al. 2010), and is considered an ecosystem service (Keys et al. 2016). Moisture recycling can be calculated using atmospheric moisture connections between evaporation sources and precipitation sinks. For moisture connections over land, a change in an evaporation source, due to climate change or land cover change, can affect precipitation over land (Wang-Erlandsson et al. 2018; Pranindita et al. 2022). Therefore, moisture recycling may inform governance of land use to prevent depletion of water resources (Keys et al. 2017). Furthermore, the variability of moisture sources for specific regions can illustrate the vulnerability of precipitation to certain land cover changes, which is relevant for, for example, rainfed agricultural areas (Keys et al. 2012).

Basin recycling and regional recycling have been used to study rainfall effects of land cover within specific regions at spatial scales of several hundred kilometres or more (e.g., Staal et al., 2018; Wang-Erlandsson et al., 2018; te Wierik et al., 2021). Previous studies on source-sink relations could not isolate the more local effects of land cover on precipitation. Furthermore, studies on moisture recycling rarely focus on Mediterranean-type climate regions (te Wierik et al. 2021), despite their

vulnerability to climate change. Therefore, in this study, we identify which landscape characteristics relate to local moisture recycling in Mediterranean regions. We separate landscape characteristics into ecohydrological and non-ecohydrological variables. Ecohydrological variables are directly related to vegetation or the hydrological cycle, and can therefore be altered through land cover changes; non-ecohydrological variables are not directly related to vegetation or the hydrological cycle. There are two indicators of recycling that allow us to study the local hydrological impacts of changes in evaporation. First, local evaporation recycling describes how much evaporated water returns as local precipitation; second, local precipitation recycling describes how much precipitation originated as local evaporation. By definition, local evaporation recycling does not directly depend on the influx of externally evaporated water whereas local precipitation recycling does.

To quantify local evaporation recycling, Theeuwes et al. (2023a) recently defined the local evaporation recycling ratio (ELMR) as the fraction of evaporation that returns within 0.5° as precipitation (Figure 3.1) using the output of an atmospheric moisture-tracking model. Analogously, we here define the local precipitation recycling ratio (PLMR) as the precipitation equivalent of ELMR, i.e., the fraction of precipitation that originates within 0.5° from its sink location (Figure 3.1). Although ELMR and PLMR conceptually resemble the regional recycling ratios developed by Van der Ent et al. (2010b), regional recycling does not allow to study local processes, whereas local recycling does.

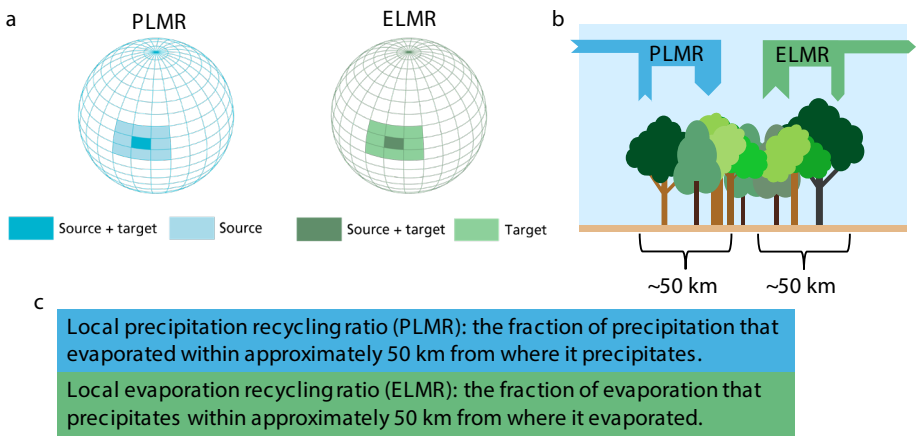


Figure 3.1. A schematic overview of (a) the calculation of local evaporation recycling (ELMR) and local precipitation recycling (PLMR), (b) a visual representation of these processes in which the arrows indicate the moisture fluxes, and (c) their definition. Each grid cell has an area of $0.5^\circ \times 0.5^\circ$, however, the grids shown in the schematic in (a) do not resemble this resolution.

We aim to identify the relations ELMR and PLMR have with ecohydrological and non-ecohydrological variables in the five Mediterranean-type climate regions globally. This provides insight into how susceptible the local water cycle is to land cover changes. Gaining insight into these relations is the first step in determining if and where land cover changes may enhance rainfall locally.

3.2 Methods

3.2.1 Atmospheric moisture recycling and moisture tracking

We study local moisture recycling using first, local evaporation recycling (ELMR), which is defined as the fraction of evaporated moisture that rains out within 0.5° from its source ($0.5 \times 0.5^\circ$) (Theeuwes et al. 2023a). On a grid, ELMR can be calculated as follows:

$$ELMR = \frac{\sum_{l=-1}^1 \sum_{k=-1}^1 P_{E,i+l,j+k}}{E_{i,j}} \quad (3.1)$$

Here, $E_{i,j}$ is the total evaporation from the source grid cell and $P_{E,i+l,j+k}$ is the fraction of $E_{i,j}$ that rains out in the source grid cell and its eight neighbouring grid cells. Second, we define and calculate the local precipitation recycling ratio (PLMR) as the fraction of precipitation that originates from within 0.5° from this sink location ($0.5 \times 0.5^\circ$). On a grid, PLMR can be calculated as follows:

$$PLMR = \frac{\sum_{l=-1}^1 \sum_{k=-1}^1 E_{P,i+l,j+k}}{P_{i,j}} \quad (3.2)$$

Here, $P_{i,j}$ is the total precipitation in the sink grid and $E_{P,i+l,j+k}$ is the fraction of this total precipitation that evaporated from within this grid cell and its eight surrounding grid cells. Both ELMR and PLMR are determined for a single grid cell but dependent on moisture flows between that grid cell and its eight surrounding grid cells (Figure 3.1a). Regions with a similar latitude, such as the Mediterranean-type climate regions, have a similar grid cell size and thus, recycling is calculated over a constant surface area.

Both local recycling metrics are calculated with atmospheric moisture connections from evaporation source to precipitation sink from the dataset by Tuinenburg et al. (2020b). These moisture connections are multi-year (2008-2017) monthly averages and have a spatial resolution of 0.5° . These data were calculated using the UTrack-atmospheric-moisture model, which is a Lagrangian moisture-tracking model (Tuinenburg and Staal 2020). In this model, moisture parcels are released from each grid cell of 0.25° , which is currently the best available resolution for such a model. Within the grid cell, each mm of evaporation is represented by one hundred

moisture parcels. These parcels are transported through the atmosphere by the wind in three directions. At each time step (0.1 h), the moisture budget is made for each parcel. The evaporated moisture is randomly distributed over 25 vertical atmospheric levels according to the vertical moisture profile. Parcels are tracked for up to 30 days or up to the point at which only 1% of their original moisture is still present. Input data for evaporation, precipitation, precipitable water, and wind speed and direction were obtained from the ERA5 dataset (Hersbach et al. 2020). We refer to Tuinenburg and Staal (2020) for a full description of the model, and to Tuinenburg et al. (2020b) for additional settings used for the dataset.

We calculate multi-year (2008-2017) monthly averages of ELMR and PLMR at a spatial resolution of 0.5° , using the atmospheric moisture connections as input for Equations 3.1 and 3.2. To obtain multi-year seasonal averages and multi-year averages of ELMR and PLMR, we average ELMR weighted by the total evaporation of each month in the source grid cell i,j , and we average PLMR weighted by the total precipitation of each month in the sink grid cell i,j .

In addition to the local recycling ratios we also calculate the regional evaporation recycling ratio (ERMR) and regional precipitation recycling ratio (PRMR) for each of the five Mediterranean regions. We compare ERMR and PRMR with ELMR and PLMR to get insight into how local and regional patterns overlap or vary. ERMR is defined as the fraction of evaporated water from a specific study region that returns as rainfall within the same study region; PRMR is defined as the fraction of precipitation within a specific study region that originates as evaporation within that same study region. ERMR is calculated as follows:

$$ERMR = \frac{P_{E,region}}{E_{region}} \quad (3.3)$$

Here, E_{region} is the total amount of water that evaporated from the study region and $P_{E,region}$ is the fraction of E_{region} that returns as rainfall to this study region. PRMR is calculated as follows:

$$PRMR = \frac{E_{P,region}}{P_{region}} \quad (3.4)$$

In this equation, P_{region} is the total amount of rainfall that falls within the study region and $E_{P,region}$ is the fraction of P_{region} that evaporated from within this study region.

3.2.2 Study areas

Based on the Köppen-Geiger climate classification (Peel et al. 2007), there are five major Mediterranean-type climate regions globally. We include all these terrestrial regions and some additional small terrestrial areas with a semi-arid climate to obtain

five consecutive areas: south-west Australia (SWA), south-west US (SWUS), central Chile (CC), the Mediterranean Basin (MB) and the Cape region of South Africa (CSA) (Figure S1). These Mediterranean regions are found on both hemispheres between 30° and 40° latitude downwind from the ocean, which is typically on the western side of the continents (Lionello et al. 2006). The Mediterranean climate is characterized by dry and warm summers and wet and mild winters (Lionello et al. 2006). Annual precipitation varies between 250 and 1200 mm, which falls predominantly in winter. Furthermore, the most important drivers of Mediterranean ecosystem functioning are climate, topography, soils and wildfire (Esler et al. 2018).

The five Mediterranean regions show differences in aridity and topography. For example, south-west Australia and the Cape region of South Africa are relatively dry, with little rainfall and low aridity indices and south-west US and central Chile are relatively wet (Table 3.1). Furthermore, all regions except for south-west Australia include elevated terrain (Table 3.1). On average, for most regions, short vegetation cover is larger than tall vegetation cover except for the south-west US where the tall vegetation cover is larger (Table 3.1). Finally, for all five regions, transpiration is the largest and most variable evaporation flux throughout the year. More detailed information per region is presented in Table 3.1. These data were obtained from ERA5 and ERA5-Land data, and were temporally and spatially averaged to obtain a multi-year (2008-2017) average of each variable for each region separately. More information about the data obtained from ERA5 and ERA5-Land data can be found in Section 3.2.3.

Table 3.1. Characteristics of the five Mediterranean regions: south-west Australia (SWA), south-west US (SWUS), central Chile (CC), the Mediterranean Basin (MB) and the Cape region of South Africa (CSA). This table shows spatial multi-year (2008-2017) averages calculated with data obtained from ERA5 and ERA5-Land. One grid cell is 0.5° (around 50×50km). In-between brackets are the coefficients of variation over time which refer to annual variation and are defined as the ratio of the standard deviation over the annual average for the specific variable. Summer is defined as JJA for the Northern Hemisphere and DJF for the Southern Hemisphere. Winter is defined as DJF for the Northern Hemisphere and JJA for the Southern Hemisphere.

	SWA	SWUS	CC	MB	CSA
Land surface area (# grid cells)	241	168	116	675	40
Average annual precipitation (mm)	360 (0.14)	1060 (0.50)	800 (0.52)	650 (0.38)	390 (0.24)
Average annual evaporation:					
Total evaporation (mm)	551 (0.22)	470 (0.35)	552 (0.41)	535 (0.28)	381 (0.18)
Vegetation transpiration (mm)	174 (0.31)	256 (0.50)	249 (0.51)	302 (0.51)	228 (0.33)
Evaporation from tree canopy (mm)	59 (0.27)	88 (0.29)	52 (0.07)	75 (0.28)	62 (0.10)
Evaporation from bare soil (mm)	123 (0.11)	88 (0.33)	144 (0.40)	120 (0.33)	115 (0.16)
Evaporation from open water (mm)	20 (0.37)	17 (0.44)	5 (0.46)	16 (0.42)	20 (0.36)
Average vapor pressure deficit (hPa)	908 (0.44)	733 (0.51)	483 (0.45)	791 (0.58)	847 (0.30)
Average aridity index summer (-)	0.13	0.32	0.28	0.13	0.14
Average aridity index winter (-)	0.83	16	9.4	3.5	0.95
Average tall vegetation cover (-)	0.21	0.63	0.22	0.40	0.09
Average short vegetation cover (-)	0.75	0.31	0.65	0.49	0.86
Average elevation (m)	200	800	1290	665	530
Max mountain peak (m)	465	2657	3692	2417	1010
Average wind speed (ms ⁻¹)	1.5 (0.35)	0.96 (0.23)	1.4 (0.15)	0.95 (0.24)	1.2 (0.29)

3.2.3 Ecohydrological and non-ecohydrological variables

The main drivers of moisture recycling are in the interface between the land surface and atmosphere (Van der Ent et al., 2010b; Tuinenburg and Staal, 2020): (1) horizontal wind speed, which transports the moisture away to remote locations; (2) precipitation, as it scales with the fraction of evaporated moisture that rains out locally; and (3) evaporation, as it affects the water available for precipitation. Local moisture recycling could be affected by orography, distance to nearest coast, aridity, and vegetation (Vautard et al. 2010; Shahidian et al. 2012; Tuinenburg et al. 2012; Zurbenko and Luo 2015; Theeuwens et al. 2023a).

We study the correlation between local recycling and 20 different variables. These variables are divided equally between ecohydrological and non-ecohydrological variables. Ecohydrological variables are directly related to vegetation or the hydrological cycle. Although we do not study the processes of land cover change specifically, these ecohydrological variables include some main processes that are affected by a change in vegetation. The ecohydrological variables (10) are: total precipitation (tP), total evaporation (tE), transpiration of vegetation (Evt), evaporation over bare soil (Ebs), evaporation over tree canopy (Etc), evaporation over open water (Eow), aridity index (AI), vapor pressure deficit (VPD), tall vegetation cover (≥ 3 m, vch), and short vegetation cover (vcl). The non-ecohydrological variables are (10): orography (z), zonal orography gradient (following latitude lines, dzdx), meridional orography gradient (following longitude lines, dzdy), zonal wind component at 10 and 100 m (u10 and u100), meridional wind component at 10 and 100 m (v10 and v100), total wind speed (V), wind direction ($\theta(V)$), and distance to the nearest coast (d).

All data, except for the distance to the nearest coast, were obtained from or calculated with data from ERA5 or ERA5-Land. We used monthly averages for the years 2008-2017 of the ERA5 data (Hersbach et al. 2020) 'on single levels' with a spatial resolution of 0.25° and ERA5-land data (Muñoz-Sabater et al. 2021) with a spatial resolution of 0.1° to calculate multi-year seasonal averages. As atmospheric moisture recycling has a temporal scale of up to several weeks, we study seasonal averages to understand which processes underlying LMR are important throughout the year. The gradient of orography in zonal and meridional directions, AI, VPD and wind direction and magnitude were calculated using ERA5 data. All data were centrally averaged to obtain a spatial resolution of 0.5° .

As ERA5 data do not include the different evaporation fluxes we used ERA5-Land to quantify these. This leads to some discrepancies in the evaporation balance. We find that total evaporation is not always equal to the sum of the separate evaporation fluxes. This could be due to different model settings. However, the two products are internally consistent.

Furthermore, we obtained the variable 'distance to nearest coast' from NASA (downloaded from: <https://oceancolor.gsfc.nasa.gov/docs/distfromcoast/>) (NASA 2009) with an original spatial resolution of 0.01° . We centrally averaged the data spatially to obtain a resolution of 0.5° .

3.2.4 Statistical methods

Spearman rank correlation is used to quantify the correlation between the local recycling metrics and each variable separately; principal component analysis (PCA) (Abdi and Williams 2010; Bro and Smilde 2014) is used to validate the results of the Spearman rank correlation and to study the clustering of ecohydrological and non-ecohydrological variables (i.e., covariance). For PCA, clustering is based on the angle between the loading of two variables. A more detailed description of PCA is presented in Supplementary Text S1. We calculated the correlation coefficients and conducted the PCA using data for each region on 0.5° resolution for ten-year averages (2008-2017) for every season and year. Combining these two statistical methods allows us to study one-on-one monotonic (both linear and non-linear) relations with the Spearman rank correlation method as well as multivariate linear correlations with the PCA. We hereby study the nonlinearities in the Earth system and how they can be affected by multiple processes. The Python packages *scipy-stats* and *scikit-learn* were used to conduct the analyses. Finally, we use the *numpy* package to calculate the maximum recycling ratios for each region.

3.3 Results

3.3.1 Spatiotemporal variation in moisture recycling

3.3.1.1 Local evaporation recycling and local precipitation recycling

For each Mediterranean area, ELMR, which is the evaporated moisture that returns as precipitation within 50km from its source location, is on average, 1%-2% (Figure 3.2). Furthermore, PLMR, which is the fraction of precipitation that originates locally (within 50km from this sink location), is also on average 1%-2% (Figure 3.3), across all Mediterranean areas. A large spatial variation in the annual ELMR and PLMR is found over elevated areas and maximum recycling ratios are obtained over mountain peaks (Figures 3.2 and 3.3). In south-west Australia, the driest region of all, the annual averaged ELMR is exceptionally small ($< 1\%$) compared to the other four regions (Figure S2). In the south-west US and central Chile, the regions with the highest annual precipitation, PLMR is, on average, small ($< 1\%$) compared to the other regions (Figure S2), indicating the large contribution of water that evaporated externally. The highest annually averaged ELMR and PLMR are found for the Mediterranean Basin ($> 4\%$).

Furthermore, for all regions, PLMR and ELMR are highest during summer (JJA on Northern Hemisphere and DJF on the Southern Hemisphere) and lowest during winter. For some regions, the difference between summer and winter is larger, which is the case for the Mediterranean Basin, than for other regions, such as south-west Australia. However, for all regions the seasonal pattern of PLMR is stronger than the pattern of ELMR (Figures 3.4a and 3.4b). Especially for the Mediterranean Basin, there is a strong variation in the spatial mean of PLMR throughout the year, with a peak ($>11\%$) in summer (Figure 3.4b). Peaks in the spatial mean of ELMR throughout the year are less distinct (Figure 3.4a). For the Mediterranean Basin the relatively high maxima in ELMR across the region (Figure 3.2) are cancelled out by large areas with a very low ELMR. Similarly, we find differences in the spatial variation among the Mediterranean-type climate regions (Figures 3.4c, 3.4d & S2). Throughout the year, the spatial variation in ELMR and PLMR is largest for the Mediterranean Basin and smallest for south-west Australia (Figure S2). Especially during summer, PLMR can become relatively large in some grid cells compared to the mean value, even exceeding 15% (Figure 3.4d). Such high values are not observed for ELMR.

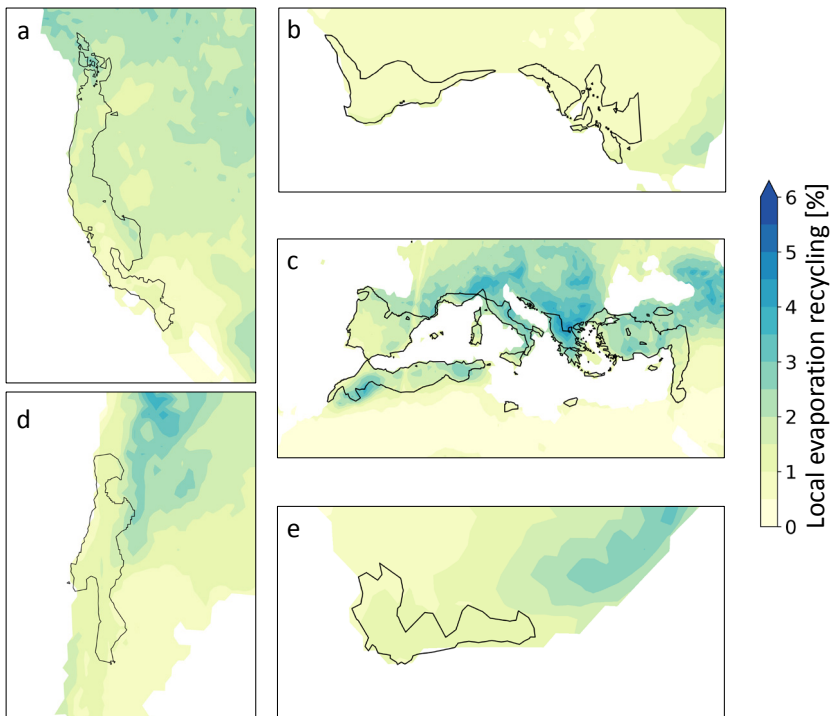


Figure 3.2. The multi-year (2008-2017) average of ELMR at a spatial resolution of 0.5° in all Mediterranean regions: (a) south-west US, (b) south-west Australia, (c) Mediterranean Basin, (d) central Chile, and (e) the Cape region of South Africa. The outlined areas indicate the study regions.

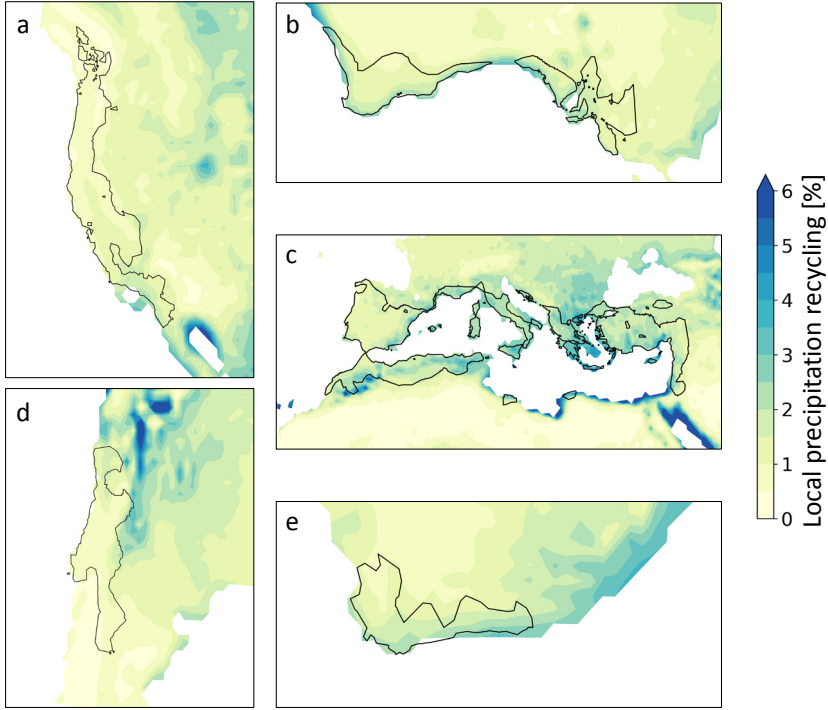


Figure 3.3. The multi-year (2008-2017) average of PLMR at a spatial resolution of 0.5° in all Mediterranean regions: (a) south-west US, (b) south-west Australia, (c) Mediterranean Basin, (d) central Chile, and (e) the Cape region of South Africa. The outlined areas indicate the study regions.

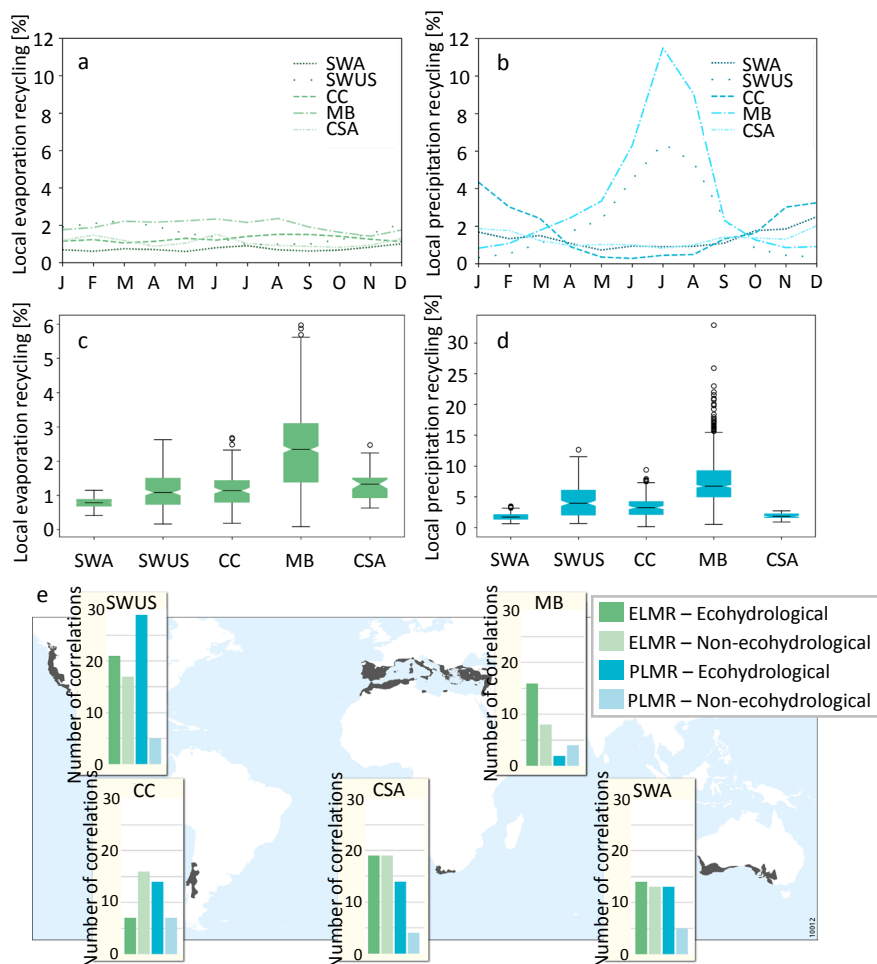


Figure 3.4. Differences in ELMR and PLMR among the five major Mediterranean-type climate regions for the period 2008-2017. SWUS: south-west US, MB: Mediterranean Basin, CC: central Chile, CSA: the Cape region of South Africa, SWA: south-west Australia. (a) Variation of ELMR throughout the year, where the values are averages over the 10-year period and all grid cells of that specific region. (b) Variation of PLMR throughout the year, similar to (a). (c) Boxplots indicating the distribution of ELMR for all grid cells in each region during summer (JJA on the Northern Hemisphere and DJF on the Southern Hemisphere). The values are 10-year seasonal averages. The green box indicates the interquartile range, and the black horizontal line in this box indicates the median value of ELMR. (d) Boxplots indicating the distribution of PLMR for all grid cells during summer, similar to (c). (e) The number of moderate to strong ($\rho \geq 0.4$) significant correlations between either PLMR/ELMR and ecohydrological/non-ecohydrological variables.

3.3.1.2 Regional evaporation recycling and regional precipitation recycling

Similar to ELMR and PLMR, regional evaporation recycling (ERMR) and regional precipitation recycling (PRMR) vary among the five Mediterranean regions and are highest in the Mediterranean Basin, the largest Mediterranean region. Here, on average, 18.9% of evaporation returns as precipitation within the region and 16.2% of precipitation originates from within the region (Table S1). Furthermore, for south-west US and central Chile, ERMR decreases and PRMR increases with increasing distance to the coast (Figures S3 and S4). For the Mediterranean Basin, PRMR increases towards the eastern side of the basin. Finally, contrasting with ELMR and PLMR, both ERMR and PRMR are smallest for the Cape region in South Africa (both are 2.9%), which is the smallest Mediterranean region (Figures S3 and S4 & Table S1).

3.3.2 Correlations between local moisture recycling and ecohydrological and non-ecohydrological variables

In this section we describe the results that are most relevant to determine how ELMR and PLMR relate to ecohydrological and non-ecohydrological variables. We refer to Supplementary Text S2-S3, Figures S5-S10, and Tables S2-S8 for a more detailed description of the results.

3.3.2.1 Monotonic, univariate correlations

The number of significant moderate to strong correlations between ELMR/PLMR and ecohydrological/non-ecohydrological variables obtained from the Spearman rank correlation is plotted per region (Figure 3.4e). For all regions, there are more significant correlations between ELMR and ecohydrological variables than between ELMR and non-ecohydrological variables, except for central Chile. We find a similar result for PLMR, which correlates most with ecohydrological variables in all regions, except for the Mediterranean Basin. A detailed description of the number of significant correlations per region and per season is presented in Tables 3.2 and 3.3 and described in Supplementary Text S2.

ELMR correlates most with variables related to wetness (i.e., total precipitation, aridity index and vapor pressure deficit), specifically total precipitation, and wind speed (Table 3.2). However, it does not solely depend on these variables, given that ELMR is highest in the Mediterranean Basin, which is not the wettest region. This high ELMR is instead likely caused by the complex topography of the Mediterranean Basin. PLMR correlates most (both positive correlations and negative correlations) with evaporation over tree canopy and vapor pressure deficit (Table 3.3), followed by total evaporation and distance to the coast. Different from the Spearman rank correlation, the PCA indicates that the evaporation fluxes related to vegetation also play an important role for ELMR, in two of the regions. Temporal patterns in the correlation coefficients vary among the regions, as well as between ELMR and PLMR.

For example, some variables correlate with ELMR throughout the year, such as the ecohydrological variables for south-west US and the Mediterranean Basin and the non-ecohydrological variables for central Chile. During summer specifically, ELMR correlates with a relatively large number of variables. For PLMR, this peak in number of correlations is not as clearly observed, despite its clear seasonality. Generally, correlations between ecohydrological variables and ELMR are consistent with correlations between ecohydrological variables and PLMR, i.e., moderate to strong positive correlations for ELMR do not co-occur with strong negative correlations with PLMR for the same variables, and vice versa. However, for south-west US, we do observe such inconsistencies for precipitation, aridity index and vapor pressure deficit.

Finally, both ELMR and PLMR also have insignificant correlation coefficients for all regions (Tables 3.2 and 3.3). Especially the Cape region of South Africa has a large number of insignificant correlations for both ELMR and PLMR, which may be explained by the small sample size of this region. Furthermore, for central Chile, ELMR has many insignificant correlations with ecohydrological variables compared to non-ecohydrological variables, suggesting the dependence of ELMR on the latter. Through similar reasoning we find that, for the south-west US, ELMR seems to depend more on ecohydrological variables and for both the south-west US and Mediterranean Basin, PLMR seems to depend more on the ecohydrological variables.

3.3.2.2 Linear, multivariate correlations: Clustering of variables

Complementary to the Spearman rank correlations, the PCA gives insight into the clustering of the ecohydrological and non-ecohydrological variables (Figures S5-S10 and Tables S3-S8). For the average of all regions, there are 11 sets of ecohydrological variables, and two sets of non-ecohydrological variables (Figure S10 and Table S8). A set is the combination of two variables from which the angle between their loadings $\leq 30^\circ$. None of the ecohydrological variables form a set with any of the non-ecohydrological variables (Figure S10 and Table S8). For all regions, except central Chile, there are more sets of ecohydrological variables than of non-ecohydrological variables (Supplementary Text S3 and Tables S3-S7). Furthermore, on average, there is a stronger clustering among the ecohydrological variables than the non-ecohydrological variables.

Finally, taking into account the results of the PCA and Spearman rank correlation analysis, we observe that variables related to vegetation correlate to ELMR and PLMR across regions. Furthermore, these vegetation-related variables appear to be linked to the hydrological cycle as they cluster with other ecohydrological variables. The dependence of ELMR and PLMR on vegetation related variables also appears to be visible from the relatively large amount of insignificant correlations that ELMR and PLMR have with non-ecohydrological variables for some of the regions, and from the lack of clustering between ecohydrological and non-ecohydrological variables.

Table 3.2. Significant ($p < 0.05$) correlation coefficients for Spearman rank correlation (ρ) between ELMR and ecohydrological and non-ecohydrological variables for five Mediterranean regions and all seasons. The colour indicates a positive (red) or negative (blue), and a strong (dark) or weak (light) correlation. Empty cells represent insignificant correlations. Coefficients larger than 0.4 are embolded. tP: total precipitation; tE: total evaporation; Evt: vegetation transpiration; Ebs: evaporation from bare soil; Etc: evaporation from tree canopy; Eow: evaporation from open water; AI: Aridity index; VPD: vapor pressure deficit; vch: vegetation cover tall vegetation; vcl: vegetation cover short vegetation; z: orography; dzdx: zonal orography gradient; dzdy: meridional orography gradient; u10: zonal wind at 10 m; u100: zonal wind at 100 m; v10: meridional wind at 10 m; v100: meridional wind at 100 m; V: total wind speed; $\theta(V)$: wind direction; and d: distance to nearest coast.

	South-west Australia				South-west US				Central Chile				Mediterranean Basin				Cape region of South Africa			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Ecohydrological variables																				
tP	0.41	0.26	0.64	0.61	0.81	0.79	0.60	0.61	0.60	0.31	0.27	0.40	0.58	0.55	0.68	0.43	0.87	0.42	0.74	0.59
tE	-0.15	0.25	0.52	0.52		0.28		0.20			0.23		-0.22	0.20	0.17	0.26		0.39	0.67	0.36
Evt			0.46	0.61	-0.16		0.25	0.29					-0.18	0.31	0.32	0.42	0.35	0.57	0.62	0.33
Ebs	0.27		-0.33	-0.19	-0.81	-0.64	0.67		0.55	0.30	-0.20	-0.34	-0.52	-0.26	0.53		0.69			
Etc	0.25	0.34	0.55	0.63		0.43	0.48	0.43	0.51				0.38	0.59	0.41		0.67	0.59	0.58	0.58
Eow			0.29	0.14	0.16								0.12		-0.20					
AI	0.29	0.38	0.59	0.65	0.82	0.78	0.58	0.60	0.56		0.20	0.40	0.65	0.56	0.61	0.42	0.76		0.74	0.48
VPD	-0.18	-0.40	-0.33	-0.68	-0.77	-0.71	-0.26	-0.64	-0.18			-0.41	-0.43	-0.46	-0.13	-0.51	-0.38	-0.68	-0.41	
vch	0.32		0.39	0.33	0.57	0.56	0.28	0.24	0.21				-0.08	0.08	0.23	0.13	0.49	0.60		0.48
vcl	-0.26		-0.46	-0.32	-0.64	-0.61	-0.30	-0.31	-0.23	-0.26					-0.12	-0.14				
Non-ecohydrological variables																				
z	0.40	-0.47		0.22			0.55	0.26	0.69	0.59		0.36	0.09	0.32	0.38	0.20	0.44		-0.40	
dzdx	-0.43		0.24		0.37	0.20	0.17	0.28	-0.26		0.30		0.13				-0.74	-0.58	0.66	
dzdy	0.28	0.22							0.39	0.21	-0.36	0.26	0.27	0.23	-0.10		0.52	0.61		
u10	-0.44	0.49		0.29	-0.54	-0.47	-0.53	-0.43	-0.46	-0.39	-0.52	-0.48	-0.73	-0.40	-0.45	-0.17	-0.70		-0.63	-0.69
u100	-0.42	0.50		0.35	-0.50	-0.43	-0.50	-0.35	-0.36	-0.32	-0.51	-0.42	-0.76	-0.39	-0.43	-0.15	-0.66		-0.64	-0.71
v10	-0.53		-0.26	-0.45	0.42	0.25		0.53	-0.55	-0.24	0.32			0.27	0.10	0.17			0.41	
v100	-0.59		-0.30	-0.42	0.57	0.35		0.64	-0.59	-0.24	0.24		0.18	0.32	0.12	0.23			0.39	
V	-0.02	-0.34	0.16	-0.23	0.41	-0.38	-0.65		-0.59	-0.47	-0.46	-0.47	-0.40	-0.49	-0.58	-0.26			-0.65	
$\theta(V)$	0.52		-0.27	-0.24	0.43	0.43	0.18	0.52	-0.59	-0.47	-0.21	-0.20	-0.40	0.23	-0.19		0.67	0.40	-0.36	0.62
d		0.51	0.13	0.19	0.16		-0.28		-0.56	-0.36	0.35	-0.20	0.14			0.23		0.38		0.50

Table 3.3. Significant ($p < 0.05$) correlation coefficients for Spearman rank correlation (ρ) between PLMR and ecohydrological and non-ecohydrological variables for five Mediterranean regions and all seasons. The colour indicates a positive (red) or negative (blue), and a strong (dark) or weak (light) correlation. Empty cells represent insignificant correlations. Coefficients larger than 0.4 are embolded. tP: total precipitation; tE: total evaporation; Evt: vegetation transpiration; Ebs: evaporation from bare soil; Etc: evaporation from tree canopy; Eow: evaporation from open water; AI: Aridity index; VPD: vapor pressure deficit; vch: vegetation cover tall vegetation; vcl: vegetation cover short vegetation; z: orography; dzdx: zonal orography gradient; dzdy: meridional orography gradient; u10: zonal wind at 10 m; u100: zonal wind at 100 m; v10: meridional wind at 10 m; v100: meridional wind at 100 m; V: total wind speed; $\theta(V)$: wind direction; and d: distance to nearest coast.

	South-west Australia				South-west US				Central Chile				Mediterranean Basin				Cape region of South Africa			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Ecohydrological variables																				
tP	-0.35	0.14	0.16	0.23	-0.62	-0.91	-0.75	-0.85	-0.33	-0.36	-0.62	-0.66	-0.20	-0.36	-0.27					0.46
tE	0.68	0.56	0.41	0.62	0.68	-0.23	-0.37	-0.53		-0.34	0.66	0.39	0.51	-0.15	0.24	0.32	0.54			0.67
Evt	0.40			0.53	0.42		-0.47	-0.66		-0.32	0.39	0.30		-0.11			0.40	0.40		0.63
Ebs	-0.55			-0.47	0.76	0.79	-0.41	0.62		0.40	0.66	0.28	0.37		-0.28		0.36			
Etc	0.26	0.23	0.19	0.47	0.45	-0.39	-0.64	-0.77	-0.22	-0.36	0.34		0.08	-0.35	-0.18	0.09		0.52	0.32	0.48
Eow	0.22		0.26							-0.26	-0.22		0.08		0.09	0.12	0.32			0.36
AI		0.23		0.40	-0.58	-0.86	-0.72	-0.83	-0.35	-0.40	-0.80	-0.77	-0.28	-0.21	-0.20					0.59
VPD	-0.45	-0.24	0.15	-0.53	0.69	0.87	0.58	0.74		0.38	0.74	0.75	0.63	0.26	-0.09	-0.15	-0.35	-0.37		-0.61
vch	0.29		0.21		-0.47	-0.63	-0.19	-0.66		-0.29	-0.59	-0.42	-0.21	-0.15	0.08	-0.09		0.54	0.53	
vcl	-0.40	-0.16	-0.34		0.35	0.67	0.31	0.68	0.14		0.76	0.66	-0.18		-0.30	-0.20		-0.68	-0.50	
Non-ecohydrological variables																				
z		-0.57	-0.32		-0.59			0.20		0.59	-0.48	-0.40	-0.45	-0.10	-0.28	-0.16	-0.58			-0.35
dzdx	0.17			0.35	-0.29	-0.39		-0.29	0.31		0.22		-0.13	-0.15	0.15	-0.13		-0.72	-0.34	
dzdy	0.18	0.34	0.38	0.15			0.16			0.36	-0.21		-0.23			-0.16		0.64	0.43	
u10	0.13	0.26	0.26	0.23	0.20	0.38		0.31	-0.25		-0.20		0.16				-0.32			
u100	0.13	0.25	0.23	0.23	0.15	0.33		0.25	-0.27		-0.32		0.15				-0.37			
v10	0.19	0.34			-0.30	-0.34		-0.30		-0.34	0.40	0.37					0.35			
v100	0.20	0.28		0.14	-0.40	-0.44		-0.40	-0.43	-0.33	0.45	0.40			-0.19		0.33			
V			0.25	0.16	-0.33	0.27		-0.31		-0.19	-0.29		0.38			0.21	0.33			
$\theta(V)$		0.16	0.14	-0.18	-0.24	-0.50		-0.31		-0.33	0.33	0.40	-0.10		-0.22	-0.10	0.35	0.50	0.39	
d	-0.47	-0.66	-0.55	-0.40	-0.39		0.25	0.32		0.31	-0.28	-0.25	-0.50		-0.43	-0.57	-0.37	-0.40	-0.57	-0.33

3.4 Discussion

Local moisture recycling has stronger correlations with ecohydrological variables than with non-ecohydrological variables, which indicates that the local water cycle corresponds more strongly to vegetation and the hydrological cycle than to other landscape characteristics. In this study we split up local moisture recycling in local evaporation recycling (ELMR) and local precipitation recycling (PLMR), which we obtained from the output of a dynamical model. The clear statistical relations of ecohydrological variables with ELMR and PLMR may have implications for our understanding of the effect of land cover changes on the local hydroclimate, as the proportion of locally recycled water does not seem to be fixed, but dependent on vegetation itself. This is further supported by our finding that variables that are associated with an increase in vegetation, such as transpiration and evaporation over tree canopy, tend to coincide with a larger fraction of locally recycled water. Furthermore, clustering among the ecohydrological variables suggests that changes in either the water cycle or vegetation could affect local recycling either directly or indirectly through interactions among ecohydrological variables, enhancing the importance of ecohydrological variables for local recycling.

3.4.1 *Patterns in local evaporation recycling and local precipitation recycling*

Although ELMR and PLMR are low on average (1%-2%), they vary strongly in space and time. Both ELMR and PLMR peak over elevated regions and during summer. Peaks over mountainous regions can be explained by the orographic lift that pushes air upward over mountains, which causes the air to cool down and the moisture in it to condensate, forming raindrops (Roe 2005). In the Mediterranean Basin, maximum ELMR exceeds 5% and maximum PLMR exceeds 30%. These high values are likely caused by the complex topography within the region. Furthermore, ELMR is larger on the Northern Hemisphere than on the Southern Hemisphere (Figure S2a). This may result from the geographical location of the two driest regions, south-west Australia and the Cape region of South Africa, on the Southern Hemisphere. There was no clear difference in PLMR between the Northern and Southern Hemisphere, which could be due to differences in the contribution of oceanic moisture sources to total precipitation (Jana et al. 2018) among the Mediterranean regions. Differences between ELMR and PLMR, and how strongly they vary throughout the year, are the result of a mismatch between evaporation and precipitation. This mismatch results from the strong seasonality of precipitation as Mediterranean regions are characterized by wet winters and dry summers. During winter, there is a larger moisture transport from the ocean and sea towards land compared to summer (Batibeniz et al. 2020; Holgate et al. 2020) and during summer, there is a larger contribution of terrestrial moisture sources to precipitation (Gómez-Hernández

et al. 2013; Holgate et al. 2020), resulting in smaller PLMR in winter and larger PLMR in summer.

Peaks in evaporation and precipitation recycling over elevated regions and during summer were also found in previous studies at a larger regional scale, for example for recycling within 150km (Van der Ent et al. 2010). In addition, continental moisture recycling also peaks during summer (Van der Ent et al. 2010; Rios-Entenza et al. 2014; Tuinenburg et al. 2020b). Earlier findings have shown that the spatial and temporal patterns of ELMR are robust between two models (Theeuwes et al. 2023a). However, the models yielded a different range of values (Theeuwes et al. 2023a), indicating that exact values of ELMR and PLMR should be interpreted and treated more carefully than their patterns. Isotopic ratios have been suggested as proxies for recycling observations, however, their relationship with atmospheric moisture recycling is complex and needs further investigation (Cropper et al. 2021). Therefore, aside from comparing output from different models, it is currently not possible to validate the outcome of the different moisture-tracking models.

3.4.2 Underlying variables of local evaporation recycling and local precipitation recycling

The ecohydrological variables are more important for ELMR and PLMR than the non-ecohydrological variables in all regions except for central Chile. This anomaly is possibly due to the region's high mountains. For the other four regions overall, we find that precipitation, vapor pressure deficit, and evaporation over tree canopy relate strongly to both ELMR and PLMR. The strong correlations between evaporation over tree canopy and ELMR may be a result of that intercepted water precipitates closer to its source than transpired water (Van der Ent et al. 2014). However, specifically for the Mediterranean Basin, which has the largest transpiration flux of all five regions, we also find a positive correlation between ELMR and transpiration during spring, summer, and autumn (Table 3.1). In addition, for the Mediterranean Basin, PLMR correlates little with either ecohydrological or non-ecohydrological variables, potentially due to a strong contribution of moisture from the Mediterranean Sea. Striking is that total precipitation correlates negatively with PLMR and positively with ELMR. The latter holds for all regions and suggests that for Mediterranean-type climate regions, an increase in precipitation may result in a stronger-than-linear increase in the absolute amount of recycled evaporation, as ELMR is a relative metric. This increase in ELMR, and thus precipitation, can feed back to an increase in vegetation, which could result in a positive feedback loop (Dekker et al. 2007; Spracklen et al. 2012; Chen et al. 2020) that strengthens the water cycle.

Even though the results show some clear patterns, they should be interpreted with care and a number of limitations should be considered. First, the Mediterranean

regions vary in size, resulting in a different sample size for each region, affecting the statistical outcomes. For instance, smaller sample sizes result in less statistical power, which may explain the large amount of insignificant correlation coefficients for the Cape region of South Africa. However, most important is that the variation in size does not have a direct influence on ELMR and PLMR, as these metrics are calculated over a constant area. To compare recycling of moisture within areas with varying sizes, which is the case for regional recycling, recycling ratios need to be scaled to assess the impact of the region's size. Normalizing ERM and PRM shows that both types of regional recycling do not scale linearly with the region's size, which is probably due to differences in the characteristics of each region specifically, such as shape and topography. Also climate affects regional recycling ratios, as ERM and PRM in Mediterranean regions are smaller than in the tropics (Tuinenburg et al. 2020b).

Naturally, correlation does not imply causality. To overcome this limitation, we suggest as a follow-up to study ELMR and PLMR using regional climate models (e.g., Jach et al. 2020), or simple column models (e.g., Konings et al. 2011), for a more careful assessment of the underlying processes of ELMR and PLMR. The results of our study could inform the design of such a follow-up study, e.g., it should explicitly consider the different evaporation fluxes. Our study also did not include all relevant parameters. For example, we did not include any soil characteristics, which affect infiltration (Lehmann et al., 2018; Mayor et al., 2009) and, therefore, affect to what extent an increase in ELMR may feed back to vegetation. Finally, our results show it is possible to identify local scale processes underlying ELMR and PLMR using data with a resolution of 50km. However, a similar study at an even higher resolution is likely to bring an even more detailed understanding of the underlying local processes.

3.4.3 Outlook: the potential and impact of land cover changes to enhance rainfall

The future drying that is projected across Mediterranean regions will probably affect ELMR and PLMR due to their apparent dependency on wetness. We expect ELMR to generally decrease in the future, because ELMR is smaller during dry periods (Theeuwens et al. 2023a). Conversely, we expect PLMR to generally increase due to its negative correlation with wetness. This projected drying could be reduced by greening as it is suggested that greening may enhance rainfall. (Griscom et al. 2017; Staal et al. 2024). However, tree restoration may also enhance local drying in regions with little moisture recycling (Hoek van Dijke et al. 2022). Our results suggest that, despite generally low ELMR and PLMR, vegetation increases may enhance both types of local recycling and may initiate a positive feedback. Therefore, greening could contribute to reducing future drying, under the condition that the evaporation increase is compensated for by the increase in precipitation.

ELMR could be used to find locations in each of the five Mediterranean-type climate regions where greening has a relatively large potential to minimize drying locally. Among locations with such a greening potential, PLMR could indicate where an increase in local rainfall has a significant impact; the impact increases with higher PLMR. In regions with a relatively high ELMR and PLMR, greening may strengthen the local water cycle significantly. However, most evaporation recycles non-locally (Theeuwens et al. 2023a) and, therefore, greening will likely be more effective on a larger scale.

Although ELMR shows consistent patterns globally with peaks over wet (e.g., tropics) and elevated (e.g., montane grassland) areas and during summer (Theeuwens et al. 2023a), it is unclear if greening could also strengthen the water cycle in other-climate-type regions, given that even among the Mediterranean regions, there seems to be variation in the underlying processes of ELMR and PLMR. This variation highlights the importance of region-specific characteristics underlying ELMR and PLMR and suggests that land cover changes have a different effect on the local water cycle for each Mediterranean-type climate region and likely also other-type-climate regions.

3.5 Conclusions

We studied moisture recycling on a scale of approximately 50km for five Mediterranean-type climate regions globally. We looked at local evaporation recycling (ELMR), i.e., the fraction of evaporated moisture that returns as precipitation within 50km from its source, and established its precipitation equivalent: local precipitation recycling (PLMR), i.e., the fraction of precipitation that evaporated from within 50km of where it precipitates. This spatial scale of 50km allowed us to find the relations of ELMR and PLMR with ecohydrological and non-ecohydrological variables.

Overall, ELMR and PLMR are small (1%-2%), but peak over mountainous regions and during summer. In addition, ELMR peaks over wet regions and PLMR peaks over dry regions. In general, ELMR and PLMR correlate the strongest and most frequently with ecohydrological variables, indicating that the local water cycle is susceptible to land cover changes. This suggests potential to enhance local water availability with climate adaptation measures.

The correlations between ELMR/PLMR and ecohydrological/non-ecohydrological variables vary among the Mediterranean regions. Differences in vegetation, topography and wetness among the regions contribute to these differences. The driest region, south-west Australia, has the lowest ELMR. ELMR and PLMR are largest in the Mediterranean Basin, possibly due to its complex topography. In

central Chile, our results imply that vegetation and the hydrological cycle have a relatively small impact on ELMR compared to other regions, suggesting that ELMR may be fixed by the high mountains. Finally, differences in vegetation cover and the partitioning of evaporation fluxes among the regions could cause differences in ELMR and PLMR.

As a first step in determining local hydrological impacts of land cover changes, we showed that both ELMR and PLMR are dependent on land cover type. As a next step, region-specific studies are needed to determine if and where land cover changes may enhance rainfall locally. Our results suggest that there mainly is potential for this in mountainous regions and in the Mediterranean-type climate regions on the Northern Hemisphere, specifically the Mediterranean Basin. Finally, our results suggest that an increase in evaporation due to land cover changes may enhance precipitation and consequently reduce local drying if evaporated losses are compensated for by an increase in precipitation.



4

Forestation tends to create favourable conditions for convective precipitation in the Mediterranean Basin

Chapter 4 | Forestation tends to create favourable conditions for convective precipitation in the Mediterranean Basin

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Abstract

The Mediterranean Basin is identified as a climate change hotspot and is prone to future drying. Previous studies indicate that the effect of forests on precipitation remains unclear for the Mediterranean Basin specifically. Here we use a simple model to simulate the development of the atmospheric boundary layer (ABL) to determine the impact of forest on convective rainfall potential. There is convective rainfall potential when (1) the ABL reaches the lifting condensation level, and (2) there is sufficient convective available potential energy. We model the ABL development over the Mediterranean Basin covered fully with bare soil and forest to determine its land cover sensitivity. In addition, we examine the sensitivity of the ABL to variations in soil moisture for the forest scenario specifically. We identify two distinct responses to forestation in the Mediterranean Basin dependent on soil moisture content. Forestation contributes to warming and drying in relatively dry regions (low soil moisture content) and to cooling and wetting in relatively wet regions (high soil moisture content), indicating that dry gets drier and wet gets wetter. We find that both forestation and an increase in soil moisture can contribute to convective rainfall potential. In regions with a relatively high soil moisture content, forestation could positively influence both the convective available potential energy, and the crossing of the ABL and lifting condensation level. The results show that forestation in the Mediterranean Basin may reduce future drying in relatively wet regions and enhance future drying in relatively dry regions.

In this chapter, supplementary tables and figures are referenced using an 'S' (e.g., Table S1, Figure S2). These supplementary materials are not included in the thesis itself but can be accessed via the following link and QR-code: [Supplement to Chapter 4](#).



4.1 Introduction

Unsustainable land use and global warming lead to water scarcity and desertification in different regions across the globe (Bestelmeyer et al. 2015; Intergovernmental Panel on Climate Change (IPCC) 2023a). Especially Mediterranean-type climate regions are identified as climate change hotspots (Differbaugh et al. 2008; Döll 2009; Fraser et al. 2013; Ali et al. 2022) and are prone to drying (Pokhrel et al. 2021). In those regions, forestation may increase freshwater availability when the increase in evapotranspiration promotes precipitation (Cui et al. 2022). It is expected that forestation may enhance rainfall in dry regions due to the buffering effect of Mediterranean forests on precipitation (O'Connor et al. 2021a) as deep roots make deep soil moisture available during dry periods (Brunner et al. 2015). However, increased evapotranspiration can also reduce streamflow (Galleguillos et al. 2021) and therefore, forestation should be done strategically, such that it contributes to rainfall enhancement (Staal et al. 2024), and not to local drying.

Rainfall enhancement through forestation has more potential in regions characterized by high atmospheric moisture recycling ratios (Hoek van Dijke et al. 2022; Tuinenburg et al. 2022). Atmospheric moisture recycling describes the return of evaporated water over land and can be studied at different spatial scales. Local evaporation recycling, which is the return of evaporated water as precipitation locally, reduces local drying as evaporative losses are partially compensated for by rainfall (Theeuwes et al. 2023a). The Mediterranean Basin shows most potential to enhance local rainfall with greening compared to all other Mediterranean-type climate regions, particularly during summer when the local recycling ratio is largest (Theeuwes et al. 2024b). As the amount of evaporated water that recycles is also influenced by greening, greening could potentially increase moisture recycling and rainfall in regions that currently have low local recycling ratios.

Atmospheric moisture recycling is often calculated using historical meteorological data (Van der Ent et al. 2014; Hoek van Dijke et al. 2022; Tuinenburg et al. 2022) even though a change in land cover is expected to affect the recycling ratio through changes in land-atmosphere interactions. A limited number of studies combines an Earth system model with a moisture-tracking model to calculate the moisture recycling ratio for different land cover scenarios (De Hertog et al. 2024; Staal et al. 2025). In such a set-up, remote impacts on local precipitation cannot be excluded (De Hertog et al. 2024). To isolate the local effects of changes in land cover on local precipitation a different modelling approach is necessary. In this research we explore if forestation creates favourable atmospheric conditions for local convective precipitation through changes in local land-atmosphere interactions for the Mediterranean Basin.

First, we focus on how changes in the energy balance and evaporation due to land-use changes affect the development of the atmospheric boundary layer (ABL) and the level at which water vapor starts to condense (i.e., lifting condensation level, LCL). The ABL is the lower part of the atmosphere that grows from ~100 m to several kilometres during the day due to the release of thermal heat at the Earth's surface. When the ABL crosses the LCL, water vapor in the ABL starts to condense and convective clouds can develop. Second, we focus on the Convective Available Potential Energy (CAPE). Sufficient CAPE ($\geq 400 \text{ Jkg}^{-1}$) needs to be available for the development of deep convective clouds that can produce precipitation (Yin et al. 2015). When both the ABL and LCL cross and the CAPE is at least 400 Jkg^{-1} there is convective rainfall potential.

It is expected that forestation enhances convective rainfall potential due to an increase in ABL height, a decrease in LCL height and an increase of CAPE. Due to the lower albedo of forests compared to bare soil the net surface radiation increases (Figure 4.1), which enhances the latent and sensible heat fluxes (Bonan 2008). An increase in these surface fluxes is beneficial for the deepening of the ABL (Van Heerwaarden and Teuling 2014) as well as the development of CAPE (Yin et al. 2015). In addition, evapotranspiration is expected to increase due to forestation (Figure 4.1). The larger amount of moisture present in the atmosphere reduces the LCL height (Yin et al. 2015). These changes are beneficial to the crossing of the ABL and LCL as well as to reaching a sufficient amount of CAPE.

To simulate the development of the ABL throughout the day we use a model in which the ABL is represented as a homogenous “slab” with uniform properties. We determine the impact of forestation in the Mediterranean Basin on the development of the ABL, the LCL and CAPE to investigate under which conditions the ABL and LCL cross and sufficient CAPE is available to trigger rainfall. We simulate the ABL development in the entire Mediterranean Basin for the months May and June. To study the impact of forestation across the Mediterranean Basin, our study compares the occurrence of convective rainfall potential over bare soil and forest.

4.2 Methods

We use the Chemistry Land-surface Atmosphere Soil Slab (CLASS) model (van Heerwaarden et al. 2010; Vilà-Guerau de Arellano et al. 2015) to study the impact of land cover changes and soil moisture availability on the potential for convective rainfall in the Mediterranean Basin in May and June for the years 2013-2022. This simulation is done for early summer as this is the start of the dry season. Using this model we simulate the development of the atmospheric boundary layer (ABL) and lifting condensation level (LCL) throughout the day (between 6 AM and 3

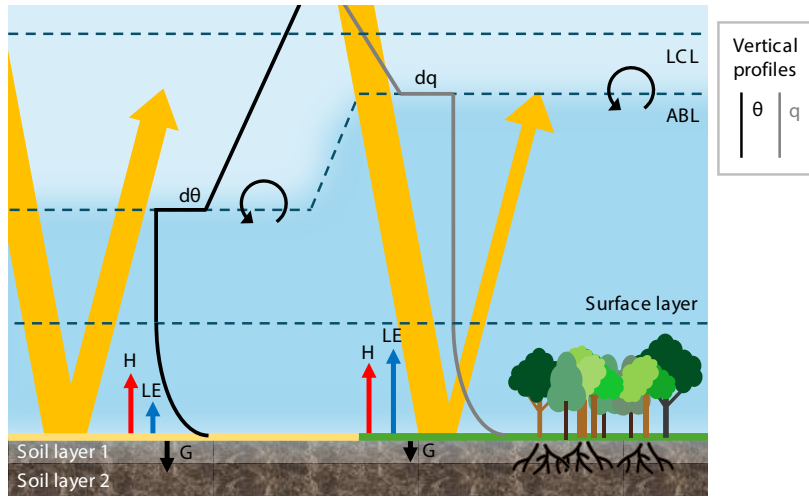


Figure 4.1. Conceptual model that describes the vertical potential temperature (black) and specific humidity (grey) profiles of the atmospheric boundary layer (ABL) and the ABL development over two different land cover types (left: bare soil, right: forest). For the ABL over bare soil only the vertical temperature profile is shown and for the ABL over forest only the vertical humidity profile is shown. θ : potential temperature, q : specific humidity, LCL: lifting condensation level, BLH: boundary layer height, $d\theta$: jump in θ at the top of the ABL, dq : jump in q at the top of the ABL, H : sensible heat flux, LE : latent heat flux, G : ground heat flux. The circular arrows at the top of the ABL indicate entrainment from dry and warm air into the ABL. The yellow arrows indicate the incoming solar radiation and the part that is reflected back towards the atmosphere, which varies due to the different albedo of the two land cover types. Throughout the day the ABL deepens. Clouds can develop when the ABL and LCL cross.

PM) for two land cover scenarios and five soil moisture scenarios. In this section, we describe the study region, CLASS model, input data, sampling of input data, experimental design, postprocessing, validation and analysis of the model output.

4.2.1 The Mediterranean Basin

The study region, the Mediterranean Basin, includes all regions located around the Mediterranean Sea that have a Mediterranean climate according to the Köppen-Geiger climate classification (Figure S1). Some additional small areas with a semi-arid climate were included to minimize fragmentation of the study region. The Mediterranean Basin is the largest of five major Mediterranean-type climate regions globally. A Mediterranean climate is characterized by wet winters with mild temperatures and dry and warm summers (Esler et al. 2018). Although precipitation falls predominantly in winter, during late spring and summer there is convective precipitation in the region (Wallace and Hobbs 2006; Treppiedi et al. 2023). The

region has multiple mountains with peaks up to 2400 m that promote local moisture recycling (Theeuwes et al. 2024b). Throughout the Mediterranean Basin the soil moisture content varies between $0 \text{ m}^3/\text{m}^3$ and $0.4 \text{ m}^3/\text{m}^3$ (Figure S1). The study region consists of 2868 grid cells of $0.25^\circ \times 0.25^\circ$, which means that it spans a distance of approximately 1500 km from north to south and approximately 4300 km from west to east. As the region is located in several time zones, we refer to the local solar time of each specific grid cell throughout this chapter.

4.2.2 The CLASS model

The CLASS (Chemistry Land-surface Atmosphere Soil Slab) model is based on multiple models that describe the land and atmosphere (van Heerwaarden et al. 2010; Vilà-Guerau de Arellano et al. 2015). The soil moisture and heat transport in and out of the soil are described with a two layer force-restore soil model. Force refers to the external inputs that affect soil moisture and temperature; restore refers to the intrinsic properties of the soil (Noilhan and Mahfouf 1996). A slab model is used to simulate the development of the convective ABL (Tennekes 1973; Tennekes and Driedonks 1981). During the day, the ABL is well mixed and potential temperature and specific humidity within this layer can be represented by a single value, i.e., slab (Vilà-Guerau de Arellano et al. 2015). The exchange of heat and moisture between the soil and the atmosphere is regulated by a surface energy balance where the Penman-Monteith equation is used for closure (Monteith 1965). The modelled atmospheric surface layer is based on the Monin–Obukhov similarity theory (Monin and Obukhov 1954). In our set up, we used the land surface, radiation, mixed layer, shear growth, and surface layer modules. In addition, we used the land surface parameterization Jarvis-Stewart (Jarvis 1976). Advection fluxes of heat and moisture were prescribed and large-scale subsidence was neglected. Finally, the integration timestep was 15 seconds and output was collected in 15 minute interval means. The code for CLASS is available through <http://classmodel.github.io/>. Previous studies with CLASS that used observations for validation showed that the model reproduces the ABL processes well (Van Heerwaarden and Teuling 2014; Wouters et al. 2019).

4.2.3 Model input

For our study, the input data for CLASS are divided into parameters and variables from which the latter group is split into variables that can directly be retrieved from data and variables that we needed to calculate (Table S1). The equations that we used to calculate these variables are presented in Supplementary Text S1. Variables were directly obtained from ERA5 data (Hersbach et al. 2020) or calculated from ERA5 data (Table S1). We use ERA5 data as it provides the best available spatial and temporal coverage of the study region. However, the accuracy of the spatial and temporal variations in ERA5 surpasses the accuracy of its absolute values (Hersbach et al. 2020).

Therefore, we need to carefully interpret our results and should mainly focus on spatial patterns as the absolute changes in the different variables are likely less meaningful. We used hourly ERA5 data, both “at pressure levels” and “at a single level” (Table S1). All parameter values were obtained from the ECMWF IFS documentation (ECMWF 2010).

A typical ABL height in the morning is in the order of tens of meters to several hundred meters (Stull 1988), so, first, we assumed that at 6 AM local time the boundary layer has a height of 100 m and is shear-mixed. Second, to calculate the soil moisture content for the soil sensitivity scenarios we used wilting point, field capacity and saturation for a medium textured soil as the most common soil types in the Mediterranean region are Cambisols (26%), Calcisols (22%), Leptosols (20%), and Luvisols (10%) (Allam et al. 2020), which vary from coarse to fine-textured. We assume that wilting point and field capacity are constant throughout the study region. Third, for the forest scenario we assumed a typical LAI for a mixed forest ($\text{LAI} = 5 \text{ m}^2/\text{m}^2$). Finally, for the albedo we assumed that the bare soil is light coloured, which maximizes the difference between the albedo of forest and albedo of bare soil.

To calculate the atmospheric conditions, we assumed a constant air density within the ABL and hydrostatic equilibrium. Furthermore, we assumed idealized linear profiles for the specific humidity and potential temperature.

4.2.4 Sampling

Due to the large number of days and grid cells in the study period and region we designed a specific sampling method for our input data that ensures a distribution that represents the entire Mediterranean Basin during this period. For each grid cell we ran the model 20 times. Each year was sampled twice, where the exact days were obtained randomly. This resulted in a total amount of 57,360 samples. For each of these samples we ran the model using the specific input data for that location and day.

4.2.5 Experimental design

To study the influence of land cover and soil moisture on the LCL and the development of the ABL we designed two land cover scenarios and five soil moisture scenarios (Table 4.1). The impact of forestation is studied within grid cells specifically and does not affect the interactions between grid cells. For the land cover scenarios we vary the vegetation fraction, LAI, albedo, aerodynamic resistance, and roughness length for heat and momentum (Table S1). For the land cover scenarios, soil moisture varies among the grid cells and is obtained from ERA5. For the soil moisture scenarios the land is covered in forest. In these scenarios soil moisture is constant throughout the Mediterranean Basin for each simulation, however, soil moisture varies among different simulations, ranging from wilting point (WP) to field capacity (FC) (Table 4.1).

Table 4.1. Experimental set-up describing the land cover and soil moisture scenarios. WP: wilting point and FC: field capacity. A more detailed description of the differences in input data for the bare soil runs and forest runs can be found in Table S1.

	Soil moisture	Land cover
Land cover sensitivity scenarios		
Bare soil	ERA5 data	Bare soil
Forest	ERA5 data	Forest
Soil moisture sensitivity scenarios		
Low	WP	Forest
Medium-low	WP+1/4(FC-WP)	Forest
Medium	WP+1/2(FC-WP)	Forest
Medium-high	WP+3/4(FC-WP)	Forest
High	FC	Forest

4.2.6 Postprocessing

To account for extreme values in our output data due to inconsistencies that are part of the input data, we filter out unrealistic output of CLASS by filtering the values of soil moisture of the top layer, relative humidity of the ABL, ABL height, potential temperature, and the jumps of potential temperature and specific humidity at the top of the ABL. The filters truncate the distribution for each of the variables and remove samples with values from below the 5th percentile and above the 95th percentile for all variables except the ABL height. As the ABL height was not normally distributed we removed the simulations in which the ABL did not grow (≤ 100 m) and the variables above the 85th percentile. The exact filters can be found in Table S2. 29,957 Samples (52%) pass the filter for both land cover type scenarios and these samples are used to study the land cover sensitivity. Due to the poor quality of the ERA5 data, specifically over dry regions, it was expected that there would be an error in the model output. The larger uncertainty in the ERA5 data for drier regions (<https://confluence.ecmwf.int/display/CKB/ERA5>, accessed 16-12-2024) explains why, after sampling, there are fewer samples available in relatively dry regions, i.e., low soil moisture, than in wet regions (Figures S2 and S3). After this postprocessing step, each grid cell had on average 10 ± 5 samples and there are 69 grid cells (2%) without any samples. The model output might be biased as 48% of the samples is discarded, mostly samples from dry regions. Therefore, the results from the dry regions need to be interpreted with care.

The samples that pass the forest filter (31902 samples) were used to run CLASS for the soil moisture sensitivity scenarios as these scenarios are based on the forest

scenario. However, due to different model input, CLASS produced some unrealistic output. We filtered this output using the same postprocessing filters as for the land cover scenarios (Table S2).

4.2.7 Validation

To validate the output of the CLASS model we compare different variables with the ERA5 data. We validate the output for the bare soil scenario using all grid cells that in reality have a short and tall vegetation cover that is equal to or smaller than 0.1. We validate the output for the forest scenario using all grid cells that in reality have a tall vegetation cover that is equal to or larger than 0.8. As a result, 268 grid cells (9%) are used to validate the bare soil scenario output, and 279 grid cells (10%) are used to validate the forest scenario output. We validate the model output of the last time step (3 pm).

To validate the model output we studied the distribution of values for different output variables of CLASS and compared this to the distribution within the ERA5 data (at 3 pm). We study the distribution by calculating the mean, median and standard deviation of all samples for the relative humidity, potential temperature, boundary layer height and CAPE. These distributions show some discrepancies between the ERA5 data and the CLASS output (Table S3). The ERA5 data has some uncertainty due to biases in its underlying observations and models, making it challenging to interpret differences between ERA5 and CLASS. These biases are larger in dry areas compared to wet areas, though spatial and temporal patterns are less uncertain than absolute values. Therefore, we focus on the spatial patterns while interpreting our results.

4.2.8 Model output interpretation

To determine the convective rainfall potential from the model output we calculated CAPE and determined whether the ABL and LCL cross. We calculated CAPE using the `cape_sin` function of the MetPy python package (https://unidata.github.io/MetPy/latest/api/generated/metpy.calc.cape_cin.html). For the input of this function, surface pressure, and the profiles of potential temperature and specific humidity of the free atmosphere were assumed constant throughout the day and were obtained from the ERA5 input data. The potential temperature and specific humidity of the ABL and the jumps of potential temperature and specific humidity at the top of the ABL were obtained from the CLASS model output.

To analyse the sensitivity of different output variables and convective rainfall potential to land cover type we calculated the difference between both land cover scenarios for each sample specifically and the average of these differences for each grid cell. In addition, we determined the amount of samples that have sufficient

CAPE as well as a crossing of the ABL and LCL. This is also done for the different soil moisture scenarios. To analyse the uncertainty of the convective rainfall potential we study the convective rainfall potential for a change in BLH, LCL and CAPE of $\pm 10\%$.

4.3 Results

4.3.1 Land cover sensitivity

The differences in boundary layer characteristics between the forest and bare soil scenarios show significant spatial variation (Figures 4.2 and S4-S7). For ten different output variables, the anomalies between the forest scenario and bare soil scenario show the same spatial pattern (Figure 4.2) that overlaps with the spatial variability of soil moisture content (Figure S1). Hence, the impact of forestation on several variables seems to be closely related to soil moisture content across the Mediterranean Basin. We find two different effects of forestation, depending on soil moisture.

For wet regions where soil moisture content is relatively high (Figure S1), the additional energy that becomes available due to the reduced albedo for the forest scenario, is used for evapotranspiration (latent heat flux) whereas the sensible heat flux remains relatively consistent or decreases when forest cover increases (Figure 4.2). The increase in evapotranspiration enhances the moisture content of the ABL, enhancing the specific humidity (up to 0.002 kg/kg), relative humidity (up to 20%) and the jump in specific humidity at the top of the boundary layer (up to 0.002 kg/kg, Figure 4.2). As the sensible heat flux decreases in the relatively wet regions, the potential temperature within the ABL is reduced as well (Figure 4.2). The jump in potential temperature at the top of the ABL shows a small increase due to the enhanced forest cover.

In these wet regions, both increases and decreases in CAPE occur as a result of forestation (up to 800 J/kg, Figure 4.2). CAPE strongly increases over mountainous regions (e.g., south Turkey, west of Greece and Adriatic coastline). For the relatively wet regions, the height of the ABL is little affected by an increase in forest cover (Figure 4.2) due to the relatively small change in the sensible heat flux. The LCL is also little affected by an increase in forest cover for most grid cells in the relatively wet regions (Figure 4.2). However, for a few grid cells the LCL decreases due to an increase in humidity.

For the relatively dry regions where the soil moisture content is relatively low (Figure S1), the additional energy that becomes available due to a decrease in albedo results in an increase in the sensible heat flux (up to 250 W/m², Figure 4.2). Compared to the relatively wet regions, less soil moisture is available for

evapotranspiration in these relatively dry regions. The higher sensible heat flux contributes to the warming (up to 5 K) and drying (over -0.002 kg/kg) of the ABL (Figure 4.2), as well as the deepening of the ABL (up to 1km). The deepening of the ABL resulting from an increase in forest cover enhances the entrainment of warm air from the free atmosphere into the ABL (Miralles et al. 2014). This entrainment contributes to the high potential temperatures over forest compared to bare soil for dry regions and brings dry air from the free atmosphere into the ABL. As the latent heat flux is not affected by forestation in these relatively dry regions, the ABL becomes less humid. The warming and drying of the ABL contribute to the rising of the LCL (more than 5km). Furthermore, over these relatively dry regions, the land cover change does not affect CAPE much, which shows that for the Mediterranean Basin, first, the presence of sufficient soil moisture seems to be necessary for CAPE to develop and, second, that an increase in temperature alone does not necessarily enhance CAPE.

There is a spatial variation in the impact of land cover change on convective rainfall potential across the Mediterranean Basin (Figure 4.3). Despite that the ABL height and LCL vary little over the relatively wet regions there is an increase in the number of crossings when the forest cover increases (Figure 4.3). Hence, only a small change in the ABL height and/or LCL seems to have a significant impact on the convective rainfall potential. We find that 8.2% of the samples have convective rainfall potential when the grid cells are covered in forest and 4.9% of the samples have a rainfall potential when the grid cells are covered in bare soil (Figure 4.3). Focusing on the two conditions for convective rainfall potential, for the bare soil scenario, 10% of the samples have a crossing and 16% of the samples have sufficient CAPE (≥ 400 J/kg) and for the forest scenario, 26% of the samples have a crossing and 32% of the samples have sufficient CAPE (Figure 4.3).

For the western Iberian Peninsula, Italy, the Adriatic coastline and western Turkey, most of the grid cells show an increase in convective rainfall potential when the forest cover is enhanced (Figure 4.3). However, approximately thirty of the grid cells (1%) show a decrease in convective rainfall potential when going from bare soil to forest (Figure 4.3). For the relatively dry regions the increase in forest cover enhances the LCL, which explains why there is no convective rainfall potential here (Figure 4.2). To test the robustness of the results we varied the ABL height, LCL, and CAPE with 10%. Both for a 10% increase as well as a 10% decrease of these variables, the spatial variability of the sensitivity of the convective rainfall potential to land cover type is little affected. However, the total amount of samples with convective rainfall potential is affected (Figures S8-S10).

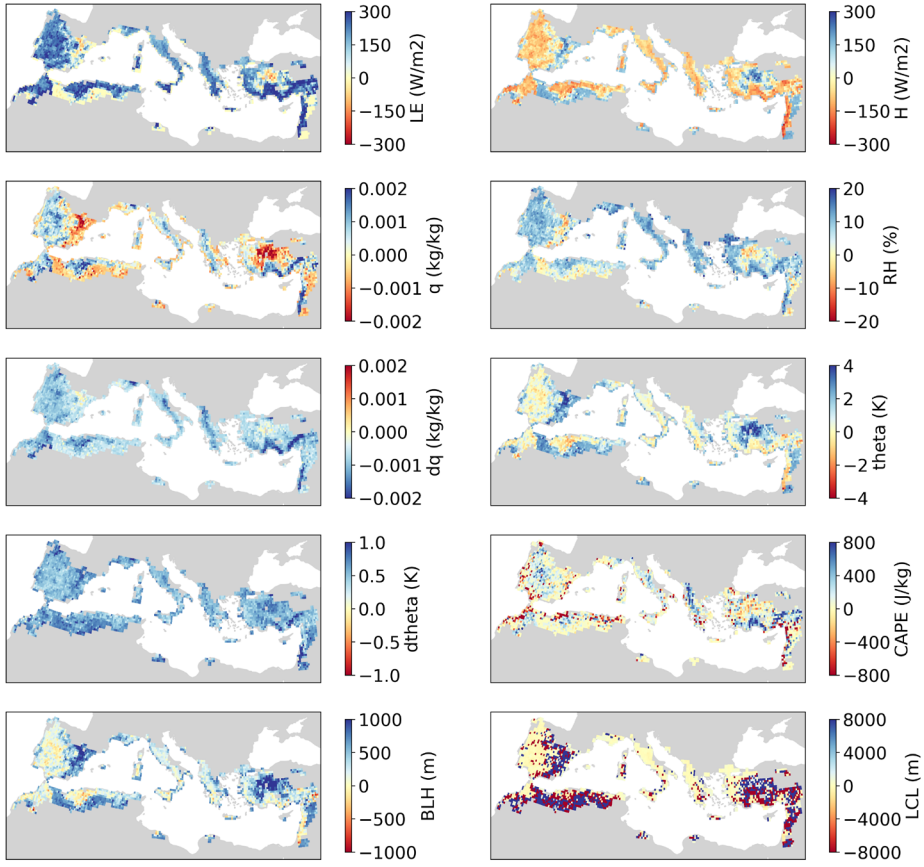
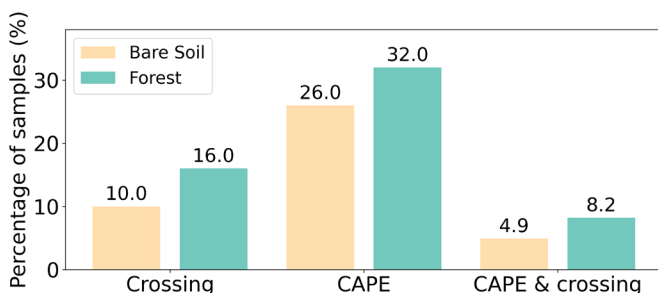


Figure 4.2. The difference between forest scenario and bare soil scenario for different output variables of CLASS. Each grid cell shows the mean value of all samples for that specific grid cell. The total amount of samples per grid varies between 0 and 20 due to the postprocessing step. The output variables that are shown are the latent heat flux (LE), sensible heat flux (H), specific humidity (q), relative humidity (RH), jump in specific humidity at the top of the boundary layer (dq), potential temperature (theta), jump in potential temperature at the top of the boundary layer (dtheta), convective available potential energy (CAPE), boundary layer height (BLH), and lifting condensation level (LCL).



Spatial variation in land cover sensitivity of the rainfall potential

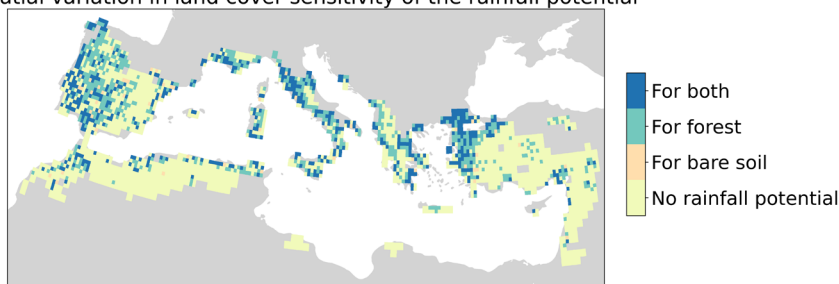


Figure 4.3. Top: The percentage of samples with a crossing, sufficient CAPE (≥ 400 J/kg), or both sufficient CAPE and a crossing for the Mediterranean Basin when covered in either forest or bare soil. Bottom: The spatial variability of the land cover sensitivity of the convective rainfall potential, i.e., there is both a crossing and sufficient CAPE. This plot indicates for each grid cell if most samples have a convective rainfall potential over bare soil, forest or both land cover types or if they have no convective rainfall potential in any of the samples.

4.3.2 Soil moisture sensitivity

The model output for the different soil moisture scenarios shows that the fraction of samples with a crossing of the ABL and LCL at 3 pm increases linearly with the soil moisture content (Figure 4.4). This relationship is determined for soil moisture content ranging between the wilting point and field capacity. In addition, the fraction of samples for which CAPE exceeds 400 J/kg increases linearly with the soil moisture content (Figure 4.4), supporting our previous finding that CAPE increases over relatively wet regions when forest cover increases. With a change in soil moisture, the rate of change in the number of simulations with sufficient CAPE is larger (i.e., steeper slope) compared to the rate of change in the number of crossings. Finally, the fraction of samples with convective rainfall potential also increases linearly with soil moisture content. With a change in soil moisture the convective rainfall potential has a similar rate of change as the fraction of samples with a crossing (Figure 4.4).

The convective rainfall potential does not increase everywhere in the Mediterranean Basin when soil moisture increases (Figure 4.4). In some grid cells in the central parts of the Iberian peninsula, Italy, Turkey, the Balkans, and northern Africa convective rainfall potential is more pronounced when soil moisture equals wilting point compared to when soil moisture equals field capacity (Figure 4.4). This could be explained by a decrease in the sensible heat flux when soil moisture increases, minimizing the ABL development and crossing. However, a larger amount of grid cells shows that the convective rainfall potential increases with an increase in soil moisture content.

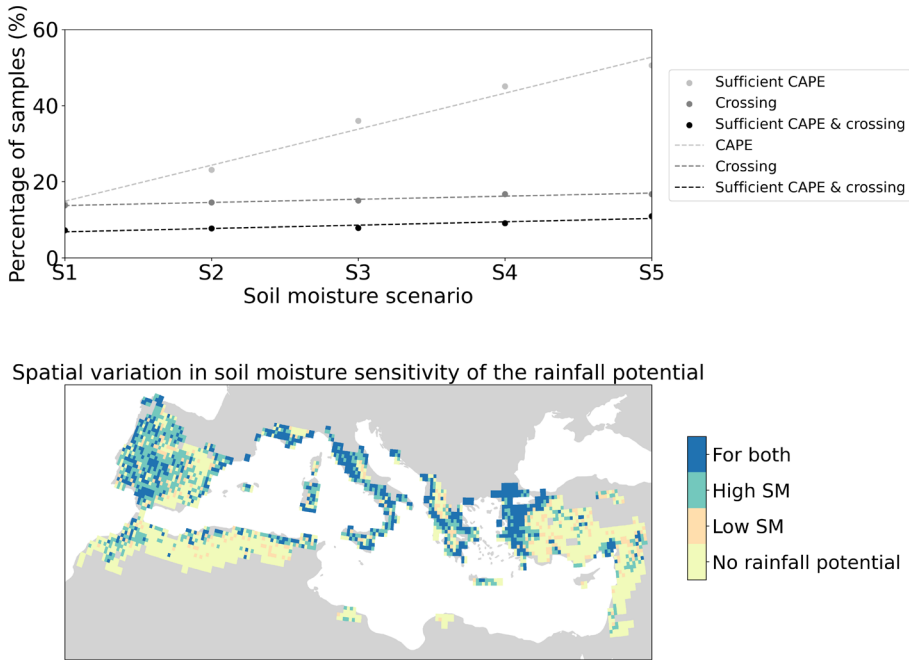


Figure 4.4. Top: The percentage of samples with a crossing, sufficient CAPE (≥ 400 J/kg), or both sufficient CAPE and a crossing for varying soil moisture content. The different soil moisture scenarios increase linearly from wilting point (S1, $0.15 \text{ m}^3\text{m}^{-3}$) to field capacity (S5, $0.35 \text{ m}^3\text{m}^{-3}$). The dotted lines are the regression lines (CAPE: $R^2 = 0.98$, crossing: $R^2 = 0.93$, CAPE & crossing: $R^2 = 0.87$). Bottom: The spatial variability of the soil moisture sensitivity of the convective rainfall potential, i.e., a crossing of the ABL and LCL and sufficient CAPE. This plot indicates for each grid cell if most samples have a convective rainfall potential for soil moisture scenario 1, soil moisture scenario 5, or both soil moisture scenarios, or no convective rainfall potential in any of the samples.

4.4 Discussion

4.4.1 Boundary layer development under change

Changing the land cover in the Mediterranean Basin from bare soil to forest affects the atmospheric boundary layer (ABL) characteristics and the convective rainfall potential locally. There is a rainfall potential when the ABL reaches the lifting condensation level (LCL) and when there is sufficient convective available potential energy ($\geq 400 \text{ J/kg}$, CAPE). Under these conditions parcels can likely rise enough to trigger precipitation. There is correlation between LCL and CAPE, as both are computed following a rising parcel. Therefore, changes that lead to an earlier LCL crossing may also result in an increase in CAPE (Yin et al. 2015). We find that the impact of forestation on convective rainfall potential varies with soil moisture and that it does not increase the convective rainfall potential everywhere in the Mediterranean Basin. A change in land cover from bare soil to forest enhances convective rainfall potential mainly in relatively wet regions. However, not all grid cells in the relatively wet regions show an increase in convective rainfall potential due to forestation and some grid cells, specifically in the centre of the Iberian Peninsula, show a decrease in convective rainfall potential. In dry regions there is no convective rainfall potential for either the bare soil scenario or the forest scenario.

The soil moisture content also has an impact on whether an increase in forest cover has a cooling or warming effect. For relatively dry regions, the increased net radiation is mainly transferred into sensible heat, contributing to the warming of the ABL. For relatively wet regions, the increase in net radiation enhances evapotranspiration, preventing the potential temperature within the ABL to rise and even contributing to cooling in some locations. This cooling effect can explain why some locations have a convective rainfall potential in the bare soil scenario and not in the forest scenario as it minimizes the deepening of the ABL.

When soil moisture is varied across the Mediterranean Basin we find that, overall, the convective rainfall potential increases linearly with soil moisture content. However, for some grid cells across the basin, the convective rainfall potential decreases with increasing soil moisture content. These grid cells have a convective rainfall potential when soil moisture equals wilting point, yet these cells do not have a convective rainfall potential when the soil moisture equals field capacity. This negative relation between soil moisture and convective rainfall potential could be explained by a stronger cooling effect over wetter soils. Additionally, it shows that the relationship between soil moisture and convective rainfall potential is more complex than the overall linear relationship that we found.

An increase in soil moisture does not necessarily relate linearly to evapotranspiration but their coupling is dependent on the aridity of the region and is stronger in relatively dry regions (Seneviratne et al. 2010). However, this stronger coupling in dry regions does not necessarily reflect in an increase in rainfall as only a limited range of free atmospheric conditions allows for convective rainfall potential (Findell and Eltahir 2003c; Juang et al. 2007; Konings et al. 2011). This may explain why the effect of an increase in soil moisture on convective rainfall potential seems to be most pronounced close to regions that already have a convective rainfall potential for lower soil moisture. Here the atmospheric conditions may already be near the threshold for convective rainfall potential.

In the eastern and southern Mediterranean Basin, atmospheric conditions appear to limit convective rainfall potential, as increasing soil moisture, even up to field capacity, does not effectively trigger precipitation (Findell and Eltahir 2003a). This regional difference may be attributed to the large-scale atmospheric circulation patterns characteristic of the Mediterranean Basin, which create contrasting weather conditions between its eastern and western regions (Roberts et al. 2012). This climatic 'see-saw' likely explains why enhanced soil moisture supports convective rainfall potential in the western Mediterranean but fails to do so in the eastern part. In the eastern Mediterranean, unfavourable free atmospheric conditions may inhibit the development of convective rainfall potential despite increased soil moisture.

4.4.2 Discussion on the simulation

The results presented here need to be interpreted carefully for several reasons. First, the CLASS model provides a simple description of the processes within the ABL and therefore, this study is limited to studying convective triggering, as it is assumed that forestation is applied locally and that the upper atmosphere remains unchanged because of it. Consequently, we approximated the potential for convective precipitation using CAPE and the crossing of the ABL and LCL. Furthermore, as clouds are not explicitly modelled, there is some uncertainty in the energy balance. Clouds increase the albedo as they partially reflect incoming radiation, which is not included in the model. This feedback would likely have a cooling effect (Fraedrich and Kleidon 1999; Cerasoli et al. 2021), specifically over wet regions, which has a negative impact on the development of the ABL and CAPE (Seeley and Roms 2015; Vilà-Guerau de Arellano et al. 2015).

Second, as the model describes the ABL as a 1-dimensional column, the horizontal spatial component is not taken into account. This horizontal spatial component is essential to simulate the impact of surface roughness on convection (Pielke 2001) or to simulate the development of a sea breeze during the day. Hence, moisture convergence, which contributes to the development of convective precipitation,

may be underestimated in the CLASS model. The spatial component can be included in more complex models such as a large eddy simulation model. Although CLASS does not simulate all processes it allows us to improve our understanding of the main interactions between the land surface and the ABL that are responsible for convective precipitation.

Finally, ERA5 has some uncertainty, specifically over dry regions (<https://confluence.ecmwf.int/display/CKB/ERA5>, accessed 16-12-2024). However, by using ERA5 as input data we can represent the present-day climate realistically for a large region. To the best of our knowledge, this is the first study to use ERA5 as input data for CLASS. Previous studies mainly use in-situ observations as input for and validation of an ABL model (Vilà-Guerau de Arellano et al. 2004; Van Heerwaarden and Teuling 2014; Wouters et al. 2019), due to the size of our study region this was not possible. Compared to the uncertainty of exact values over dry regions, the spatial and temporal variation of the ERA5 data have a higher accuracy. Therefore, we mainly focus on the spatial patterns. Our results showed that a change in BLH, LCL or CAPE of 10% does not affect the spatial pattern of the land cover sensitivity of the convective rainfall potential (Figures S8-S10), so the inaccuracy of the exact values may be of less importance.

4.4.3 *The uncertainty of rainfall potential under change*

In line with previous literature, our results indicate that forestation can have both cooling and warming effects in the Mediterranean Basin. Ruijsch et al. (2024) found that land restoration has a net cooling effect in parts of northern Africa due to increased evaporation, whereas Portmann et al. (2022) observed a net warming effect throughout the entire Mediterranean Basin due to global forestation. King et al. (2024) did not find a significant temperature effect of forestation in temperate regions. While these studies highlighted the potential for both warming and cooling effects from forestation, they did not acknowledge the dependence of these effects on soil moisture content. The coupling between vegetation and soil moisture has been previously established (Bonan 2008; Matera et al. 2022) and is especially strong in arid regions (Forzieri et al. 2017).

The increase in precipitation potential due to forestation that we found is also in line with previous climate modelling efforts that found an increase of terrestrial precipitation due to global forestation (Fraedrich and Kleidon 1999; Gibbard et al. 2005; Portmann et al. 2022). This precipitation increase ranges from 0.8% (Portmann et al. 2022) to 100% (Fraedrich and Kleidon 1999). Although these previous studies suggest an increase in precipitation due to forestation, the impact on local precipitation remains unclear because the local and remote effects are not isolated. There are some modelling efforts that were able to identify local

reductions in precipitation resulting from deforestation (Winckler et al. 2017; Luo et al. 2022) as well as a data analysis effort that was able to identify a positive effect of vegetation on local water availability and precipitation (Cui et al. 2022). These results suggest that forestation may enhance local precipitation in addition to terrestrial precipitation, which is further supported by the results in our study.

Similar to previous studies, our results indicate a positive relation between CAPE and soil moisture content (Leutwyler et al. 2021; Liu et al. 2022; Emanuel 2023). Even though we found that CAPE increases linearly with soil moisture, it is expected that this relationship is more complex. This is expected because first, convective storms might not develop over too wet soils due to a larger amount of energy that is needed to raise an air parcel from the surface to the level of free convection (Emanuel 2023) and second, storms could also intensify when moving towards drier areas (Liu et al. 2022). Nevertheless, soil moisture availability seems to be an important factor to establish CAPE and convective rainfall potential, especially over mountainous regions (Liu et al. 2022), and as a result, precipitation is promoted over wet soils and reduced over dry soils during summer, indicating a soil moisture-rainfall feedback (Findell and Eltahir 2003c; Leutwyler et al. 2021; Ardilouze et al. 2022).

By only modelling the local processes under current climate conditions, remote effects on convective rainfall potential as well as the impact of atmospheric warming are overlooked. Changes in temperature and humidity due to forestation will likely affect the transport of moisture and heat (Pielke 2001; Meier et al. 2021; Lian et al. 2022; Portmann et al. 2022; Staal et al. 2024), and therefore, remote precipitation events. However, the exact impact remains unclear and the warming of the atmosphere and sea surface due to climate change may have a bigger impact on precipitation (King et al. 2024), enhancing uncertainty. Nevertheless, for the Mediterranean Basin, a large fraction of evaporated water recycles within the region (Schicker et al. 2010; Batibeniz et al. 2020; Theeuwens et al. 2024b). Therefore, it is expected that an increase in evaporation due to forestation will likely affect precipitation elsewhere within the Mediterranean Basin. However, whether this would result in regional wetting or drying remains unclear. Studies in other regions show that restoration efforts can be beneficial for rainfall within the wider region (Tian et al. 2022).

4.4.4 Regreening to enhance the rainfall potential locally

The results of this study indicate where forestation may contribute to more rainfall. However, it should be noted that due to competing land use (e.g., agriculture or cities), soil type, or climatic conditions some of these areas are not suited for forestation efforts (Tóth et al. 2008; Noce et al. 2017). Nevertheless, for forestation efforts to contribute to convective rainfall, they need to be conducted in relatively wet regions as it seems that forestation makes wet regions wetter and dry regions

drier. Not only sufficient soil moisture needs to be available, also a relatively humid atmosphere is beneficial to enhance rainfall locally (Theeuwes et al. 2023a; Theeuwes et al. 2024b). Evidently, the soil moisture content and atmospheric humidity are closely linked (Seneviratne et al. 2010), specifically in regions that are neither extremely wet, nor extremely dry (Konings et al. 2011). Moving towards the south, the wetness of the Mediterranean Basin decreases. This suggests that it is more likely that forestation enhances convective rainfall in the north than in the south of the Mediterranean Basin.

Forestation efforts need to be conducted in regions where the conditions of the free atmosphere allow for the development of convective rainfall potential. The climatic 'see-saw' that has been observed in the Mediterranean Basin (Roberts et al. 2012) may explain why the atmospheric conditions in the western and northern parts of the basin seem to be more favourable to trigger convective rainfall potential through regreening than the conditions in the east and south. Furthermore, forestation mainly seems to increase convective rainfall potential in grid cells adjacent to those already exhibiting significant convective rainfall potential over bare soil, likely because the atmospheric conditions in these areas are favourable for convective rainfall potential.

Specifically coastal regions show potential for convective rainfall enhancement through forestation. This is observed in Italy, Greece and northern Africa and corresponds to previous research efforts that show a negative relation between local evaporation recycling and the distance to the nearest coast (Theeuwes et al. 2024b). Finally, mountains seem to promote the crossing of the ABL and LCL (e.g., in the South of Turkey). Complex terrain enhances the sensitivity of convection to soil moisture (Liu et al. 2022). Therefore, our results suggest that forestation in coastal regions with elevated terrain and relatively high soil moisture may contribute to local rainfall, specifically in the northern and western parts of the basin.

4.5 Conclusion

The goal of this study was to investigate the impact of forestation on the convective rainfall potential in the Mediterranean Basin during early summer. There is convective rainfall potential when the atmospheric boundary layer (ABL) and lifting condensation level (LCL) cross and the convective available potential energy (CAPE) is at least 400 J/kg. Using the CLASS model, the boundary layer development was simulated for two land cover scenarios: each grid cell covered fully in (1) bare soil, and (2) forest.

We found that forestation enhances CAPE, the amount of crossings, and the convective rainfall potential in various locations within the Mediterranean Basin. The impact of forestation on the development of the ABL varies across the

Mediterranean Basin and relates to soil moisture. In relatively dry regions, forestation contributes to the warming and drying of the ABL, resulting in a deepening of the ABL and increase of the LCL, which overall does not contribute to a crossing. In relatively wet regions, forestation moistens the ABL and enhances CAPE, which overall contributes to convective rainfall potential. However, for a few relatively wet grid cells forestation seems to reduce the convective rainfall potential.

Furthermore, additional simulations of the Mediterranean Basin with different soil moisture scenarios ranging from wilting point to field capacity underlined the crucial role of soil moisture for convective rainfall potential. Similar to the impact of forestation on convective rainfall potential, for a few grid cells an increase in soil moisture has a negative impact on the convective rainfall potential suggesting that there is an optimal amount of soil moisture. We also found that soil moisture is not the only driver of the crossing. It seems that for specific atmospheric conditions no crossing occurs, even when soil moisture content reaches field capacity. Nonetheless, our results suggest that, overall, there is a positive relation between soil moisture content and the convective rainfall potential. Thus to potentially enhance local rainfall through forestation, forestation initiatives in the Mediterranean Basin could be conducted in relatively wet regions close to the coast and over elevated terrain.



5

Targeted rainfall
enhancement as an
objective of forestation

Chapter 5 | Targeted rainfall enhancement as an objective of forestation

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Abstract

Forestation efforts are accelerating across the globe in the fight against global climate change, in order to restore biodiversity, and to improve local livelihoods. Yet, so far the non-local effects of forestation on rainfall have largely remained a blind spot. Here we build upon emerging work to propose that targeted rainfall enhancement may also be considered in the prioritization of forestation. We show that the tools to achieve this are rapidly becoming available, but we also identify drawbacks and discuss which further developments are still needed to realize robust assessments of the rainfall effects of forestation in the face of climate change. Forestation programs may then mitigate not only global climate change itself, but also its adverse effects in the form of drying.

5.1 Introduction

Forestation, including both afforestation and reforestation, is on the rise. The current decade is the UN Decade on Ecosystem Restoration and to keep global warming 'well below 2 degrees Celsius', as agreed in the Paris Agreement, large-scale forestation will likely be needed to realize net negative emissions later this century (Intergovernmental Panel on Climate Change (IPCC) 2023b). However, forestation is not a silver bullet approach to halt climate change, and it is sometimes criticized for being ineffective or even harmful (e.g., Calder, 2007; Veldman et al., 2015). Researchers and practitioners are making progress in understanding how, where and why forestation can be most effective and should therefore be prioritized (e.g., Brancalion et al., 2019; Griscom et al., 2017; Hua et al., 2022; Mo et al., 2023). Several recent studies developed optimizations of not only forest conservation but also reforestation, considering different effects such as on biodiversity (Strassburg et al. 2020; Jung et al. 2021). Further, 'ten golden rules' (Di Sacco et al. 2021) and 'fifteen essential science advances' for reforestation (Marshall et al. 2023) were recently proposed. However, the literature that outlines current forestation frontiers does not consider its effects on rainfall (Sheil et al. 2019).

It has long been recognized that forests participate in the regional hydrological cycle (see the discussions in Bonan, 2023; te Wierik et al., 2021). Especially the negative effects of deforestation in the Amazon on rainfall were noted already by some early influential papers (Salati et al. 1979; Shukla et al. 1990; Nobre et al. 1991; Nepstad et al. 1994) and corroborated on relatively local (Smith et al. 2023) to more regional scales (Staal et al. 2020b). Trees pump water around from their roots via the stomata in their leaves to the atmosphere, enhancing rainfall regionally (Spracklen et al. 2018). Therefore, deforestation, especially but not exclusively in tropical areas such as the Amazon, may synergize with climate-change-induced drought. Also in drier areas such as the Sahel, the importance of land cover-rainfall feedback has been understood for decades (Savenije 1995). It should, then, be no surprise that the idea that ecological restoration could be used for the benefit of the hydroclimate has been proposed along the margins of the wider restoration wave. Indeed, the idea appears in notions as 'conservation of water cycle on land via restoration' (Makarieva et al. 2006), '[water] supply-side thinking' (Ellison et al. 2012), 'aerial river management' by 'smart reforestation' (Weng et al. 2018), 'induced precipitation recycling' (Layton and Ellison 2016), 'moisture recycling governance' (Keys et al. 2017), 'moisture recycling as an ecosystem service' (Keys et al. 2016), 'managing moisture recycling for nature-based resilience' (Ellison et al. 2019), 'forest restoration for drought mitigation' (Tuinenburg et al. 2022), and 'planting trees to combat drought' (Baker 2021). Across the globe, climate change is creating or intensifying problems related to drought: forest fires are becoming

more frequent and intense, rivers are running dry, heat waves are getting more severe, and crop yields are suffering from lack of water (Pörtner et al. 2022). It becomes clear that ecosystem restoration projects may not only mitigate climate change by enhancing carbon sequestration but also provide hydroclimatic buffers to already ongoing change.

Building on these ideas and the latest published results, we here put forward that forestation could be used to mitigate climate-change induced drying if it is done wisely (e.g., Hoek van Dijke et al., 2022; Tuinenburg et al., 2022), but acknowledge that it may have adverse local hydrological effects if done unwisely (e.g., Filoso et al., 2017; Hoek van Dijke et al., 2022). Specifically, we go one step further than the existing literature by arguing that—in addition to other considerations such as biodiversity effects—it is starting to become possible to purposely account for spatially explicit non-local rainfall effects of forestation in holistic reforestation prioritization and climate-change vulnerability assessments globally. We call this concept *targeted rainfall enhancement* (TRE). We explain that, despite a solid biophysical underpinning and although results are now becoming available that allow for the first steps towards TRE, more research is needed before reliable planning of TRE can be made that are robust to projected climatic changes. We further suggest that moisture recycling networks (Zemp et al. 2014b; Keune and Miralles 2019; Wunderling et al. 2020; Wunderling et al. 2022b) could be constructed and used to guide this TRE. In addition to outlining the state-of-the-art regarding targeted rainfall enhancement through forestation, we discuss how it can be viewed in the wider context of geoengineering. Lastly, we provide avenues for future research in this Decade on Ecosystem Restoration.

5.2 Biophysical underpinning of targeted rainfall enhancement

Forests connect the global hydrological and energy cycles (Ellison et al. 2017). They promote rainfall elsewhere by increasing atmospheric moisture content through enhanced evapotranspiration (Keys et al. 2016). Therefore, the regional-scale impacts on rainfall, in particular, depend on the evapotranspiration-enhancing properties of forests relative to other, short-vegetation, types. Evapotranspiration can be considered forest-limited in areas where it would be enhanced by increased forest cover. However, we can differentiate two ways in which forests may lift the limitation for evapotranspiration by changing the local energy balance (Figure 5.1). Firstly, under energy-availability-limited conditions, forestation darkens the land surface and thus reduces albedo. This increases the absorbed solar radiation, making more energy available for evapotranspiration (Bonan 2008). Secondly, under water-availability-limited conditions, forests are able to sustain higher rates of evapotranspiration by deeper roots that allow them to store and access

deep soil- and groundwater (e.g., Nepstad et al., 1994; Seneviratne et al., 2010); by forest litter, large canopies, and branches and trunks hosting epiphytes and lichens that allow for larger interception capacities (Wang-Erlandsson et al. 2014; Savenije 2018); as well as by more soil organic matter that promotes the infiltration of rainwater into the soil (Zhang et al. 2015a).

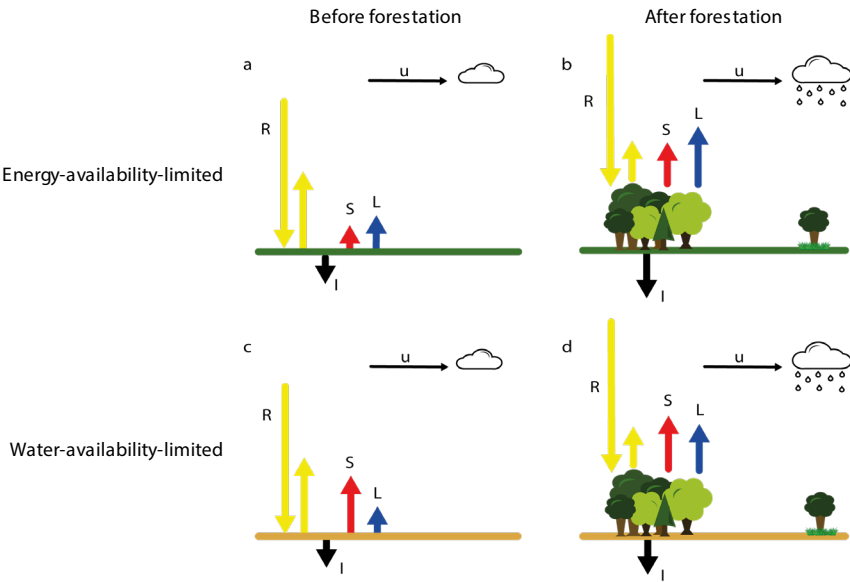


Figure 5.1. Simplified illustration of how forestation may enhance evapotranspiration through changing the energy balance. This may occur under both (a, b) energy-availability-limited and (c, d) water-availability-limited conditions. In energy-availability-limited systems, reduced albedo due to forestation leads to greater absorption of solar radiation R , increasing the amount of energy available for evapotranspiration, or latent heat (L), but also increasing sensible heat (S). Independent of how the additional energy is partitioned between latent and sensible heat, the moisture flux towards the atmosphere is expected to increase. In water-availability-limited systems, forestation increases not only access to deeper water layers but may also increase water infiltration (I) into the soil itself, alleviating the water limitation for evapotranspiration. In both types of systems, the increase in evapotranspiration may enhance rainfall downwind. u represents the horizontal wind flow that carries the moisture downwind to the target location of the enhanced evapotranspiration.

In addition to (non-local) targeted rainfall enhancement, forestation may also be employed to enhance local rainfall (Theeuwens et al. 2023a) (not shown in Figure 5.1), but the net local hydrological effects of forestation are not always straightforward. Trees extract water from the landscape, but could also enhance rainfall by feeding convection, following an increase in the sensible heat flux (Branch and Wulfmeyer 2019). However, especially in the tropics, forestation may cause cooling rather

than warming, leading to greater atmospheric stability and hampering upward air motion. Yet, it has also been proposed that a larger latent heat flux would locally enhance rainfall if atmospheric moisture content is high enough. Close to saturation, a small increase in atmospheric moisture would trigger rainfall, which would induce moisture convergence and thus rainfall again (Makarieva et al. 2023) (not shown in the simple Figure 5.1). This would add to another biological pathway of local rainfall initiation via emissions of biogenic volatile organic compounds that stimulate cloud formation (Peñuelas and Staudt 2010). However, empirical evidence indicates that, depending on spatial patterns, patchy deforestation in tropical forests can locally also enhance rainfall through increasing turbulence (Lawrence and Vandekar 2015), implying that forestation that smoothens out such heterogeneous surface roughness would locally reduce rainfall.

In summary, forest can enhance rainfall via different mechanisms, suggesting that it is possible to target rainfall under a range of geographical and climatic conditions. However, to realize spatially explicit assessments of targeted rainfall enhancement, we need more specific tools than a mechanistic understanding of the processes only.

5.3 Spatially resolving forest effects on rainfall

Targeted rainfall enhancement relies not only on the extent to which enhanced evapotranspiration reaches the desired target locations, but crucially also on how precise we are able to identify these target locations. How much of the evapotranspiration from a certain area ends up as rainfall on terrestrial systems depends on a range of meteorological conditions that affect wind patterns and moisture recycling ratios. Although such regional effects of forests on rainfall have been long recognized (see te Wierik et al., 2021), only recently have there been significant advances in atmospheric moisture tracking to understand atmospheric moisture recycling on relatively fine spatial scales (down to 0.25° , around 25×25 km around the equator) and the relatively fine temporal scale of a single month. These advances allow for understanding rainfall effects of reforestation beyond large-scale, general estimates. Specifically, the spatially explicit, regional connections between evapotranspiration and rainfall can be reconstructed by the latest generation of atmospheric moisture-tracking models (Van der Ent et al. 2014; Tuinenburg and Staal 2020; Keune et al. 2022). Although different models (with different assumptions, complexity, and input data) exist (Van der Ent et al. 2013; Tuinenburg and Staal 2020), the same set of principles is shared among these moisture-tracking models: by using reanalysis data of evapotranspiration, atmospheric moisture profiles, wind speeds and directions, and precipitation, moisture is ‘tracked’ through the atmosphere either forward from evapotranspiration to precipitation or backward from precipitation to evapotranspiration. A similar tracking approach has been

implemented in the Weather Research and Forecasting (WRF) model (Dominguez et al. 2016; Insua-Costa and Miguez-Macho 2018; Yang and Dominguez 2019; Gao et al. 2020; Dominguez et al. 2022; Insua-Costa et al. 2022). This meteorological model is more complex than the moisture-tracking models that are fed by reanalysis data only, allowing users to experiment with different meteorological or land-cover conditions, but also suffering from uncertainties inherent in the complexity involved. Earth system models can also be used to study land-cover change effects on climate. However, not many have specifically looked at forestation effects on rainfall and if so, these studies tend to involve simultaneous large-scale forest cover changes, at regional-to-continental (e.g., Laguë and Swann, 2016) or global scales (e.g., Portmann et al., 2022). They show that such massive changes may affect atmospheric circulations at global scales and are thus useful to assess effects of such rather extreme changes on these circulations. Yet, these models may be less suitable to isolate detailed targeted rainfall enhancements due to their computational requirements. Methods do exist, however, to differentiate between local (within a grid cell) and non-local (from outside the grid cell) climatic effects of land cover change (Winckler et al. 2017).

As with all models, to work with them requires experience and time investment, and especially the latest models can be particularly data demanding. However, several global datasets of evapotranspiration-to-precipitation links have recently been published, which can be used more easily than the source code itself. The highest spatial resolution is achieved by Tuinenburg et al. (2020b), who published a dataset of mean-monthly climatologically averaged (2008–2017) global evapotranspiration-precipitation connections between each pair of grid cells at 0.5° resolution ($\sim 50 \times 50$ km around the equator). For these results, the Lagrangian model UTrack is forced with the most detailed and latest (ERA5) hourly atmospheric reanalysis data for 25 atmospheric layers (Tuinenburg and Staal 2020). Time series, however, of the destinations of terrestrial evapotranspiration are published by Link et al. (2020), using the Eulerian moisture-tracking model WAM-2layers (Van der Ent et al. 2014) at 1.5° resolution.

In addition to spatially resolving moisture flows, understanding how land-cover changes affect rainfall requires reliable estimates of the effects of those changes on evapotranspiration. Different methods and approaches have been employed in order to estimate them. Spracklen et al. (2012) used the back-tracked moisture flows themselves to do this: rainfall across the tropics was related to the cumulative leaf area index (LAI) of the land surface along the trajectories that the precipitated moisture had passed over. They found a positive correlation between rainfall and the LAI along the trajectory, providing correlational evidence of the effects of vegetation on rainfall. Meier et al. (2021) and Smith et al. (2023) used statistical approaches

to estimate local effects of forest change on rainfall, complemented in Meier et al. (2021) by a trajectory-based approach to estimate remote effects. An alternative approach is to use ecohydrological models in which actual evapotranspiration is calculated based on soil moisture and vegetation properties (e.g., Staal et al., 2018; Wang-Erlandsson et al., 2014).

Moisture tracking has also been employed to study more local-scale moisture recycling. It was found that, globally, the proportion of evapotranspiration that rains out locally is rather low: within ~50km it is in the order of 1%–5% (Theeuwes et al. 2023a). Nevertheless, in recycling models, the process of fast recycling, i.e., local showers yielding rain before locally evaporated moisture is fully mixed in the atmospheric column (Burde 2006a), may generally be underestimated due to the assumption of complete vertical mixing of locally evaporated moisture with advected moisture (Dominguez et al. 2020).

In summary, atmospheric moisture tracking is a tool that can be used to move from a general understanding for forest-atmosphere interactions to spatially and temporally resolving effects of forestation. However, they cannot account for atmospheric circulation changes following forestation, for which Earth system models are currently more suitable. Moisture tracking within Earth-system and WRF models may offer better opportunities to study effects of specific mechanisms on atmospheric moisture flows, whereas existing moisture flow databases offer more user-friendliness. Intercomparison among different type of moisture-tracking modelling approaches and comparison with observation-based isotope studies are necessary to narrow the uncertainty span.

5.4 Benefits and trade-offs of targeted rainfall enhancement

Although the above advances in atmospheric moisture tracking and other scientific progress suggest that targeted rainfall enhancement (TRE; Figure 5.2) can be applied in principle, this idea is further substantiated by recent work specifically on the effects of forest increase on rainfall. Two independent studies recently assessed hydrological effects of the ‘global tree restoration potential’ as estimated by (Bastin et al. 2019), which amounts to an increase of 900 million ha of forest compared to present-day forest cover. The studies, by Tuinenburg et al. (2022) and Hoek van Dijke et al. (2022), used the same moisture-tracking model (UTrack), but different methods to estimate the effects of forest cover change on evapotranspiration. Their estimates of the globally averaged rainfall increase range between 4.8 mm yr⁻¹ (Hoek van Dijke et al. 2022) and 7 mm yr⁻¹ (Tuinenburg et al. 2022). Two-thirds of the additional evapotranspiration would precipitate over land; for 21%, this would be in areas that are projected to become drier due to global climate

change (Tuinenburg et al. 2022). However, higher evapotranspiration is not always desired, as it can lead to lower water yield (precipitation minus evapotranspiration, equivalent to streamflow) locally (e.g., Farley et al., 2005; Hoek van Dijke et al., 2022). Indeed, in about half of the global land area, water yield would decrease; in the other half, water yield would increase due to enhanced atmospheric moisture recycling (Hoek van Dijke et al. 2022). This is consistent with the finding that the global increase in evapotranspiration under high forestation would be greater than that in terrestrial precipitation (Tuinenburg et al. 2022). A third study, by Cui et al. (2022), analysed recent changes in global leaf area and used output of the WAM2-layers model (Van der Ent et al. 2014; Link et al. 2020) to assess how water yield has changed as a consequence of the leaf-area changes. They found that as a global average, recent greening has led to an annual increase in water yield of 0.26 mm yr⁻¹. Importantly, they find that vegetation increase enhances water yield both locally and in downwind areas in almost half (45%) of the globe. However, differences in rainfall partitioning to infiltration, interception evaporation, and runoff could affect water yield (Zhang et al. 2022b). The above further illustrates that the hydrological effects of forestation are not straightforward (Ellison et al. 2012) and highlight the importance of location (Staal 2022): whether effects of forestation on water yield are positive, positive but unacceptable (in case of increased floods), negative, or negative but acceptable (if water is not limiting), depends on the location of both the source of the moisture and its target.

Regardless of their hydrological effects, massive forest increases should not come at the expense of native well-functioning ecosystems such as natural grasslands (Veldman et al. 2015a; Veldman et al. 2015b; Dudley et al. 2020). By excluding natural grasslands from the potential forestation map, but also focusing on rainfall locations that are projected to become drier due to global climate change, some preliminary focus areas for large-scale forestation-induced targeted rainfall enhancement were already identified by Tuinenburg et al. (2022): the southern and western Amazon, Mexico, eastern China, and Mediterranean Europe. However, depletion of local water resources should also be prevented. Hoek van Dijke et al. (2022) name the following regions where global forestation would enhance water yield: parts of the Sahel, eastern Europe, southern Africa and South America, the Sahara, and the Himalayas, all of which experience water scarcity for at least three months per year. Cui et al. (2022) attribute the net positive effect of global greening on water yield mainly to recent greening in Europe, western Siberia, parts of Africa and eastern China. These selections do not preclude the potential of TRE to combat drying in other places, also due to caveats related to the methods behind the global forest potential map (e.g., Veldman et al., 2019) and the scale of analysis. Locally, restoration of forest patches that can sustainably provide relatively large amounts of

moisture to the atmosphere (e.g. gallery forests) could be prioritized. At the same time, critical equity issues with regard to social considerations (e.g. on distribution, procedure, recognition, or context of the ecosystem restoration) can decisively influence the success and effectiveness of an ecosystem restoration project (Pascual et al. 2014; Elias et al. 2022). Further, a disproportionately large number of people live in regions with a low Human Development Index as well as high ecosystem restoration priority (Löfqvist et al. 2023). Therefore, an equity-centred dimension is key for future ecosystem restoration projects, also with regard to TRE. Which land-cover type gets replaced also matters for the TRE potential (Sterling et al. 2013). Still, where they can be sustained, forests tend to provide the most stable flux of moisture to the atmosphere compared to all other ones, as they can access deeper groundwater even during periods of little to no rainfall. Hence, they buffer against droughts (Staal et al. 2018; O'Connor et al. 2021a) and may shorten dry seasons, such as in the Amazon (Wright et al. 2017; O'Connor et al. 2021b).

Most of these results regarding active forestation so far remain hypothetical. However, one notable example offers an empirical case study for large-scale ecosystem restoration, where recent findings appear to provide a proof-of-principle, but also illustrate the complexities involved. In the Chinese Loess Plateau, grassland area has increased by $\sim 12,000\text{km}^2$ and forest area by $\sim 9000\text{km}^2$ between 1985–2015, largely by replacing decreasing croplands and barren lands (Sun et al. 2022). As expected, evapotranspiration rates have increased in the region (Feng et al. 2016; Shao et al. 2019; Tian et al. 2022). At the same time, tree cover increase has improved soil water holding capacity and soil water availability in the area (Zhang et al. 2021), and importantly, for over 80% of the Loess Plateau, local-scale moisture loss due to increased evapotranspiration has been compensated or surpassed by an increase in rainfall (Zhang et al. 2022a). However, in the remaining areas (primarily in arid regions, with mean annual rainfall below 400 mm), water yield decreased. In these cases, forests were the main revegetation type (Zhang et al. 2022a). On average, rainfall has increased by 54 mm yr^{-1} , due to both increased internal recycling and enhanced net moisture inflow into the Loess Plateau, compared to an average increase in evapotranspiration of 23 mm yr^{-1} (Tian et al. 2022). It should, however, be noted that a simultaneous reduction in agricultural water use may obscure some of the actual water loss caused by the forestation efforts (Zhou et al. 2020). The case of the Loess Plateau illustrates the importance of targeted rainfall enhancement to promote rainfall, while avoiding the negative effects of forestation on water storage (Zhao et al. 2020), and on streamflows and downstream wetlands (Xi et al. 2022).

Many benefits of forestation, such as carbon capture, will occur on the time scale of decades. TRE, however, is an ecosystem service that will return relatively fast after forestation. As soon as photosynthesis is restored, given sufficient rooting

depth, evapotranspiration will increase, although in measurements from Japan, evapotranspiration continued to increase for 20 years, after which it seemed to stabilize (Murakami et al. 2000). Measurements from France suggest that, although the partitioning of evapotranspiration depends on stand age, total evapotranspiration is independent of stand age (Delzon and Loustau 2005). Forest recovery is fastest and easiest in wetter regions such as in the tropics (Poorter et al. 2016), but those areas may not be the regions that would benefit most from enhanced atmospheric moisture recycling. Thus, there might be a trade-off between ease of recovery and rainfall benefits of recovery.

In summary, forestation should not be seen as a silver bullet for solving water shortages either locally or regionally, so each project should be assessed individually to prevent adverse hydrological effects. However, increasing evidence indicates that targeted rainfall enhancement through forestation would be beneficial in some cases.

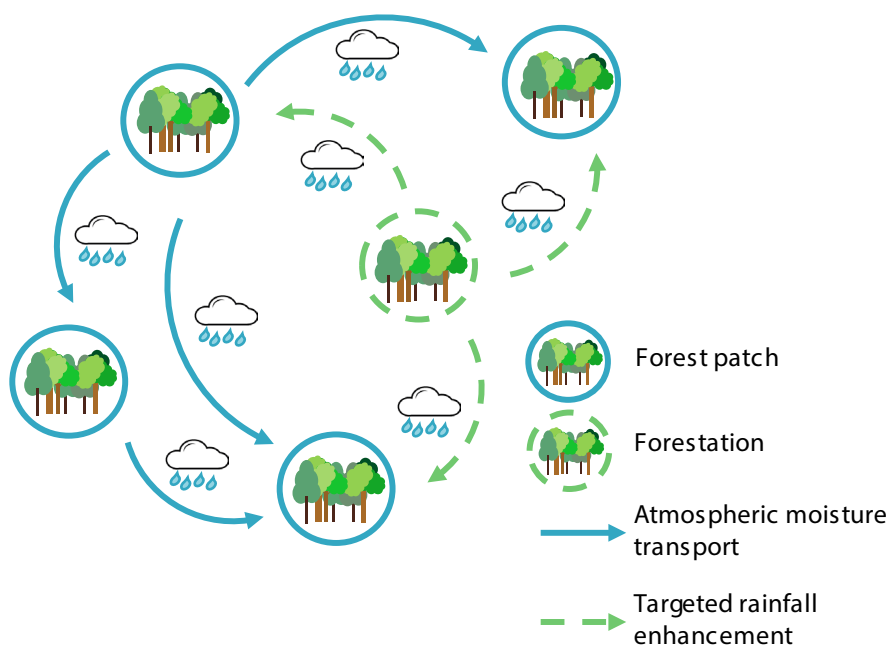


Figure 5.2 Targeted rainfall enhancement as an objective of forestation. Forestation tends to enhance atmospheric moisture transport, which would increase rainfall in target areas directly, but may also have cascading effects in the forest system. These cascading effects may feed back to the original forested patch, adding to other local effects of forestation.

5.5 Is targeted rainfall enhancement geoengineering?

It has not escaped our notion that if either afforestation or reforestation becomes more deliberate and planned with regard to its (hydro)climatic effects, it may be shifting from the domain of ecosystem restoration to geoengineering, which tends to be perceived differently and raise different ethical concerns. The IPCC defines both afforestation and reforestation as mitigation, that is, a human intervention to reduce the sources or enhance the sinks of greenhouse gases, whereas geoengineering is seen as efforts to stabilize the climate system by directly managing the energy balance of the Earth, thereby overcoming the enhanced greenhouse effect (Minx et al. 2018). Tree planting does, however, affect the energy balance of the Earth and could thus affect regional rainfall levels similar to marine cloud brightening, which is widely considered to be geoengineering (Jones et al. 2009; Latham et al. 2012). TRE could also be interpreted as geoengineering when defined as an ‘intentional large-scale manipulation of the environment, particularly manipulation that is intended to reduce undesired anthropogenic climate change’ (Keith 2000). Given those definitions we think that some reflections within this context are warranted.

TRE indeed entails reducing undesired anthropogenic climate change through manipulation of the environment; the scale from which it can be considered geoengineering, however, is unclear. Planting a tree for environmental benefits, for instance shading, is a form of managing the local climate and in IPCC terms, adaptation. At larger scales, with the intention of realizing negative carbon emissions, this turns into mitigation. However, the biophysical effects of full forest potential are likely to have such large global effects on the radiation balance and moisture recycling (Portmann et al. 2022) that realizing it could be considered geoengineering. Despite nonlinearity in the effects of forest expansion on rainfall (Zemp et al. 2014a; Lawrence and Vandecar 2015), there is no clear transition from small-scale non-geoengineering measures to large-scale geoengineering. In principle, if forestation is strictly *reforestation* in the sense that previous deforestation is reversed, then it can reasonably be considered ecosystem restoration even if TRE is taken into account.

Simply *reforestation*, considering historical baseline conditions, may, however, not suffice. A Holocene baseline of forest distributions (Steffen et al. 2015) and the hydrological cycle (Wang-Erlandsson et al. 2022) can be justified as a safe space to operate in, meaning that it can serve as a guide to prioritize restoration without it pushing measures outside the historical domain. As planting trees where they did not occur before would coincide with larger unknowns, the term ‘geoengineering’ may apply. However, a key question is whether we can always assume no harm from reforestation. Locally, Holocene conditions were not always constant (e.g., Dermody et al., 2012) and planting forests may not reverse past anthropogenic effects but

add to them (Heck et al. 2016). Furthermore, as discussed, different climate futures may imply different reforestation strategies: restoring forests that fed rainfall to certain areas in the past may not do so in the future. Holocene conditions at the global scale may still imply major redistribution locally and regionally. Thus, it can be argued that controlling forest distributions for those reasons, even when reforestation in a strict sense is employed, is geoengineering.

Beyond definition questions of geoengineering, TRE involves ethical considerations around restoration in general. Redistributions of biomass and hydroclimatic conditions are prone to have both winners and losers, and ensuring justice can be necessary for gaining social and political acceptance. Already, all kinds of restoration efforts consider multi-functional use of grasslands for biodiversity restoration, or multiple-use of forests for climate mitigation. Such assessments are not neutral and necessitates an ethically explicit judgement (Batavia and Nelson 2018). Further, it can be argued that geoengineering through plantation is already happening in many ways. For instance, a shift is currently happening from planting of seedlings grown from locally sourced seeds (geographically based reforestation) to genomics-based assisted migration by selecting seeds based on expected future climates (Findlater et al. 2022). Forest managers also increase climate benefits by using more reflective and deciduous tree species (Jackson et al. 2008). Those combined effects of carbon sequestration and biophysical effects in terms of energy and hydrology are not taken into account in current climate policy (Boucher et al. 2014). Thus, a debate around TRE would be in line with different forest management efforts already taking place and helps ensure that justice issues related to moisture redistribution are accounted for.

5.6 Outlook

What could be considered sensible targeted rainfall enhancement currently, may not be so in the future. Firstly, global climate change may affect global atmospheric moisture flows and thereby regional moisture connections (Baker and Spracklen 2022). Other relevant hydrological variables will probably also change: the timing and intensity of evapotranspiration and rainfall (Intergovernmental Panel on Climate Change (IPCC) 2023a); water-use efficiency following CO₂ fertilization (Dekker et al. 2016); and the moisture holding capacity of the atmosphere, resulting in different recycling rates (Dominguez et al. 2006) and distances (Gimeno et al. 2021). The continued drying and warming trends can also lead to changes in prioritization of forestation areas to stop remote carbon emissions (Pires 2023; Staal et al. 2023) and to shifting forest suitability ranges (Staal et al. 2020a). Secondly, TRE should be robust under land-cover changes, which includes TRE itself. For instance, large-scale forest cover changes may alter temperature and pressure gradients and,

consequently, moisture flows. This may cause certain other areas to either become more or less suitable for TRE such that global or regional TRE potential feeds back to itself (Tuinenburg et al. 2022). Therefore, to better account for the complex and dynamic nature of the Earth system, we need explicit integration of future simulated evapotranspiration and rainfall flows with harmonized land-use change scenarios including better integration with ecohydrological processes, as well as wind patterns and atmospheric moisture content at high spatial and temporal resolution for a range of scenarios. The ‘tagging’ of moisture in an Earth system model (Harrington et al. 2023) would be a logical and significant step forward in this regard.

A network perspective on targeted rainfall enhancement could inform about possible target locations to strategically enhance moisture flows (Figure 5.2). In previous work, atmospheric moisture connections among forest patches (in the order of 100km) have been converted to directed networks, here meaning one-way flows between moisture sources and sinks (Zemp et al. 2014b; Krönke et al. 2020). By analysing the networks’ structures for their role in overall dynamic behaviour (Wunderling et al. 2020; Wunderling et al. 2022b), it is possible to, for instance, identify major transmitters of moisture flows. Thus, the ‘importance’ of a forest patch on the entire forest-rainfall network can be assessed. Forestation may significantly enhance evapotranspiration and can thus add particular evaporation-to-rainfall links to the network. It may also enhance transmission of moisture previously contributed by forest to the network. As such, counterintuitively, forestation could enhance the importance of upwind forest patches to the overall forest system. Interestingly, it is consistently found in the network literature that networks are usually very robust to random removal of links, but considerably less robust to targeted attacks and removals of links (Albert et al. 2000; Newman 2018)—a ‘targeted attack’ in this context meaning deliberate restoration of important patches and ‘targeted removal’ meaning deliberate deforestation of important patches. Indeed, deforestation of particular patches in the Amazon may lead to disproportional loss of resilience of the full forest-climate system (Wunderling et al. 2022a). Targeted rainfall enhancement, in turn, could then also disproportionately enhance forest rainfall by stabilizing the network as a whole (Figure 5.2), as well as connecting different parts of the network that were not interacting before (Chen et al. 2007). By tapping into the numerous ways to determine and tune the resilience of networks (e.g. in network control theory Gao et al., 2016; Liu et al., 2011), explicit assessments of moisture-recycling network structures and dynamics (Wunderling et al. 2021; Wunderling et al. 2022b) could become an important tool for realizing targeted rainfall enhancement.

Despite an emerging scientific basis for TRE, major uncertainties remain. The foundations for our arguments rest on model simulations fed by inputs from observation-based data, and major model developments are still required for

reliable assessments. Refined estimates that account for cross-scale dynamics require coupled modelling, including vegetation-induced changes in atmospheric circulation (Portmann et al. 2022) and climate-change-induced modifications of moisture flows (Findell et al. 2019). Care should also be taken to fit forestation efforts in line with prevailing and projected future hydroclimate. Importantly, TRE should not be a stand-alone consideration, but integrated into existing or emerging frameworks for restoration and conservation prioritization (Brancalion et al. 2019; Aronson et al. 2020; Griscom et al. 2020; Strassburg et al. 2020; Jung et al. 2021; Hua et al. 2022). This includes accounting for water-related trade-offs and co-benefits such as changes in water yield and groundwater recharge, as well as broader sustainability and ethical concerns. Through a balanced inclusion of TRE in forest ecosystem service provisioning valuations, it could also add to the value of these services (Asbjornsen et al. 2022). As such, TRE can become part of holistic assessments of reforestation potential in the current Decade on Ecosystem Restoration and beyond.

5.7 Conclusion

A number of recent papers have discussed or hinted at the possibility of using forests to manage rainfall. Considered together, it emerges that the effects on rainfall of potential forestation are significant and relevant. Forestation programs would mitigate not only global climate change itself, but also its adverse effects in the form of drying. With increasingly better data and models, we argue that targeted rainfall enhancement (TRE) now can be considered by and integrated in forestation initiatives and conservation prioritization frameworks.





Towards regreening for
natural water production:
a transdisciplinary
model for impact

Chapter 6 | Towards regreening for natural water production: a transdisciplinary model for impact

Abstract

Mission-driven research aims to generate societal impact by addressing complex challenges through integrated, transdisciplinary approaches. This study evaluates the societal impact of a mission-driven research program using the Theory of Change framework. This research program explores the potential for enhancing local rainfall in arid and semi-arid regions through regreening practices, as well as deploying water technologies to initiate rainfall in extremely dry areas. It fosters collaboration between companies and knowledge institutions, spanning fields from ecology to mechanical engineering. Our findings indicate that the program's transdisciplinary approach significantly enhances science communication effectiveness, as stakeholder engagement ensures the immediate application of research outputs. Furthermore, all partners, i.e., both companies and academic institutions, derive clear benefits from the collaborative framework. For early-career scientists, participation in transdisciplinary teams notably promotes personal and professional growth. However, effective collaboration requires time investment, which may limit opportunities to focus on traditional research outputs. Despite this trade-off, the research program exemplifies how integrating diverse knowledge and stakeholder input enhances the generation of societal impact.

6.1 Introduction

In recent years, the focus of research to address real world challenges has shifted from mainly scientific impact to societal impact. This shift has led to the adoption of a mission-driven, or challenge-oriented approach in research. A mission-driven research approach tackles big and ambitious societal challenges that are cross-sectoral, time bound and measurable (OECD 2022). It is a goal-oriented research approach in which the link between the scientific research and practical applications is realized through stakeholder engagement. Research that integrates knowledge from various disciplines and stakeholders, such as companies and governments, is called transdisciplinary research, which is crucial to find holistic solutions to big societal challenges (Rombach et al. 2024) and is an important aspect of a mission-driven approach (Barth et al., 2023). This collaborative process is called co-creation and helps to shape research agendas and enhance the relevance and applicability of research outputs. This ensures that the research activities achieve the intended impact.

Reflecting this trend, national and European funding agencies are now promoting a mission driven approach, with Horizon Europe being a well-known example. From the five missions as defined by the European Union, four are related to water, i.e., (1) adaptation to climate change, (2) healthy oceans, seas, and coastal and inland waters, (3) climate-neutral and smart cities, and (4) soil health and food (OECD 2022), demonstrating the importance of sufficient and clean water. However, one urgent challenge facing societies worldwide is water scarcity. Water scarcity is an example of a societal challenge that demands innovative and holistic solutions that can only be achieved through transdisciplinary collaborations. The water sector has long applied a mission-driven approach, fostering partnerships between scientists, governments, and companies to tackle water-related issues (Ghodsvali et al. 2019).

Here we explore the impact of the natural water production (NWP) research program that is situated at Wetsus, an applied water technological research institute in the Netherlands. This NWP research program addresses the global water scarcity challenge. Specifically, it focusses on how regreening strategies may enhance rainfall in arid and semi-arid regions and how water technology can be used to realize such regreening projects. This program is a collaborative effort between various knowledge institutes and companies and exemplifies a mission-driven approach designed to generate societal impact. We examine the impact of this research program using the Theory of Change framework (Connell and Kubisch 1999) to map the pathways through which we expect the NWP program creates impact. This framework connects the research activities and its outputs to its short-term impacts and long-term societal

impacts. Outlining an impact pathway provides a structured way to evaluate if research activities are contributing to achieving the intended impact.

With this framework we evaluate how the NWP research program has generated impact and if the transdisciplinary approach and co-creative practices contributed to this. We also examine how a transdisciplinary approach influences the professional development of an early career scientist (ECS) and discuss the potential benefits and challenges of including an ECS in a transdisciplinary research team.

6.2 Methods: Theory of Change

The Theory of Change framework is used to assess the societal impact of the research and outreach activities within the research program, which is described in more detail as a case study in Section 3. The Theory of Change framework is selected as methodology because it has been recognized as a useful tool to evaluate the impact of a research program by the Dutch Research Council (NWO). NWO motivates researchers to apply this framework to “purposefully increase the chance of social impact of research” (<https://www.nwo.nl/en/impact-plan-approach>).

The Theory of Change is a strategic framework that outlines how research programs aim to achieve their desired long-term impact, i.e. change (Connell and Kubisch 1999). It helps to outline the connections between inputs (data, expertise, funding), activities (actions), outputs (direct results of activities), and outcomes (short-, medium-, and long-term changes). By identifying assumptions and linking each step to its impact, the Theory of Change explains how and why change is expected to occur and it gives insight into the related challenges. These challenges can be used to formulate new research questions and the assumptions help to evaluate the progress of the research program. The Theory of Change can be used to ensure that every research step contributes to achieving the desired impact.

In the Theory of Change framework, outputs are the direct, immediate results of activities in a research project or program. They are actual and measurable products, such as scientific publications, datasets, models, organized events or people trained. The changes or effects that result from these outputs over time are referred to as the outcomes. These outcomes can be (1) short-term, such as a change in attitude, a contribution to knowledge or the creation of awareness, (2) medium-term, such as changes in behaviour, or (3) long-term, such as systematic changes or societal impact. Outcomes explain the broader, lasting impact of research activities that go past the direct outputs.

The inputs, activities, outputs and outcomes make up the different steps in the Theory of Change and these steps are linked by assumptions. These assumptions

explain how each step leads to the next step and these assumptions must be true to reach the desired impact. If assumptions are unrealistic, the expected change may not occur, and therefore, identifying and testing assumptions throughout the research process helps to reduce the risks of a research program and allows for evaluation of the progress (Connell and Kubisch 1999). The feedback from such evaluation can lead to alterations in activities and assumptions, which improves the effectiveness of the research process. Applying the Theory of Change makes sure that all research activities are aligned with the desired long-term impact and it helps to identify and address new challenges throughout the research process.

6.3 Case study: The natural water production research program

The research activities in the natural water production (NWP) research program at Wetsus, including the work that is presented in this PhD thesis, are used for the case study in this chapter. The related research activities are outlined and reflected on to determine the outcomes. These research activities were mainly conducted at Wetsus (Box 6.1). Wetsus is the European Centre of excellence for sustainable water technology located in Leeuwarden, the Netherlands. Part of this research program is a collaboration with two company partners: international dredging company DEME and The Weather Makers, which is an engineering company that develops projects related to water cycle and biosphere restoration (Box 6.2). Both companies have expertise on engineering and conducting large scale environmental projects. The researchers in the NWP program are connected to the Copernicus Institute of

6

Box 6.1: Wetsus, European centre of excellence for sustainable water technology

At Wetsus researchers from different backgrounds come together to contribute to solutions for global water problems. The mission of Wetsus is to develop key enabling water technologies to foster a sustainable and fair society in a healthy and circular environment. To achieve this the research at Wetsus is divided into multiple themes in which knowledge institutes, tech companies, private end-users and public end users are stimulated to work together, which speeds up innovation towards societal impact. In general, researchers at Wetsus generate outputs in the form of scientific publications, patents, prototypes, and applications which are used by partners to generate more impact (Wetsus 2021).

The Natural Water Production program is one of the programs at Wetsus in which researchers from Utrecht University and Wageningen University collaborate with The Weather Makers (Box 6.2) and dredging company DEME to develop technologies and tools that can be used to regreen arid regions to restore local water cycles and enhance freshwater availability. The three main research objectives that are currently studied in the Natural Water Production theme are:

1. Understanding the role of local moisture recycling in restoring local water cycles through greening in Mediterranean-type climate regions globally.
2. Identifying meteorological pathways for more rain in dry areas through enhanced atmospheric moistening resulting from enhanced seawater evaporation.
3. Developing a seawater evaporation technology based on heat localized solar evaporation.

Box 6.2: The Weather Makers & the Sinai initiative

The Weather Makers is a Dutch engineering company that focusses on the restoration of water cycles and the biosphere. They work on several international projects in which they collaborate both nationally and internationally with farmers, local and national governments, and companies. Their main project is the Sinai project. This ambitious project aims to restore the water cycle of the Sinai Peninsula in Egypt. Restoring the biosphere is expected to have a cooling and moistening effect, contributing to rainfall within the region and possibly affect the climate on a larger scale. Their plan is based on an engineering approach which starts with the regeneration of Lake Bardawil in the north of the Sinai. The organic material that becomes available in this step is used for the next step: the restoration of the wetlands around the lake, which they hope will enable them to take the final step the restoration of a larger area in the Sinai Peninsula.



Figure Box 6.2 The masterplan to restore the water cycle in the Sinai desert as designed by The Weather Makers. The project starts with the regeneration of Lake Bardawil, then the wetlands are restored, followed by regions further inland. The restored landscape will have a cooling and wetting effect. It is expected that this will result in the development of clouds and rainfall at the top of the mountains in the south of the Sinai. Lake Bardawil is located in the north of the Sinai peninsula and the mountains are located in the south. The landscape depicted here is a cross section of the region. The partners for each phase of the masterplan are depicted at the bottom.

Sustainable Development at Utrecht University and to Wageningen University & Research, bringing expertise from various fields ranging from ecohydrology and ecosystem resilience to environmental engineering.

6.3.1 Long term impact

The research conducted in the NWP program aims to develop tools and technologies that can help to restore the water cycle in degraded arid and semi-arid landscapes to enhance freshwater availability (Figure 6.1). The tools that are being developed are expected to provide insight into best practices of regreening

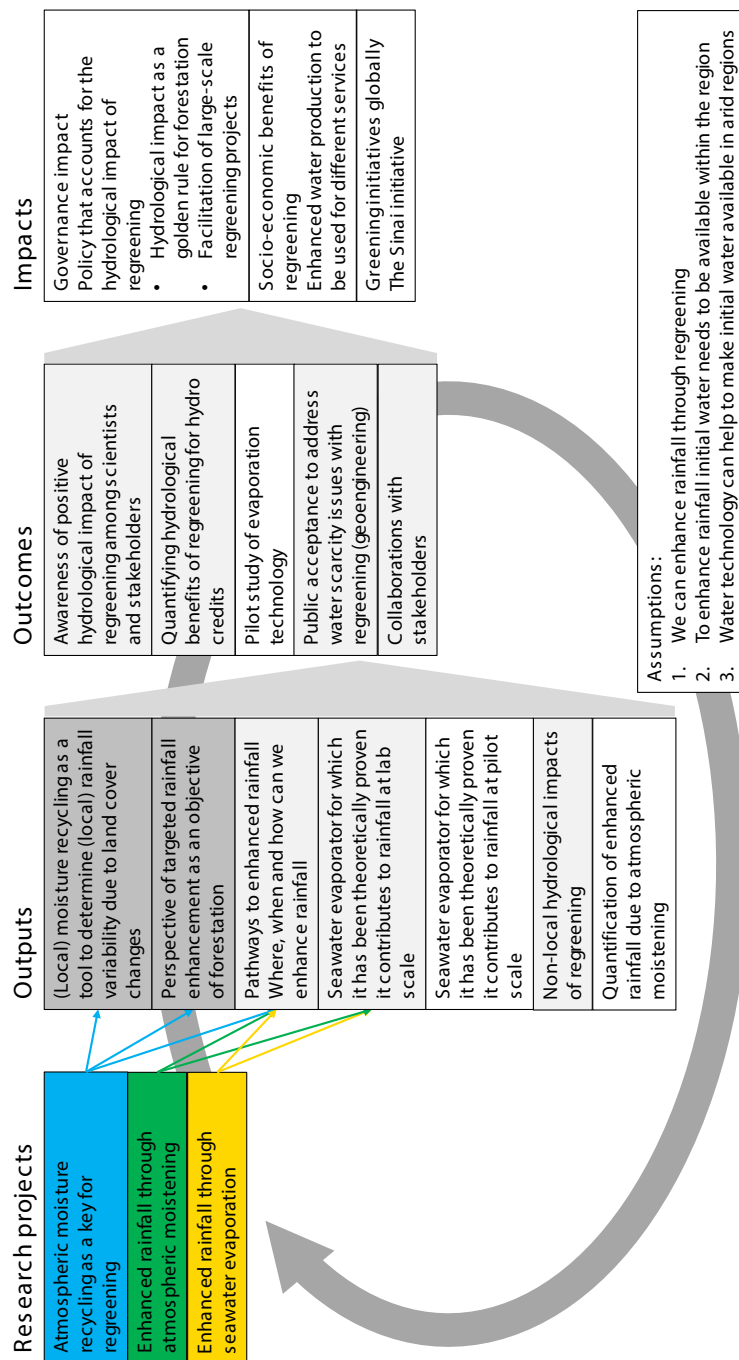


Figure 6.1 The theory of change designed for the natural water production research program at Wetsus. Research projects result in outputs that contribute to outcomes. All research activities contribute to the intended impact. The research activities in this program are based on several assumptions. The circular arrow indicates the dynamic aspect of the research program, i.e., research progress and impact evaluation can contribute to new research projects. The intensity of the shading for each of the outputs and outcomes indicates the progress; darker colors indicate more progress.

for freshwater production. The research activities within the NWP program as well as the tools we are developing will provide insight into where an increase in evaporation due to land cover changes will likely contribute to wetting and not to local drying as a result of enhanced local moisture recycling. Local moisture recycling describes the return of evaporated water as rainfall within a distance of 50km from where it evaporated (Theeuwes et al. 2023a). The acquired knowledge within the NWP program could help to formulate a “golden rule” for forestation to maximize hydrological benefits (Di Sacco et al. 2021). Additionally, identifying best practices for greening helps governmental institutions to develop policies to facilitate large-scale greening projects and optimize the socio-economic benefits of these projects (Figure 6.1) such as the increase of agricultural productivity, creation of livelihoods, and mitigation of extreme weather. The technologies that are being developed in the NWP program are expected to enable restoration of arid regions where currently insufficient freshwater is available to successfully restore the biosphere. Whereas The Weather Makers focus at restoring the Sinai desert specifically, the outcomes are expected to benefit greening initiatives globally.

6.3.2 Assumptions

The NWP program is based on several assumptions or hypotheses (Figure 6.1). These assumptions need to be tested to maximize the impact of the research program. The first assumption is that we can enhance rainfall through greening (e.g., Millán, 2014). We expect that an increase in vegetation will enhance evapotranspiration which has a cooling and moistening effect (Figure 6.2). Enhanced wetness and reduced temperatures are more beneficial for rainfall to occur. Second, we expect that for rainfall to occur initial water needs to be available within the region, i.e., within the soil and atmosphere (Figure 6.1). Finally, we expect that in arid regions we can enhance the initial availability of water with a simple water technology that enhances seawater evaporation (Figure 6.1).

6.3.3 Inputs

The NWP program integrates various types of expertise in three main research foci (Box 6.1). These research foci are, first, develop a seawater evaporation technology to kick-start the water cycle by conducting experiments in the Wetsus laboratory. Second, identify meteorological pathways for more rainfall in arid regions using a modelling approach. Third, identify what regions and types of landscapes show potential to restore the local water cycle using a modelling and data analysis approach. Within this research program, ECSs with experience in ecohydrology, meteorology and mechanical engineering are collaborating to work on these objectives. These ECSs are supervised by senior researchers from different knowledge institutes (Figure 6.3). We bridge different disciplines by

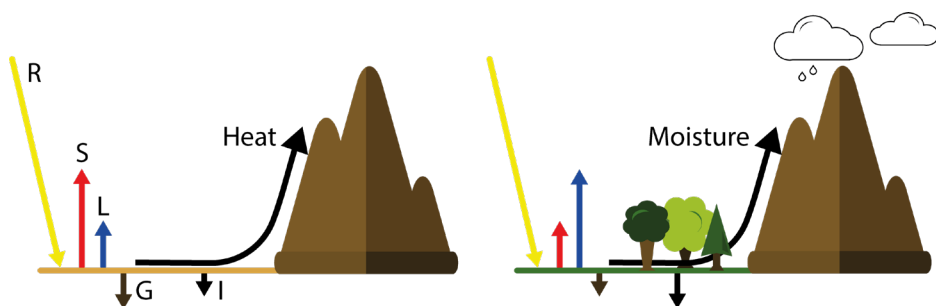


Figure 6.2 The assumed mechanism underlying local rainfall enhancement through greening in arid and semi-arid regions. Incoming solar radiation (R) is transferred into the sensible heat flux (S), latent heat flux (L) and ground heat flux (G). The sensible heat flux warms up the atmosphere directly from the surface, the latent heat flux is related to evaporation and the ground heat flux warms up the soil. In a degraded landscape little soil moisture is available due to limited infiltration (I). As a result, little of the incoming radiation is used for evaporation (L) and more is used to warm up the atmosphere (S), resulting in warm and dry conditions unfavourable for rainfall. In a restored landscape, rainfall can infiltrate into the soil and vegetation roots can access water in deep soil layers. Compared to the degraded landscape, more energy will be used for evaporation (L) and less energy will be used to warm up the atmosphere (S). This results in more humid and cooler conditions compared to the conditions for the degraded landscapes. When this cooler and moister air is pushed up a mountain this promotes condensation, the formation of clouds, and rainfall.

connecting these knowledge institutes within the NWP program, which promotes new collaborations and fosters creativity (Moirano et al. 2020).

In addition to working in an interdisciplinary team, the close collaboration with different companies (Figure 6.3), illustrates a transdisciplinary research approach. The company partners, The Weather Makers and DEME, partly fund the conducted research. The remaining funding comes from various organizations (Figure 6.3). The company partners have experience in designing large scale environmental engineering projects. Hence, they bring experience from “real-life” challenges which helps to ensure innovation and transformation (Wagner-Ahlfs 2022). Knowledge sharing among the different participants in the NWP research program is established through at least three meetings throughout the year. In these meetings the ECSs share their research progress and the university and company partners reflect on this progress and feed the discussion drawing from their expertise and practical experience. In addition, these meetings are used to discuss the research agenda of the theme, making sure that the future research activities align with the current and foreseen future challenges. Our partners have partnerships with other companies and organizations outside the NWP research program possibly enhancing the impact of the NWP research program.

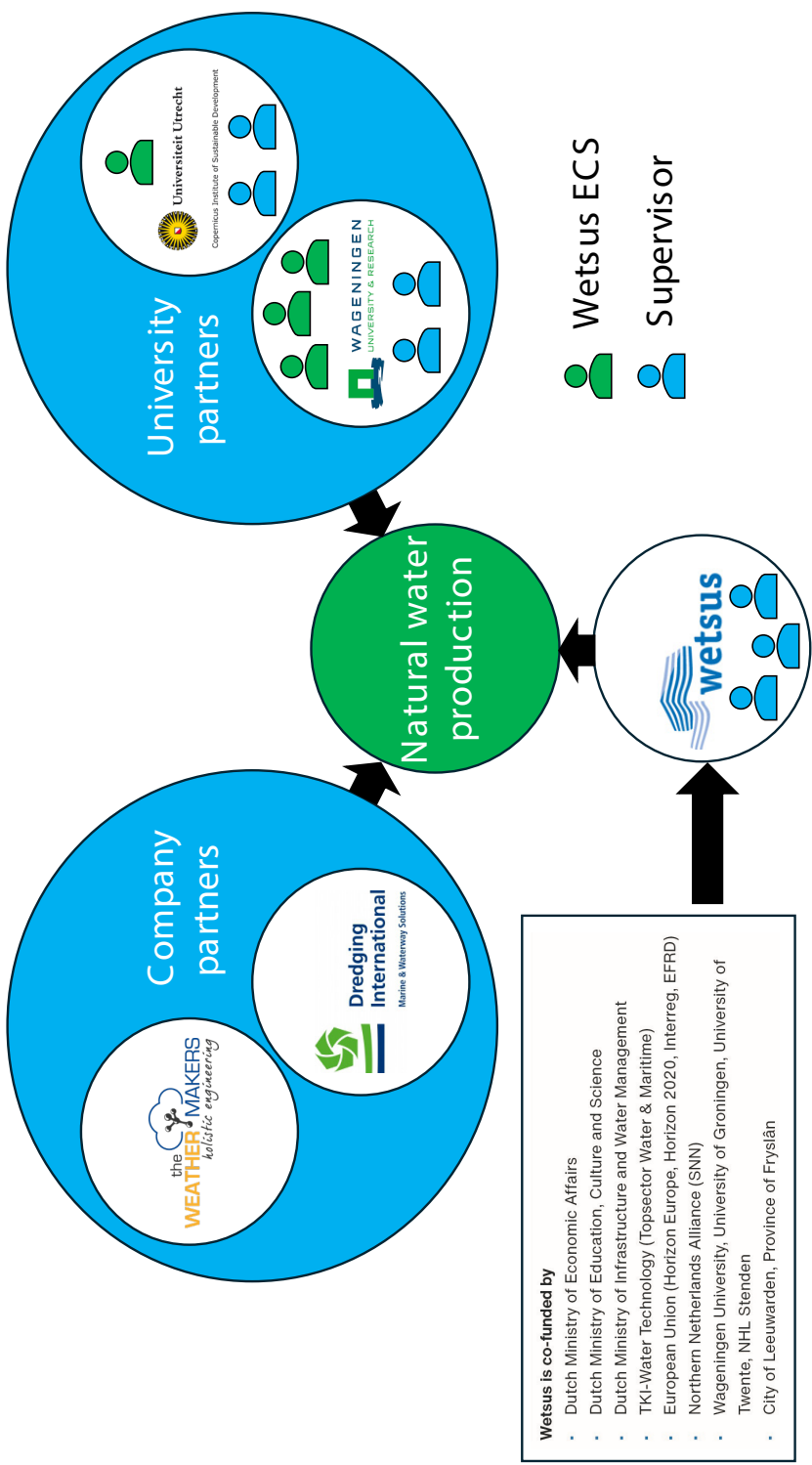


Figure 6.3 Schematic overview of the inputs of the natural water production research program at Wetsus.

6.3.4 From research outputs to outcomes

6.3.4.1 Identifying hydrological benefits of greening and creating awareness of these benefits

To enhance rainfall through greening we need to understand the hydrological impacts of greening projects. We need to understand under what conditions greening can have a positive impact on rainfall, reduce drying, and when it may contribute to local drying. To do so we need to quantify the hydrological impact of such a land cover change. Furthermore, it is important to create awareness among scientists and stakeholders of these potential hydrological benefits of greening. This might promote the amount of research that is being done on the hydrological benefits of greening.

So far we generated several datasets (Tuinenburg et al. 2020a; Theeuwes et al. 2023b; Theeuwes et al. 2024a) that describe the return of evaporated water as rainfall (Box 6.3), which is a crucial aspect of the hydrological cycle. The first dataset describes where evaporated water rains out. This dataset includes global atmospheric moisture connections between evaporation source and precipitation sink. The other datasets describe the return of evaporated water as precipitation within a distance of 50km from its source (local moisture recycling) or within the climate region (regional recycling). These datasets can be used to quantify the contribution of vegetation to precipitation or to gain insight into the hydrological effects of greening. However, these data are not yet sufficient to quantify the total hydrological impact of greening projects. These data have been presented to the scientific community through scientific articles and presentations. The presentations allowed us to communicate the potential hydrological benefits of greening to a wide range of geoscientists and water technologists.

The dataset including the global atmospheric moisture connections has been used by various researchers and knowledge institutes to study the relation between land cover, for example, vegetation, and precipitation (e.g., Fahländer et al., 2024; Li et al., 2023; Posada-Marín et al., 2024). These research activities are not part of the NWP research program, and thus show that there is awareness of the crucial role of vegetation in generating rainfall. In addition, they can contribute to creating awareness, and therefore, extend our impact. This dataset also helped us to set up new collaborations. On top of that these collaborations help to create awareness of the potential hydrological benefits of greening, they also help to promote the NWP research program among the geoscience community and to gain more credibility as a water technology institute in the field of geosciences.

Box 6.3: Outputs of research activities

Datasets

- Global evaporation to precipitation flows obtained with Lagrangian atmospheric moisture tracking
- Local moisture recycling across the globe
- Atmospheric moisture recycling in Mediterranean-type climate regions across the world

3 peer-reviewed scientific publications directly linked to this thesis.

- Local moisture recycling across the globe
- Targeted rainfall enhancement as an objective of forestation
- Ecohydrological variables underlie local moisture recycling in Mediterranean-type climates

3 peer-reviewed scientific publications as co-author indirectly linked to this thesis

- High-resolution global atmospheric moisture connections from evaporation to precipitation
- Comparing deuterium excess to large-scale precipitation recycling models in the tropics
- Shifts in regional water availability due to global tree restoration

Scientific presentations

- Moisture recycling in five different regions with Mediterranean climates around the world (EGU21)
- Enhancing the local water cycle in Mediterranean areas – the role of satellite data in greening (Wetsus congress 2021)
- Using local moisture recycling to assess the impact of greening on the local water cycle in five Mediterranean regions (EGU22)
- Atmospheric moisture recycling as a key to successful greening (EWTW 2022)
- Local moisture recycling across the globe (EGU23)
- Where to regreen in Mediterranean-type climate regions (poster, Wetsus congress 2023)

The data illustrate the potential hydrological benefits of vegetation as vegetation seems to promote atmospheric moisture recycling and therefore, rainfall. However, these data also show that in some regions there is very little moisture recycling, meaning that evaporated water will not return as rainfall locally or over land, contributing to drying. To maximize hydrological benefits through greening, we need to better understand under what conditions greening contributes to more rainfall and not to drying. We need to be transparent about both the benefits and drawbacks in our outreach activities.

6.3.4.2 Quantifying the hydrological benefits of regreening

To realize large-scale restoration projects investors are needed. Additionally, landowners might need financial motivation to restore their lands. Therefore, it is important to valorise regreening projects. It would be interesting to introduce “hydrocredits” that reflect the hydrological benefits of regreening to valorise such projects. “Hydrocredits” can be analogous to carbon credits but focused on incentivizing hydrological benefits through regreening. In order to do so we need to valorise the hydrological benefits of regreening. This could include the role of vegetation in mitigating droughts or floods as well as rainfall generation. To valorise regreening projects we need to quantify the impact that vegetation can have on the hydrological cycle.

As described in the previous subsection, the NWP program created datasets that can be used to determine the contribution of vegetation to rainfall. These data give insight into the hydrological impacts of regreening. However, these data are not sufficient to quantify the changes in rainfall due to regreening as they were generated using historical weather data and land use. To fully understand the impact of regreening in a future climate we need to calculate such data for future climate and land-use scenarios, i.e., actually model a land-use change. In our current and future research activities, we model the impact of a change in land cover on the underlying dynamics of rainfall.

To get a complete understanding of the hydrological benefits of regreening we also need to understand the impact of regreening on soil characteristics, infiltration, groundwater flow, runoff, hydrological extremes, and more (e.g., Colloff et al., 2010; Liang et al., 2015; Meaza et al., 2022; van Meerveld et al., 2021). Currently, we do not have sufficient experience within our research team to research all relevant processes to quantify the hydrological impact of regreening. Future collaborations with researchers from different knowledge institutes could fill this expertise gap in our research team.

6.3.4.3 Pilot of the evaporation technology

The local moisture recycling data suggested that it is more likely we may enhance local rainfall with regreening in regions where rainfall is already present. This is relevant information for our company partners as their main goal is to regreen the Sinai desert, which is an arid region with limited freshwater available. Our outputs suggest that to regreen this desert we need to first make it rain. As described in the assumptions, we expect that we can initiate rainfall using water technology. Currently two PhD candidates within the NWP program are investigating if enhanced seawater evaporation using technology, can initiate rainfall. One PhD candidate aims to identify what atmospheric conditions enable the initiation of

rainfall using water technology, and the second PhD aims at developing such an evaporation technology on lab scale.

We are currently finalizing a proof of concept, i.e., that enhanced seawater evaporation can initiate rainfall, for the region of Valencia in Spain. Our results seem to indicate that it is indeed possible to enhance rainfall using water technology. However, it is unclear if these technologies could also trigger rainfall in more arid regions. This will be explored in future research. For now, this research line has high priority, as we expect that the technology will be a crucial element to restore water cycles in arid regions.

6.3.4.4 Reduce societal resistance towards this specific form of geoengineering

Regreening initiatives may have several drawbacks that could cause societal resistance and prevent those initiatives to be realized. Two main examples are (1) the competition for land use (de Jong et al. 2021), and (2) that regreening may be considered geoengineering as it can alter the climate (Zhang et al. 2015b; Cheng et al. 2017). Regarding the first example, a common competitor for regreening initiatives is agricultural land. However, water availability and soil fertility could benefit from regreening initiatives when the land is shared (Octavia et al. 2023). Regarding the second example, geoengineering is a concept that, in general, laypeople are not familiar with. Therefore, the framing of such technologies strongly affects the public opinion (Raimi 2021). When geoengineering concepts are framed negatively, it can lead to societal resistance. However, the general lack of public familiarity with geoengineering presents an opportunity to foster acceptance through clear, transparent and understandable communication of sustainable solutions and their benefits to a wider audience.

So far, several outreach activities have been conducted by the ECSs in the NWP program. These activities include but are not limited to various presentations to a general public, water professionals and government stakeholders, and guest lectures in the master programs Sustainable Development (Utrecht University) and Water Technology (Wetsus). A complete list of outreach activities is provided in Box 6.4. In these outreach activities the concept of regreening and its hydrological effects are clearly explained. These activities contribute to the understanding of the relationship between regreening initiatives and the climate and the value of forest as land-use type.

Feedback from the different audiences often includes two main points. First, people are interested in how they can personally contribute. For example, they are interested in the positive hydrological benefits of regreening their garden. Second, they are interested in the negative effects of regreening and how we can account for those. For example, people are worried about the “stealing” of water. Making it rain in a specific location, might affect rainfall downwind, possibly having negative effects on

Box 6.4: Outreach activities done by an ECS in the NWP program as part of a PhD trajectory.

Articles in newspapers and magazines, and blogs

- Zelf zorgen voor meer regen is niet zo moeilijk – H2O waternetwerk
- Luchtdeeltjes gevormd door planten maken wolken lichter – New scientist
- Van gortdroog naar weelderig groen. Bestaat er een truc? Jolanda uit Leeuwarden won er een prestigieuze prijs mee – Leeuwarder Courant
- Onderzoek Wetsus: Wolkenfabriek en bossen kunnen woestijn vergroenen – H2O waternetwerk
- Wolkenfabriek zorgt voor weelderige woestijn – Land en Water
- Wolkenfabriek om woestijnen te vergroenen? Volgens onderzoekers uit Leeuwarden kan dat – Leeuwarder Courant
- Ecosysteemherstel door herbebossen lukt niet altijd. In de Sinaï mogelijk wel – H2O waternetwerk
- Moisture recycling as a key for successful greening – the Water Channel

Presentations, lectures and stakeholder meetings

- Presentation for Cameroonian Embassy: Natural water production using greening
- Invited expert on 'de kleine waterkringloop' - Rijksdienst voor Ondernemend Nederland and Province of Limburg
- Documentary: Ons dagelijks water – Marcel Prins
- Presentation for general public: Wolkenfabrieken: De sleutel tot een weelderige woestijn – Winter Watertech Weken organized by Wetsus
- Presentation for 400+ water technologists on the importance of atmospheric moisture recycling for successful greening
- Presentations for company and university partners in the NWP theme
- Discussions with various organizations involved in greening initiatives
- Guest lectures in several master courses at different institutes

water availability there. Therefore, to minimize societal resistance, we need to better understand this concept of “stealing” and communicate this to stakeholders and the general public. Nonetheless, the first discussion point highlights people’s willingness to address water scarcity issues themselves and their positive attitude toward using vegetation as a solution.

6.3.4.5 Collaborations with governments, companies and other stakeholders to realize greening

To successfully implement restoration programs that enhance rainfall, it is crucial to integrate political, economic, social, and scientific knowledge (Sapkota et al. 2018). To start greening for natural water production, there is a need for guiding norms and principles that can be provided by policy (Sapkota et al. 2018). Furthermore,

continuous and long-term funding is crucial to realize restoration goals (Iftekhar et al. 2017). Partnerships with governments and companies can be useful to obtain funding for long-term projects (Iftekhar et al. 2017). Additionally, collaborations with local communities help to ensure socio-economic benefits for the community. Therefore, to realize successful regreening initiatives scientists need to cooperate with governments, companies and other stakeholders.

Within the NWP research program we meet our company partners at least three times a year to foster collaboration. In addition, we attended several meetings with governmental organizations to discuss the hydrological effects of regreening. For example, we were invited to partake in the expert committee of the Netherlands Enterprise Agency to discuss what research steps are needed to design regional policy regarding land use for a sustainable local water cycle (Box 6.4). These meetings were focussed on the province of Limburg which is a small region within the Netherlands where regreening likely solely has a local impact due to the limited scale of the potential regreening initiatives here. Finally, various scientific publications have been cited in, mostly European, policy documents (<https://policyprofiles.sagepub.com>). These policy documents are related to climate risks, the global water challenge, and nature conservation. Beyond our own activities, our company partners are also actively reaching out to international governments to set-up regreening projects that aim to restore the water cycle.

It has been proven difficult to find new companies or governmental organizations that are interested in regreening to join our research program. This has either been because of lack of financial means for small companies and organizations, or the wider focus of our research, i.e., we do not focus on one specific study region, which is desired by local governments. However, in a later stage of our research, collaborations with stakeholders will be beneficial for knowledge implementation. Collaborations with governmental organizations can help to design policy and collaborations with companies are beneficial for monitoring regreening projects. In other research programs at Wetsus, finding new company partners appears to be less difficult, which could be because these programs focus on developing and improving technologies that companies can directly implement. In the NWP program we are developing an evaporation technology that may be of interest to companies, and therefore we should focus on this when setting up new partnerships.

6.4 Discussion

6.4.1 *Impact progress evaluation*

We made progress on four out of the five outcomes we defined in the impact pathway: (1) awareness of the positive hydrological impact of regreening amongst

scientist and stakeholders, (2) quantifying hydrological benefits of regreening to valorise regreening, (3) public acceptance for addressing water scarcity issues with regreening, and (4) collaborating with stakeholders. Various outreach activities to different stakeholders mainly contributed to outcomes (1) and (3), the scientific research outputs mainly contributed to outcome (2) and both the outreach activities and scientific outputs contributed to outcome (4). As we did not finalize the outcomes yet, more research and outreach activities are needed in the future. The contribution of the different activities to the outcomes highlights the importance of both scientific progress as well as science communication to achieve our intended impact.

The research progress stayed within the boundaries of our team's expertise (i.e., geosciences and water technology). However, to reach the intended impact, it is crucial to make progress in the field of economics and social sciences as well. It is unclear to what extent Wetsus could contribute to such scientific progress as its main expertise is in the field of water technology and natural sciences. Therefore, it is crucial to set up collaborations with researchers and stakeholders that are experienced in this field. Our theory of change helped us to identify opportunities for such collaborations. In addition, these collaborations will likely have an effect on our theory of change as they will provide us with new insights into the problem, which will likely help us to identify new challenges. Our company partners could guide us in setting up new collaborations as they already successfully collaborate with scientists in the field of social and political sciences.

Finally, we identified that we assume that we can collaborate with relevant partners to realize restoration projects globally, which we did not include in our theory of change on forehand. However, setting up such collaborations can be difficult due to limited financial means, and/or focussed area of interest of small companies, local communities, and local governments. We could collaborate with these "smaller" stakeholders through for example European projects. To arrange long-term financial support we need to collaborate with larger companies.

6.4.1.1 Future research projects needed to achieve intended impact

We identified several important topics to study in more detail in the (near) future. First, we find that multiple outcomes (see Figure 6.1) depend on the quantification of the hydrological impact of regreening. Therefore, we first need to further develop the tools that can estimate the net hydrological impact of regreening. Such tools may be the foundation of the valorisation of regreening initiatives. For example, they may help to design "hydrocredits", and quantify rainfall production as an ecosystem service (Keys et al. 2016). Second, the outputs we generated show the important role of water technology to kick-start the water cycle. Therefore, it is important we develop a sustainable evaporation technology and test it on a pilot scale. Third, we

identified some social challenges that we need to focus on. To minimize conflict it is important to develop water and land-use governance. Laws and policy may help to minimize the negative hydrological impacts of greening and the “stealing” of water as well as it may prevent conflict related to land-use competition.

6.4.2 A transdisciplinary research approach to achieve impact

As expected, Wetsus could set up a new research line that bridges the fields of water technology and geosciences by involving experts from different universities and companies within one research program. However, this was more complicated than was anticipated at the start. For example, it was difficult to find an experienced geoscientist to join the research team at Wetsus as Wetsus had no recognition among geoscientists. In the past years, Wetsus built recognition by collaborating with different well-established researchers in the field of ecohydrology and meteorology and through outreach activities.

This impact evaluation shows that working in a transdisciplinary team enhances the impact of research activities as acknowledged by previous research programs (e.g., Lawrence et al., 2022; Pineo et al., 2021). Our company partners showed us that, first, scientific insights do not necessarily reach outside the academic community as previously established knowledge had gone unnoticed by our partners despite their relevance to the valorisation of their projects. Our transdisciplinary research approach makes the science communication more effective and ensures that scientific outputs reach the desired audience. We can improve this further by making our outputs more easily applicable. Second, our partners incorporated the insight they gained from our collaboration in their own projects and communicated it to their networks, extending the impact of our research activities resulting in a scaling effect.

Our company partners also benefit from the transdisciplinary research approach. The collaboration with universities helps our partners to convince and inspire other stakeholders about the crucial role of vegetation in water cycle restoration. This collaboration provides scientific foundation to the holistic vision of the companies and the importance of nature for a healthy climate and water availability. It enhances the credibility of the company partners, which has proven to be helpful in finding investors and starting new partnerships. These benefits were expected as it has been previously shown that the collaboration between stakeholders and scientists helps with capacity building (Cooke 2005; Eade 2007). Capacity building is the process of developing and strengthening the skills, resources, abilities, and structures within companies and organizations that are necessary to achieve goals effectively and sustainably (Cooke 2005; Eade 2007).

Research activities also benefit from the transdisciplinary approach. Within the NWP research team a wide variety of expertise is brought together, which, as expected (Moirano et al. 2020), promotes creativity. Combining the knowledge of engineers and meteorologists already resulted in an important and innovative finding in the field of heat localized solar evaporation. A key aspect of the energy balance was missing resulting in an offset in the evaporation efficiency of solar evaporators. The meteorologists in our team were able to fill this gap. Creativity is further stimulated by the mission driven mindset and practical experience of our company partners. During meetings, the company partners challenge the researchers to make their output applicable by asking very practical questions that are not common for an ECS. Due to the clear focus of an ECS on creating scientific impact, it can sometimes be challenging to navigate the balance between generating scientific impact and producing outputs that are relevant to stakeholders. To address this, societal impact should also be acknowledged and considered valuable in the development of an ECS. However, for an ECS to grow as an independent researcher, it is crucial that they generate sufficient scientific impact. Consequently, it may not always be possible to prioritize ideas proposed by companies. Supervisors of an ECS should play a key role in helping to find the right balance between generating societal and scientific impact.

The public outreach activities also benefit from the transdisciplinary research approach. The Sinai project provides context to our research activities and appeals to many people. We use this project to illustrate the goal of the NWP research program, draw focus to our research, and underline the relevance of our outputs. This project helps to design an engaging storyline for outreach activities as the idea of restoring a desert can capture ones imagination well. It helps us to create an attractive storyline that can make our message more meaningful (ElShafie 2018).

In the future, it is expected that our partnerships will have an important role as well. Once we develop the evaporation technology on pilot scale, our partners may facilitate field tests for this technology. In the process of scaling up the technology from lab scale to pilot scale, we can also draw practical experience from our partners. Once the pilot is successful, we can easily transfer the activities to our partners and they can continue to scale up the technology further. Due to the constant transfer of knowledge, which started at the beginning of our collaboration, we expect that our partners will be able to scale up and implement the technology effectively.

6.4.3 An ECS in a transdisciplinary team

6.4.3.1 Personal development of an ECS in a transdisciplinary team

A transdisciplinary approach as implemented by the NWP program enhances the personal development of an ECS in various ways, though it also has some limitations. Interacting with companies and stakeholders helps ECSs develop communication

skills, gain motivation by better understanding their work's relevance, and learn from related disciplines. For example, in the NWP program geoscientists learn about traditional water technology. Developing clear communication skills is essential for successful collaboration due to the diverse backgrounds within the team. However, the broad scope can limit deep specialization, making it challenging for ECSs to identify strongly with a specific discipline (van der Leeuw 2020). Limited technical support within the team may also require ECSs to seek external expertise. However an ECS can also benefit from this as it further supports their personal development.

Being part of an interdisciplinary research team and engaging in outreach can greatly benefit an ECS's research. Presenting research to diverse audiences encourages ECSs to clarify the storyline of their research, get creative when linking their research relevance to the public's interests, and to simplify complex aspects of their work, which deepens their own understanding. Feedback from general audiences or stakeholders can stimulate ECSs to look at their research from new perspectives and consider adjustments to enhance its impact. The latter may encourage an ECS to work on practical applications or make their work easily accessible, understandable and directly applicable for non-experts, as complex data and models, while available, are often too intricate for public use despite the willingness of non-experts to use them.

Whether it is possible for an ECS to work in a transdisciplinary team and engage in outreach depends largely on their research environment, shaped by the research institute, department, colleagues, and supervisors. In this case study, Wetsus fosters collaboration by structuring regular meetings with company partners and supporting public outreach. Research institutions can further enhance impact by promoting interdepartmental collaboration and offering training in science communication, stakeholder engagement, or business case development. However, such activities require time, making it essential for institutions to adjust expectations for traditional research outputs, potentially through supportive university policies (Stokols et al. 2008). Personal motivation also plays a crucial role in an ECS's engagement in public outreach.

6.4.3.2 Contribution of an ECS to a transdisciplinary research team

For companies it is beneficial to collaborate with scientists. However, whether it is more beneficial to collaborate with ECSs or senior researchers is more ambiguous. For ECSs, creating scientific impact is essential, as metrics like publication count and number of citations are often key to academic evaluations, hiring, and grant applications. PhD candidates, in particular, may need a set number of publications to graduate. Universities and research institutes could adjust their policies to encourage ECSs to participate in transdisciplinary research, which may broaden their impact beyond traditional metrics (Stokols et al. 2008).

Including ECSs in a transdisciplinary research team also offers several advantages. First, PhD projects typically span multiple years, allowing ECSs to have a longer-term commitment to a research project compared to post-docs, who often have shorter contracts. Second, unlike senior researchers, ECSs generally have fewer responsibilities outside their own project, which makes them more flexible in managing their time. Lastly, ECSs have the potential to shape the future of their research field, and early exposure to transdisciplinary work may encourage a broader implementation of this approach within the research community (Bankston et al. 2020).

6.5 Conclusions

A transdisciplinary research approach is necessary to solve big societal challenges such as water scarcity. Here we evaluated the impact that was generated by the transdisciplinary research program “natural water production” at the water technology research institute Wetsus. For this specific case study, the transdisciplinary approach seems to improve the effectiveness of science communication. We found that open science alone does not necessarily contribute to the intended impact. Scientific outputs need to be easily accessible, understandable and applicable for stakeholders. Collaborations between scientists and stakeholders can ensure that research outputs are directly applied and further developed, and therefore, may bridge the gap between scientific outputs and practical application. To achieve the intended impact a research program needs to evaluate their progress by determining the outcomes for each of their activities together with their partners. Collaboration across disciplines and with partners outside of academia helps to create impact more effectively.

We found that in a transdisciplinary research team all partners that are involved can benefit from the transdisciplinary approach. For example, the personal development of an ECS can benefit from an interdisciplinary research approach. However, this approach also has its disadvantages, i.e., it may be more difficult to specialize in one specific discipline due to limited time availability. The research environment of an ECS has an important role in stimulating an ECS to do public outreach and generate societal impact and the expectation to create scientific impact may limit an ECS to generate societal impact. Universities can support ECSs to further stimulate the general shift in science towards focusing more on societal impacts.





General discussion

Chapter 7 | General discussion

7.1 Conclusions

This thesis aims to understand how regreening can contribute to local rainfall enhancement. Specifically, I study where it could be possible to enhance local rainfall in Mediterranean-type climate regions. To study this aim, five research objectives were formulated. Here I discuss the main findings for each of these objectives.

1. *Quantify local moisture recycling for Mediterranean-type climate regions globally.*

On average, 1%-2% of evaporated water returns as precipitation within ca. 50km from its source and 1%-2% of precipitation originates within ca. 50km from where it falls down. Both local evaporation and precipitation recycling vary in space and time with peaks up to more than 5% for local evaporation recycling and more than 15% for local precipitation recycling during summer in the Mediterranean Basin.

2. *Assess which atmospheric and land surface characteristics link to local moisture recycling in Mediterranean-type climate regions globally.*

Local evaporation and precipitation recycling both peak over mountainous regions due to the orographic lift promoting condensation. Furthermore, both local evaporation and precipitation recycling correlate with precipitation, vapor pressure deficit, and evaporation of intercepted precipitation in most of the Mediterranean-type climate regions. Hence, the results suggest that vegetation and atmospheric humidity, which is related to soil moisture and distance to the coast, trigger the local return of evaporated water as precipitation. Although local evaporation recycling correlates positively with precipitation, local precipitation recycling correlates negatively with precipitation due to the contribution of external moisture during precipitation events.

3. *Determine the impact of forestation on the development of the atmospheric boundary layer and deep convective clouds in the Mediterranean Basin.*

The impact of forestation on the development of the atmospheric boundary layer seems to vary with soil moisture. With an increase in forest cover the net radiation increases due to the darkening of the land surface. Over relatively dry regions, forestation increases the sensible heat flux, contributing to warming and drying of the boundary layer. Over relatively wet regions, the latent heat flux increases contributing to cooling and wetting. Convective clouds seem to be more likely to develop over the relatively wet regions as a result of forestation.

4. *Discuss how targeted rainfall enhancement can be an objective of forestation globally.*

A considerable amount of recent studies show that potential forestation has significant and relevant effects on precipitation. It seems that forestation may have an opposing effect on drying caused by climate change. Furthermore, state-of-the-art tools and knowledge, which are improving in quality, allow to consider targeted rainfall enhancement as an objective for forestation.

5. *Evaluate the societal impact of the research conducted for this thesis.*

The transdisciplinary research approach for this thesis proved to be beneficial as it improved the effectiveness of science communication, and therefore, the practical implementation of the scientific output. Some of the knowledge that is acquired in this thesis is directly applied by the stakeholders in the valorisation of their projects.

In summary, in Mediterranean-type climate regions, greening may enhance local precipitation over mountainous regions, and relatively wet or coastal areas. Out of the five major Mediterranean-type climate regions, greening is expected to most likely contribute to more local and regional precipitation in the Mediterranean Basin due to relatively high local and regional recycling ratios. The outcomes of this thesis suggest that local rainfall enhancement may be possible in regions where condensation can be triggered due to a small increase in atmospheric humidity or a strong updraft of air. This chapter discusses how the research activities and outputs related to this thesis could contribute to the strategic planning of greening initiatives that may enhance local rainfall.

7.2 An engineering approach to enhance rainfall with greening

Globally, greening initiatives are realized with the aim to mitigate climate change. However, the net hydrological effects of such initiatives remain unclear. Whereas an increase in vegetation could contribute to drying due to evaporation losses, it may also increase precipitation and enhance freshwater availability. The available state-of-the-art models, datasets and knowledge that allow to consider hydrological effects in the planning of greening projects could be used to develop an engineering-based greening strategy (Figure 7.1). This engineering approach could be used to determine where greening initiatives may contribute to local rainfall enhancement and where they may have harmful hydrological effects. I believe that this engineering approach could be applied by stakeholders in the planning of greening initiatives to optimize hydrological benefits. The different methods in this thesis could be seen as different steps in this engineering approach, with each step narrowing down where greening may have hydrological benefits and where it contributes to drying (Figure 7.1). However, this approach needs to be optimized before it can be applied in a decision making process.

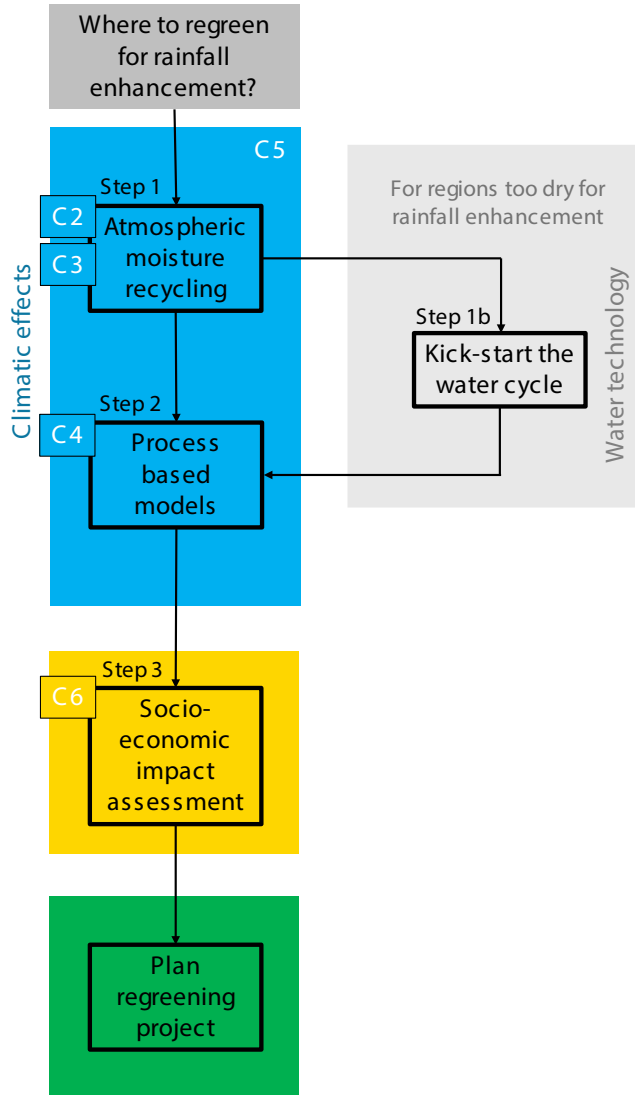


Figure 7.1. Schematic overview of the engineering approach as discussed in this chapter. This approach could be applied to identify a location where regreening may contribute to rainfall enhancement without having an harmful impact. For regions with hydrological benefits a socio-economic impact assessment needs to be conducted. When the benefits outweigh the costs a regreening project can be realized. The results from Chapters 2 and 3 are included in Step 1, and the results from Chapter 4 are included in Step 2. Chapter 5 discusses the potential of applying various methods to study hydrological effects of regreening. Finally, step 3 is based on the findings from Chapter 6.

Here, I explain each of the steps in this engineering approach and discuss how these steps could be optimized. Furthermore, I also propose two additional steps that were not included in this thesis: (1) kick-starting the water cycle with water technology in arid regions, and (2) an assessment of the socio-economic benefits of a greening project. Finally, I discuss how I believe it is possible to realize the implementation of such an engineering approach.

7.2.1 Step 1: Identifying regions where vegetation may enhance rainfall

Atmospheric moisture connections can be used to identify where evaporation contributes to rainfall locally (Chapters 2 & 3). This information helps to select a region that shows potential to enhance local rainfall through greening. Despite that the local evaporation and precipitation recycling ratios are small across the Mediterranean-type climate regions (Chapters 2 & 3), together they can provide valuable information. When local evaporation recycling is high, a large fraction of evaporation returns as rainfall locally. If such a high local evaporation recycling ratio is combined with a low precipitation recycling ratio, the local evaporation that returns as rainfall locally is only a small fraction of the total precipitation in this location, and therefore, an increase in evapotranspiration is not expected to contribute to drying. Hence, the ratio between the local evaporation recycling ratio and local precipitation recycling ratio gives an indication of whether an increase in evaporation due to enhanced vegetation cover could contribute to drying. A higher local evaporation recycling ratio than local precipitation recycling ratio implies that evaporation is smaller than precipitation. Naturally, a relatively high local evaporation recycling ratio and low precipitation recycling ratio may be found in mountainous, coastal regions. Here the ocean is an important moisture source and the mountains promote the local return of evaporated water due to the orographic lift. Furthermore, as the local evaporation recycling ratio correlates positively with rainfall, and the local precipitation recycling ratio correlates negatively with rainfall (Chapter 3), greening is expected to contribute to wetting in relatively wet regions.

This first step, using atmospheric moisture connections, has low computational costs and is relatively simple as the necessary data are freely available (Link et al. 2020; Tuinenburg et al. 2020b). Therefore, there is no need to do complex model simulations and this step can be conducted on large spatial and temporal scales, to identify patterns in local moisture recycling. This makes it a suitable tool to make a first estimate of where it may be possible to enhance rainfall with greening. In the second step, more costly methods can be used to investigate specific regions in more detail.

7.2.1.1 Outcomes of Step 1 in this thesis

The outcomes of this thesis suggest that it is rather difficult for evapotranspiration to recycle locally in arid regions. However, local recycling of evaporated water

is higher in arid regions with orographic features, suggesting that mountains should have a key role in regreening initiatives, meaning regreening should be conducted upwind from mountains. Furthermore, local evaporation recycling is higher in Mediterranean-type climate regions on the Northern Hemisphere than on the Southern Hemisphere as south-west Australia and the Cape region of South Africa are both very dry, limiting local evaporation recycling (Chapter 3). For Central Chile, local moisture recycling seems to be mostly affected by non-ecohydrological variables, this may indicate that regreening has little effect on the local recycling ratio and has little potential to strengthen the water cycle (Chapter 3). These outcomes suggest that regreening initiatives in Mediterranean-type climate regions on the Northern Hemisphere would more likely contribute to rainfall enhancement than on the Southern Hemisphere. Specifically the Mediterranean Basin shows potential for local rainfall enhancement, likely due to its complex topography. For this reason, Chapter 4 focuses on forestation in the Mediterranean Basin.

7.2.1.2 *Extending Step 1*

To maximize the hydrological benefits of regreening it is important to also explore the non-local effects as regreening could affect the water availability downwind (Ellison et al. 2012). For example, forestation may enhance rainfall in regions that are prone to drying (Hoek van Dijke et al. 2022; Tuinenburg et al. 2022). To investigate where regreening may enhance precipitation downwind (Chapter 5), the approach that was applied in Chapters 2 and 3 of this thesis can be extended by analysing regional and terrestrial moisture recycling. As regional and terrestrial recycling peak over orographic features (Van der Ent and Savenije 2011; Staal et al. 2018; Tuinenburg et al. 2020b), it is expected that regreening initiatives upwind from mountainous regions contribute to non-local hydrological benefits. Furthermore, if the aim of a regreening project is to enhance rainfall in a downwind region that is prone to drying, the precipitationshed of this region can be consulted to identify its moisture sources (Keys et al. 2014).

Despite that regional and terrestrial moisture recycling provide additional insights, local moisture recycling should not be overlooked. Only at a local scale moisture recycling can be used to assess whether regreening contributes to local drying. Furthermore, it is important to note that a contribution to precipitation downwind does not necessarily translate in drying locally and vice versa. Water may contribute to rainfall and reevaporate multiple times before it rains out over the ocean (Zemp et al. 2014a).

7.2.1.3 *Uncertainty of atmospheric moisture recycling*

A drawback of this first step is that it is challenging to validate the output of moisture-tracking models, resulting in uncertainty. Chapter 2 addresses the

uncertainty of local evaporation recycling ratios. While the spatial patterns of local evaporation recycling show little variability between two different models, the exact values demonstrate notable differences. The variability among models is in line with previous research. Different model set-ups can result in different outputs (Goessling and Reick 2013; Tuinenburg and Staal 2020; Cloux et al. 2021) and variations in model settings can further contribute to inconsistencies (Tuinenburg and Staal 2020). This uncertainty can be addressed by a systematic comparison of various models (Benedict et al. 2024).

To quantify the error of moisture-tracking models, data for validation is crucial. In addition to using models, moisture recycling can be calculated using isotopic measurements (e.g., Froehlich et al., 2008). A recent research effort compared precipitation recycling from various recycling models with deuterium excess (d-excess) in water, which is sensitive to atmospheric moisture recycling (Cropper et al. 2021). There is agreement between precipitation recycling models and measured d-excess. However, it is not yet possible to use this data for model validation (Cropper et al. 2021). Furthermore, isotopic measurements are sparse, with most measurement stations in the Northern Hemisphere, specifically in Europe (West et al. 2010; Pfahl and Sodemann 2014). More isotope data needs to be available to use d-excess to validate moisture recycling ratios obtained from moisture-tracking models (Cropper et al. 2021).

Although moisture recycling has some inevitable uncertainty, it is still possible to use this data to make a first estimate of where regreening may contribute to rainfall enhancement. It offers a cheap opportunity to start with a broad area and pinpoint specific regions where regreening could potentially increase rainfall. However, it is important that an additional step follows in which the hydrological effects of regreening are simulated in more detail to prevent drying. Nevertheless, moisture recycling data can still hold significant value for various stakeholders. It offers scientific foundation for the potential hydrological benefits of their projects, which is valuable to secure funding (Chapter 6). I believe that it is important for the scientific moisture recycling community to engage in discussions about the extent to which the data can already be applied, or identify the steps that are needed to make them directly applicable to stakeholders.

7.2.2 Step 1b: Kick-starting the water cycle in arid regions

This thesis suggests that arid regions are currently too dry to enhance rainfall through regreening due to the low recycling ratios. Here, it may be possible to kick-start the water cycle using water technology to enable irrigation (e.g., Caldera & Breyer, 2023; Zampieri et al., 2024). Once there is sufficient rain and vegetation can develop here, the vegetation may further strengthen the water cycle as it

positively correlates to local moisture recycling in Mediterranean-type climate regions (Chapter 3).

Such a technological solution has been proposed for the Los Angeles Basin, a coastal region in California, where wastewater could be used to irrigate forests, which may induce moisture recycling (Layton and Ellison 2016). The irrigated forest is expected to contribute to precipitation downwind, where the increased water availability fosters the development of new forests (Layton and Ellison 2016). This proposal highlights the role of the orographic features of the LA Basin in returning the evapotranspiration within the region, overlapping with the results that were found in this thesis. What makes the LA Basin suitable for such an engineering approach is that it is surrounded by orographic features.

In addition to using water technology to enable irrigation, there may be additional opportunities to enhance water availability. In arid and semi-arid coastal regions with orographic features, enhanced seawater evaporation (Du et al. 2023) may contribute to local rainfall (Chapter 6). The amount of seawater evaporation strongly depends on the solar forcing, and therefore, enhanced seawater evaporation is expected to be valuable in low to middle latitude areas that receive plenty of solar radiation. Here an increase in seawater evaporation may kick-start the local water cycle and contribute to the development of vegetation. An evaporation technology may allow to enhance rainfall in the relatively dry Mediterranean-type climate regions, such as the Cape region of South Africa, and the south of the Mediterranean Basin.

To enable a kick-start of the water cycle in a specific region, several conditions are likely required to be met. First, there needs to be an orographic feature that promotes local moisture recycling. Second, the mountain needs to be located downwind from the region where seawater is evaporated or a forest is irrigated to ensure that the water vapor could recycle locally. Finally, to kick-start the water cycle with enhanced seawater evaporation the region should be located in close proximity to the coast to keep costs low and to make use of the sea breeze.

7.2.3 Step 2: Investigating the climatic effects of greening

A second step can be applied to further narrow down where greening initiatives could contribute to rainfall as well as determine the climatic effects of an increase in vegetation. In this step, a process-based model is used to determine how vegetation affects the atmospheric dynamics that drive precipitation and alter moisture flows, which cannot be studied in Step 1. As Step 2 is more computationally costly than Step 1, the first step is crucial to narrow down the study region.

7.2.3.1 Outcomes of Step 2 in this thesis

Step 1 showed that of all Mediterranean regions, I expected that greening most likely contributes to local rainfall enhancement in the Mediterranean Basin. However, this region still covers a relatively large area. To further narrow down where greening may increase local rainfall and to understand how the underlying processes that drive convective precipitation are affected by forestation, a simple process-based model was used. This model allowed to conduct a local analysis for multiple grid cells across the Mediterranean Basin, in a reasonable amount of time. The focus was on convective precipitation as this type of rainfall is affected by land cover changes and occurs during summer, when an especially large fraction of evaporated water recycles locally in the Mediterranean Basin (Chapter 3).

Forestation could contribute to wetting in relatively wet areas and drying in relatively dry areas (Chapter 4), underlining that forestation efforts need to be planned carefully to minimize harm, indicating the relevance of strategically planning greening initiatives. Sufficient soil moisture seems to be one of the conditions for forestation to contribute to an increase in rainfall. In regions where soil moisture is limited, water technology could help to kick-start the water cycle, through enhanced irrigation or rainfall, indicating the benefit of including Step 1b in this engineering approach. Additionally, the triggering of convective rainfall is also highly dependent on the atmospheric humidity in the morning as well as the stability of the atmosphere (Findell and Eltahir 2003a). A sufficient humidity may be established through enhanced seawater evaporation. However, it may be more challenging to create unstable conditions. The combination of Steps 1 and 2 suggests that forestation should be conducted in coastal regions in the Mediterranean Basin, close to orographic features and regions that are already characterized by convective rainfall during summer.

7.2.3.2 Extending Step 2

In addition to the simple atmospheric boundary layer model that was used in this thesis (Chapter 4), there are several models with different levels of complexity that can be applied in this step. For example, a large eddy simulation model can be used to better understand how turbulence and shading affect the development of the atmospheric boundary layer. In such a model it is possible to calculate the amount of rainfall that recycles locally due to greening, which is not possible with the simple atmospheric boundary layer model.

Besides the more complex processes underlying local moisture recycling, it is also possible to study the non-local processes that are affected by greening. Regional weather models, and global climate models can be used to simulate the impact of forestation on the atmospheric dynamics and the moisture flows between

sources and sinks. This information can be used to identify whether the effects of greening on water yield downwind are positive or negative and whether these impacts are acceptable or harmful (Chapter 5). These more complex models also allow to study processes that do not take place at the interface of the land surface and the atmosphere.

In addition, these more complex models allow to study the hydrological effects of greening in a changing climate. Climate projections suggest that wet regions will get wetter, and dry regions will get drier (Chou and Lan 2012; Konapala et al. 2020). Changes in precipitation patterns are projected to negatively affect soil moisture (Berg and Sheffield 2018; Eekhout et al. 2018; Peng et al. 2023), reducing evapotranspiration in regions where it is constrained by soil moisture. In addition, the sensitivity of evapotranspiration to vegetation is expected to decrease due to atmospheric warming (Yang et al. 2023), which would have a negative impact on the effectiveness of greening initiatives that aim to enhance rainfall. Finally, climate change is expected to negatively affect terrestrial moisture recycling (Staal et al. 2025) and enhance the residence time of moisture in the atmosphere, likely contributing to lower local moisture recycling ratios (Gimeno et al. 2021). These results imply that an increase in evapotranspiration due to greening is more likely to contribute to drying in a warming world. This shows that global warming should be considered in the planning of a greening project.

7.2.4 Step 3: Assessing socio-economic costs and benefits

The result of Steps 1 and 2 could clarify where greening may have hydrological benefits and not contribute to drying. Chapter 6 discusses that in addition to the hydrological effects, greening likely also has socio-economic effects. To realize a sustainable greening project the costs should not outweigh the benefits. A social impact assessment can be conducted to examine how a greening project may affect local communities, and an economic assessment can be conducted to investigate the economic costs and benefits associated with the greening project. Here I discuss two main socio-economic challenges that are important to address in such impact assessments: land-use competition, and the ownership of atmospheric moisture flows.

7.2.4.1 Land-use competition

Land-use competition can be a barrier for greening projects. For instance, conventional agricultural activities may be more appealing to landowners due to the costs that are related to greening (Powlen and Jones 2019). Specifically for landowners that have a small patch of land greening is less feasible (Marey-Pérez and Rodríguez-Vicente 2011). Landowners have a crucial role in realizing greening, however, to partake in such initiatives they must see the benefits and

the strongest motivators are financial benefits (Tedesco et al. 2023). Biophysical benefits that follow from greening, such as improved soil quality, are only a minor motivator (Tedesco et al. 2023).

To better understand how changes in ecology can render economic-benefits, research on ecology and socio-economic benefits needs to be better integrated (Tedesco et al. 2023). For a more comprehensive assessment, hydrological benefits of greening could also be included in such analyses. An important motivator for landowners could be that greening may improve agricultural productivity (Soerianegara and Mansuri 1994), and water availability.

Finally, to minimize land-use competition, solutions, such as terraces, may be employed to grow vegetation in regions that currently have little value. Steep mountain slopes are prone to erosion, which makes them less fertile and unprofitable to landowners (Soerianegara and Mansuri 1994). Here, terraces could reduce erosion and allow vegetation to develop as illustrated in the Loess plateau (Chen et al. 2018), creating socio-economic benefits.

7.2.4.2 The ownership of atmospheric moisture flows

Changing land cover will alter atmospheric moisture flows, affecting precipitation downwind (Keys et al. 2014; Wang-Erlandsson et al. 2018; te Wierik et al. 2021; De Hertog et al. 2024), possibly in neighbouring countries as all countries to some extent depend on evaporation sources in other countries (Rockström et al. 2023). Land-use management practices that enhance local precipitation, may have drastic effects downwind (Zampieri et al. 2024). However, it remains uncertain whether land-use changes can contribute to drying downwind. Nevertheless, to prevent greening initiatives to have harmful hydrological effects downwind, atmospheric water needs to be governed (Te Wierik et al. 2020; Zampieri et al. 2024).

As atmospheric moisture flows are largely invisible, managing these flows is difficult (Keys et al. 2016; Keys et al. 2019). In the past years there have been several studies that suggest possibilities for atmospheric water governance. For example, the evaporationshed and precipitationshed frameworks could be used to make the moisture flows visible and manage moisture recycling (Keys et al., 2019). In addition, moisture recycling as an ecosystem service has been included in the planetary boundary framework as part of the planetary boundary for green water (te Wierik et al. 2021; Wang-Erlandsson et al. 2022). More research on how to implement these concepts is necessary as the governance of moisture recycling is still in its early stages (te Wierik et al. 2021). Nevertheless, moisture connections between countries show that it is important to assess both the local and non-local socio-economic effects of greening.

7.3 Outlook: the future is transdisciplinary

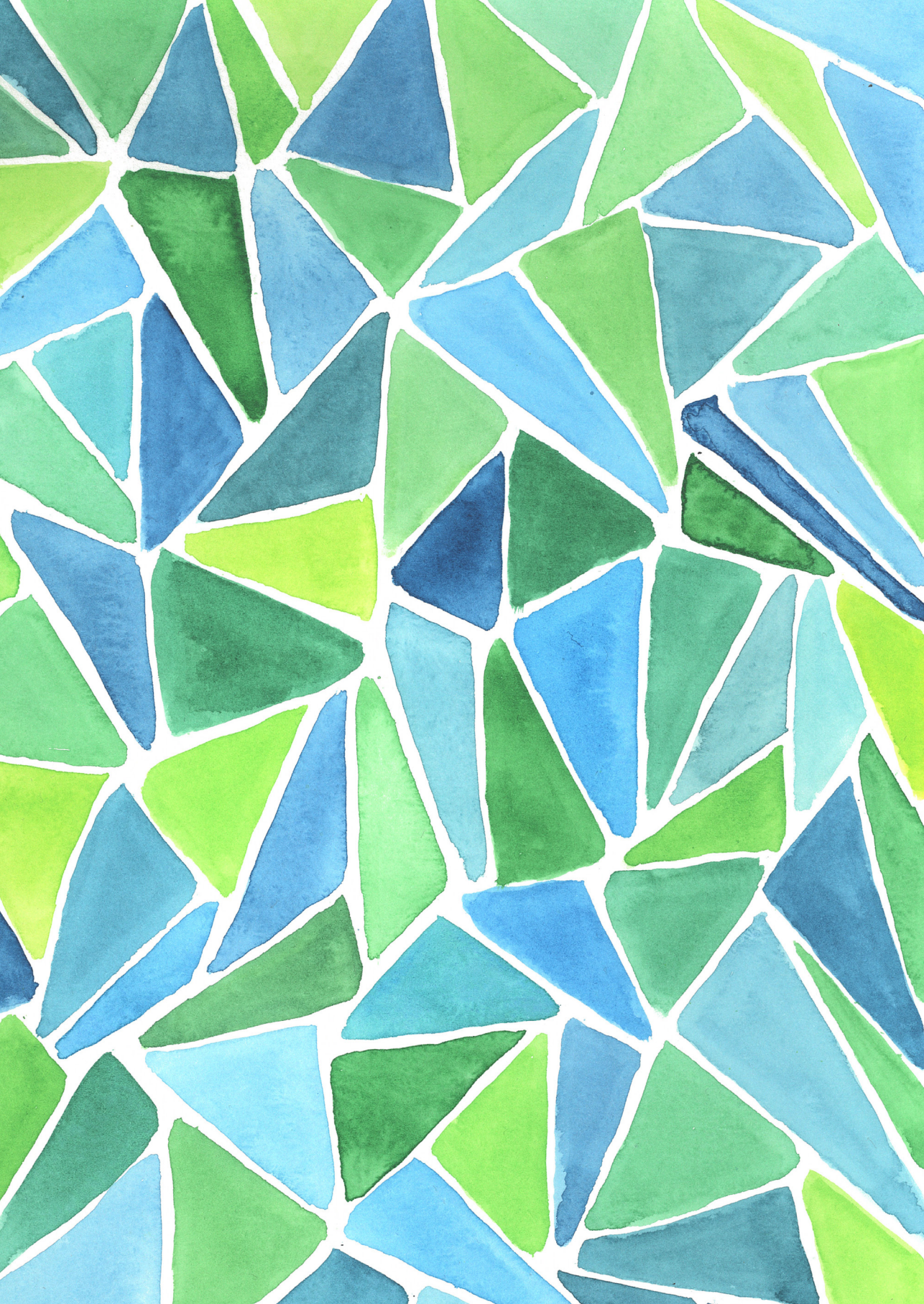
This thesis shows that the available state-of-the-art models, datasets and knowledge allow to consider hydrological effects in the planning of greening projects. Additionally, this chapter describes how these tools can be applied, adopting an engineering approach, to identify where greening may contribute to more rainfall. Considering the first step in this engineering approach, this thesis provides some general insights on local moisture recycling that can be applied globally. This allows for easy implementation of Step 1. However, further optimization and development of this engineering approach is necessary. This outlook describes how this engineering approach could benefit from a transdisciplinary research approach.

Whether greening contributes to local water availability does not only depend on the feedback with the atmosphere but also on various other factors, such as the capacity of the soil to take up the water that returns as precipitation (de Jonge et al. 1999). The hydrological processes that take place in the soil, and the impact of vegetation on these processes are beyond the scope of this thesis. Extending the engineering approach by simulating the climatic effects of vegetation in Earth system models will provide valuable insights in addition to the results presented in this thesis. However, in such models, ecological processes are often given limited emphasis, which contributes to the uncertainty of the model output (Mitman et al. 2018; Bonan et al. 2024). Different disciplines need to be integrated to better understand the interaction between vegetation and the hydrological cycle (Vereecken et al. 2022; Vilà-Guerau de Arellano et al. 2023; Bonan et al. 2024), and to find suitable solutions to the water scarcity issues worldwide.

In addition, the scientific community should discuss the ambition for various types of models. Do projects that optimize these models mainly aim to gain better scientific understanding of the Earth system processes, or is it desirable that the outputs of these models can be directly translated into policy and applied by stakeholders? In addition, the community should discuss to what extent time should be invested in optimizing models before they can be applied to design real-life greening strategies. I believe that stakeholders could provide valuable insights in such a discussion. Stakeholders are willing to apply the output of different models in their projects. However, the data and tools are often not easily applicable for non-experts. Therefore, to enhance the societal impact of scientific research, the scientific community should aim to make their outputs easily accessible, understandable, and applicable, in addition to freely available (Chapter 6).

Furthermore, to better integrate the biophysical, hydrological and socio-economic benefits of restoration projects, it is important to monitor these effects. Such a monitoring initiative should be part of a long-term project as the recovery of

hydrological processes can take a considerable amount of time (Filoso et al. 2017). Collaborations with stakeholders that are responsible for greening projects can help to set up such long-term monitoring initiatives. Additionally, citizen science could help to better understand social costs and benefits of greening. To maximize the benefits of a greening project other aspects that should also be monitored include, but are not limited to, soil quality and fertility, biodiversity, local living climate, and food production (Di Sacco et al. 2021; van Woesik et al. 2023). Finally, greening for rainfall enhancement should never come at the expense of native, well-functioning ecosystems.





Appendix

References

- Abdi, H. and Williams, L.J. 2010. Principal component analysis. *Wiley Interdisciplinary Reviews: Computational Statistics* 2(4), pp. 433–459. doi: 10.1002/wics.101.
- Albert, R., Jeong, H. and Barabási, A.-L. 2000. Error and attack tolerance of complex networks. *Nature* 406(6794), pp. 378–382. doi: 10.1038/35019019.
- Ali, E., Cramer, W., Carnicer, J., Georgopoulou, E., Hilmi, N.J.M., Le Cozannet, G. and Lionello, P. 2022. *Cross-Chapter Paper 4: Mediterranean Region*. Cambridge University Press. doi: 10.1017/9781009325844.021.2233.
- Allam, A., Moussa, R., Najem, W. and Bocquillon, C. 2020. Hydrological cycle, Mediterranean basins hydrology. In: *Water Resources in the Mediterranean Region*. Elsevier, pp. 1–21. doi: 10.1016/B978-0-12-818086-0.00001-7.
- An, W. et al. 2017. Enhanced recent local moisture recycling on the northwestern Tibetan Plateau deduced from ice core deuterium excess records. *Journal of Geophysical Research - Atmospheres* 122(23), pp. 12541–12556. doi: 10.1002/2017JD027235.
- Ardilouze, C., Materia, S., Batté, L., Benassi, M. and Prodhomme, C. 2022. Precipitation response to extreme soil moisture conditions over the Mediterranean. *Climate Dynamics* 58(7–8), pp. 1927–1942. doi: 10.1007/s00382-020-05519-5.
- Aronson, J., Goodwin, N., Orlando, L., Eisenberg, C. and Cross, A.T. 2020. A world of possibilities: six restoration strategies to support the United Nation's Decade on Ecosystem Restoration. *Restoration Ecology* 28(4), pp. 730–736. doi: 10.1111/rec.13170.
- Asbjørnsen, H. et al. 2022. Multi-Targeted payments for the balanced management of hydrological and other forest ecosystem services. *Forest Ecology and Management* 522, 120482. doi: 10.1016/j.foreco.2022.120482.
- Bagley, J.E., Desai, A.R., Dirmeyer, P.A. and Foley, J.A. 2012. Effects of land cover change on moisture availability and potential crop yield in the world's breadbaskets. *Environmental Research Letters* 7, 014009. doi: 10.1088/1748-9326/7/1/014009.
- Bagley, J.E., Desai, A.R., Harding, K.J., Snyder, P.K. and Foley, J.A. 2014. Drought and deforestation: Has land cover change influenced recent precipitation extremes in the Amazon? *Journal of Climate* 27(1), pp. 345–361. doi: 10.1175/JCLI-D-12-00369.1.
- Baker, J.C.A. 2021. Planting trees to combat drought. *Nature Geoscience* 14(7), pp. 458–459. doi: 10.1038/s41561-021-00787-0.
- Baker, J.C.A. and Spracklen, D. V. 2022. Divergent representation of precipitation recycling in the Amazon and the Congo in CMIP6 models. *Geophysical Research Letters* 49(10), e2021GL095136. doi: 10.1029/2021GL095136.
- Bankston, A., Davis, S.M., Moore, E., Niziolek, C.A. and Boudreau, V. 2020. Why scientific societies should involve more early-career researchers. *eLife* 9, pp. 1–7. doi: 10.7554/ELIFE.60829.

- Barth, M., Jiménez-Aceituno, A., Lam, D.P., Bürgener, L. and Lang, D.J. 2023. Transdisciplinary learning as a key leverage for sustainability transformations. *Current Opinion in Environmental Sustainability* 64, 101361. doi: 10.1016/j.cosust.2023.101361.
- Bastin, J.-F. et al. 2019. The global tree restoration potential. *Science* 365, pp. 76–79.
- Batavia, C. and Nelson, M.P. 2018. Translating climate change policy into forest management practice in a multiple-use context: the role of ethics. *Climatic Change* 148(1–2), pp. 81–94. doi: 10.1007/s10584-018-2186-2.
- Batibeniz, F., Ashfaq, M., Öñol, B., Turuncoglu, U.U., Mehmood, S. and Evans, K.J. 2020. Identification of major moisture sources across the Mediterranean Basin. *Climate Dynamics* 54(9–10), pp. 4109–4127. doi: 10.1007/s00382-020-05224-3.
- Benedict, I., Weijenborg, C., van der Ent, R., Keune, J., Koren, G. and Kalverla, P. 2024. A moisture tracking intercomparison study - Addressing the uncertainty in modelling the origins of precipitation. doi: 10.5194/ems2024-1040.
- Berg, A. and Sheffield, J. 2018. Climate change and drought: The soil moisture perspective. *Current Climate Change Reports* 4(2), pp. 180–191. doi: 10.1007/s40641-018-0095-0.
- Bestelmeyer, B.T., Okin, G.S., Duniway, M.C., Archer, S.R., Sayre, N.F., Williamson, J.C. and Herrick, J.E. 2015. Desertification, land use, and the transformation of global drylands. *Frontiers in Ecology and the Environment* 13(1), pp. 28–36. doi: 10.1890/140162.
- Bonan, G. 2016. *Ecological climatology: concepts and applications*. 3rd ed. Cambridge University Press.
- Bonan, G. 2023. *Seeing the Forest for the Trees*. Cambridge University Press. doi: 10.1017/9781108601559.
- Bonan, G.B. 2008. Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science* 320(5882), pp. 1444–1449. doi: 10.1126/science.1155121.
- Bonan, G.B. et al. 2024. Reimagining Earth in the Earth system. *Journal of Advances in Modeling Earth Systems* 16(8), e2023MS004017. doi: 10.1029/2023MS004017.
- Bony, S. et al. 2013. Carbon Dioxide and climate: Perspectives on a scientific assessment. In: *Climate Science for Serving Society*. Dordrecht: Springer Netherlands, pp. 391–413. doi: 10.1007/978-94-007-6692-1_14.
- Boucher, O. et al. 2014. Rethinking climate engineering categorization in the context of climate change mitigation and adaptation. *WIREs Climate Change* 5(1), pp. 23–35. doi: 10.1002/wcc.261.
- Brancalion, P.H.S. et al. 2019. Global restoration opportunities in tropical rainforest landscapes. *Science Advances* 5(7), e0297439. doi: 10.1126/sciadv.aav3223.

- Branch, O. and Wulfmeyer, V. 2019. Deliberate enhancement of rainfall using desert plantations. *Proceedings of the National Academy of Sciences of the United States of America* 116(38), pp. 18841–18847. doi: 10.1073/pnas.1904754116.
- Bro, R. and Smilde, A.K. 2014. Principal component analysis. *Analytical Methods* 6(9), pp. 2812–2831. doi: 10.1039/c3ay41907j.
- Brown, A.E., Zhang, L., McMahon, T.A., Western, A.W. and Vertessy, R.A. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* 310(1–4), pp. 28–61. doi: 10.1016/j.jhydrol.2004.12.010.
- Brunner, I., Herzog, C., Dawes, M.A., Arend, M. and Sperisen, C. 2015. How tree roots respond to drought. *Frontiers in Plant Science* 6(547). doi: 10.3389/fpls.2015.00547.
- Budyko, M.I. 1974. *Climate and life*. Academic Press: New York.
- Burde, G.I. 2006a. Bulk recycling models with incomplete vertical mixing. Part I: Conceptual framework and models. *Journal of Climate* 19(8), pp. 1461–1472. doi: 10.1175/JCLI3687.1.
- Burde, G.I. 2006b. Bulk recycling models with incomplete vertical mixing. Part II: Precipitation recycling in the Amazon Basin. *Journal of Climate* 19(8), pp. 1461–1472. doi: 10.1175/JCLI3687.1.
- Burde, G.I. and Zangvil, A. 2001. The estimation of regional precipitation recycling. Part I: Review of recycling models. *Journal of Climate* 14(12), pp. 2509–2527. doi: 10.1175/1520-0442.
- Calder, I.R. 2007. Forests and water—Ensuring forest benefits outweigh water costs. *Forest Ecology and Management* 251(1–2), pp. 110–120. doi: 10.1016/j.foreco.2007.06.015.
- Caldera, U. and Breyer, C. 2023. Afforesting arid land with renewable electricity and desalination to mitigate climate change. *Nature Sustainability* 6, pp. 526–538. doi: 10.1038/s41893-022-01056-7.
- Cao, M., Wang, W., Wei, J., Forzieri, G., Fetzer, I. and Wang-Erlandsson, L. 2024. Revegetation Impacts on Moisture Recycling and Precipitation Trends in the Chinese Loess Plateau. *Water Resources Research* 60(12), e2024WR038199. doi: 10.1029/2024WR038199.
- Cerasoli, S., Yin, J. and Porporato, A. 2021. Cloud cooling effects of afforestation and reforestation at midlatitudes. *PNAS* 118(33), e2026241118. doi: 10.1073/pnas.2026241118/-/DCSupplemental.
- Chen, H. et al. 2018. Effects of vegetation and rainfall types on surface runoff and soil erosion on steep slopes on the Loess Plateau, China. *CATENA* 170, pp. 141–149. doi: 10.1016/j.catena.2018.06.006.
- Chen, T., Rossow, W.B. and Zhang, Y. 2000. Radiative effects of cloud-type variations. *Journal of Climate* 13(1), pp. 264–286. doi: 10.1175/1520-0442(2000)013<0264:REOCTV>2.0.CO;2.

- Chen, Y., Paul, G., Cohen, R., Havlin, S., Borgatti, S.P., Liljeros, F. and Stanley, H.E. 2007. Percolation theory applied to measures of fragmentation in social networks. *Physical Review E* 75(4), 046107. doi: 10.1103/PhysRevE.75.046107.
- Chen, Z., Wang, W. and Fu, J. 2020. Vegetation response to precipitation anomalies under different climatic and biogeographical conditions in China. *Scientific Reports* 10(1), 830. doi: 10.1038/s41598-020-57910-1.
- Cheng, W., Moore, J.C., Cao, L., Ji, D. and Zhao, L. 2017. Simulated climate effects of desert irrigation geoengineering. *Scientific Reports* 7, 46443. doi: 10.1038/srep46443.
- Chou, C. and Lan, C.-W. 2012. Changes in the annual range of precipitation under global warming. *Journal of Climate* 25(1), pp. 222–235. doi: 10.1175/JCLI-D-11-00097.1.
- Cloux, S., Garaboa-Paz, D., Insua-Costa, D., Miguez-Macho, G. and Pérez-Muñuzuri, V. 2021. Extreme precipitation events in the Mediterranean area: Contrasting two different models for moisture source identification. *Hydrology and Earth System Sciences* 25(12), pp. 6465–6477. doi: 10.5194/hess-25-6465-2021.
- Colloff, M.J., Pullen, K.R. and Cunningham, S.A. 2010. Restoration of an ecosystem function to revegetation communities: The role of invertebrate macropores in enhancing soil water infiltration. *Restoration Ecology* 18, pp. 65–72. doi: 10.1111/j.1526-100X.2010.00667.x.
- Connell, J.P. and Kubisch, A.C. 1999. *Applying a theory of change approach to the evaluation of comprehensive community initiatives: Progress, prospects, and problems*. Aspen Inst. Human Studies.
- Cooke, J. 2005. A framework to evaluate research capacity building in health care. *BMC Family Practice* 6, 44. doi: 10.1186/1471-2296-6-44.
- Costa, M.H. et al. 2019. Climate risks to Amazon agriculture suggest a rationale to conserve local ecosystems. *Frontiers in Ecology and the Environment* 17(10), pp. 584–590. doi: 10.1002/fee.2124.
- Cropper, S., Solander, K., Newman, B.D., Tuinenburg, O.A., Staal, A., Theeuwes, J.J.E. and Xu, C. 2021. Comparing deuterium excess to large-scale precipitation recycling models in the tropics. *npj Climate and Atmospheric Science* 4(1), pp. 1–9. doi: 10.1038/s41612-021-00217-3.
- Cui, J. et al. 2022. Global water availability boosted by vegetation-driven changes in atmospheric moisture transport. *Nature Geoscience* 15, pp. 982–988. doi: 10.1038/s41561-022-01061-7.
- Dekker, S.C., Groenendijk, M., Booth, B.B.B., Huntingford, C. and Cox, P.M. 2016. Spatial and temporal variations in plant water-use efficiency inferred from tree-ring, eddy covariance and atmospheric observations. *Earth System Dynamics* 7(2), pp. 525–533. doi: 10.5194/esd-7-525-2016.
- Dekker, S.C., Rietkerk, M. and Bierkens, M.F.P. 2007. Coupling microscale vegetation-soil water and macroscale vegetation-precipitation feedbacks in semiarid ecosystems. *Global Change Biology* 13(3), pp. 671–678. doi: 10.1111/j.1365-2486.2007.01327.x.

- Delzon, S. and Loustau, D. 2005. Age-related decline in stand water use: sap flow and transpiration in a pine forest chronosequence. *Agricultural and Forest Meteorology* 129(3–4), pp. 105–119. doi: 10.1016/j.agrformet.2005.01.002.
- Dermody, B.J., De Boer, H.J., Bierkens, M.F.P., Weber, S.L., Wassen, M.J. and Dekker, S.C. 2012. A seesaw in Mediterranean precipitation during the Roman Period linked to millennial-scale changes in the North Atlantic. *Climate of the Past* 8(2), pp. 637–651. doi: 10.5194/cp-8-637-2012.
- Diffenbaugh, N.S., Giorgi, F. and Pal, J.S. 2008. Climate change hotspots in the United States. *Geophysical Research Letters* 35(16). doi: 10.1029/2008GL035075.
- Döll, P. 2009. Vulnerability to the impact of climate change on renewable groundwater resources: A global-scale assessment. *Environmental Research Letters* 4(3), 035006. doi: 10.1088/1748-9326/4/3/035006.
- Döll, P. and Siebert, S. 2002. Global modeling of irrigation water requirements. *Water Resources Research* 38(4), 1037. doi: 10.1029/2001wr000355.
- Dominguez, F., Eiras-Barca, J., Yang, Z., Bock, D., Nieto, R. and Gimeno, L. 2022. Amazonian moisture recycling revisited using WRF with water vapor tracers. *Journal of Geophysical Research: Atmospheres* 127(4), e2021JD035259. doi: 10.1029/2021JD035259.
- Dominguez, F., Hu, H. and Martinez, J.A. 2020. Two-layer dynamic recycling model (2L-DRM): Learning from moisture tracking models of different complexity. *Journal of Hydrometeorology* 21(1), pp. 3–16. doi: 10.1175/JHM-D-19-0101.1.
- Dominguez, F., Kumar, P., Liang, X.-Z. and Ting, M. 2006. Impact of atmospheric moisture storage on precipitation recycling. *Journal of Climate* 19(8), pp. 1513–1530. doi: 10.1175/JCLI3691.1.
- Dominguez, F., Miguez-Macho, G. and Hu, H. 2016. WRF with water vapor tracers: A study of moisture sources for the North American Monsoon. *Journal of Hydrometeorology* 17(7), pp. 1915–1927. doi: 10.1175/JHM-D-15-0221.1.
- Donatti, C.I., Andrade, A., Cohen-Shacham, E., Fedele, G., Hou-Jones, X. and Robyn, B. 2022. Ensuring that nature-based solutions for climate mitigation address multiple global challenges. *One Earth* 5(5), pp. 493–504. doi: 10.1016/j.oneear.2022.04.010.
- Du, C., Zhao, X., Qian, X., Huang, C. and Yang, R. 2023. Heat-localized solar evaporation: Transport processes and applications. *Nano Energy* 107, 108086. doi: 10.1016/j.nanoen.2022.108086.
- Dudley, N., Eufemia, L., Fleckenstein, M., Periago, M.E., Petersen, I. and Timmers, J.F. 2020. Grasslands and savannahs in the UN Decade on Ecosystem Restoration. *Restoration Ecology* 28(6), pp. 1313–1317. doi: 10.1111/rec.13272.
- Duveiller, G., Filippini, F., Ceglar, A., Bojanowski, J., Alkama, R. and Cescatti, A. 2021. Revealing the widespread potential of forests to increase low level cloud cover. *Nature Communications* 12(1), 4337. doi: 10.1038/s41467-021-24551-5.

- Eade, D. 2007. Capacity building: Who builds whose capacity? *Development in Practice* 17(4–5), pp. 630–639. doi: 10.1080/09614520701469807.
- ECMWF. 2010. *IFS Documentation CY36R1 - Part IV: Physical Processes*. ECMWF.
- Eekhout, J.P.C., Hunink, J.E., Terink, W. and De Vente, J. 2018. Why increased extreme precipitation under climate change negatively affects water security. *Hydrology and Earth System Sciences* 22(11), pp. 5935–5946. doi: 10.5194/hess-22-5935-2018.
- Elias, M. et al. 2022. Ten people-centered rules for socially sustainable ecosystem restoration. *Restoration Ecology* 30(4), e13574. doi: 10.1111/rec.13574.
- Ellison, D. et al. 2017. Trees, forests and water: Cool insights for a hot world. *Global Environmental Change* 43, pp. 51–61. doi: 10.1016/j.gloenvcha.2017.01.002.
- Ellison, D., Futter, M.N. and Bishop, K. 2012. On the forest cover-water yield debate: From demand- to supply-side thinking. *Global Change Biology* 18(3), pp. 806–820. doi: 10.1111/j.1365-2486.2011.02589.x.
- Ellison, D., Zurich, E. and Wang-Erlandsson, L. 2019. Upwind forests: managing moisture recycling for nature-based resilience. *Unasylva: An international journal of forestry and forest industries* 70, pp. 14–26.
- ElShafie, S.J. 2018. Making science meaningful for broad audiences through stories. *Integrative and Comparative Biology* 58(6), pp. 1213–1223. doi: 10.1093/icb/icy103.
- Eltahir, E.A.B. 1998. A soil moisture-rainfall feedback mechanism. *Water Resources Research* 34(4), pp. 765–776. doi: <https://doi.org/10.1029/97WR03499>.
- Eltahir, E.A.B. and Pal, J.S. 1996. Relationship between surface conditions and subsequent rainfall in convective storms. *Journal of Geophysical Research-Atmosphere* 101(21), pp. 26237–26245. doi: 10.1029/96jd01380.
- Emanuel, K. 2023. On the physics of high CAPE. *Journal of the Atmospheric Sciences* 80(11), pp. 2669–2683. doi: 10.1175/JAS-D-23-0060.1.
- Van der Ent, R.J. and Savenije, H.H.G. 2011. Length and time scales of atmospheric moisture recycling. *Atmospheric Chemistry and Physics* 11(5), pp. 1853–1863. doi: 10.5194/acp-11-1853-2011.
- Van der Ent, R.J. and Savenije, H.H.G. 2013. Oceanic sources of continental precipitation and the correlation with sea surface temperature. *Water Resources Research* 49(7), pp. 3993–4004. doi: 10.1002/wrcr.20296.
- Van der Ent, R.J., Savenije, H.H.G., Schaefli, B. and Steele-Dunne, S.C. 2010. Origin and fate of atmospheric moisture over continents. *Water Resources Research* 46(9), W09525. doi: 10.1029/2010WR009127.
- Van der Ent, R.J., Tuinenburg, O.A., Knoche, H.R., Kunstmann, H. and Savenije, H.H.G. 2013. Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking? *Hydrology and Earth System Science* 17(12), pp. 4869–4884. doi: 10.5194/hess-17-4869-2013.

- Van der Ent, R.J., Wang-Erlandsson, L., Keys, P.W. and Savenije, H.H.G. 2014. Contrasting roles of interception and transpiration in the hydrological cycle - Part 2: Moisture recycling. *Earth System Dynamics* 5(2), pp. 471–489. doi: 10.5194/esd-5-471-2014.
- Esler, K.J., Jacobsen, A.L. and Pratt, R.B. 2018. *The biology of Mediterranean-type ecosystems*. 1st ed. Oxford University Press. doi: 10.1093/oso/9780198739135.001.0001.
- Essa, Y.H., Hirschi, M., Thiery, W., El-Kenawy, A.M. and Yang, C. 2023. Drought characteristics in Mediterranean under future climate change. *npj Climate and Atmospheric Science* 6(1), 133. doi: 10.1038/s41612-023-00458-4.
- Facchini, M.C., Mircea, M., Fuzzi, S. and Charlson, R.J. 1999. Cloud albedo enhancement by surface-active organic solutes in growing droplets. *Nature* 401, pp. 257–259.
- Fahrländer, S.F., Wang-Erlandsson, L., Pranindita, A. and Jaramillo, F. 2024. Hydroclimatic vulnerability of wetlands to upwind land use changes. *Earth's Future* 12(3), e2023EF003837. doi: 10.1029/2023EF003837.
- Falkenmark, M. and Rockström, J. 2006. The new blue and green water paradigm: Breaking new ground for water resources planning and management. *Journal of Water Resources Planning and Management* 132(3), pp. 129–132. doi: 10.1061/(asce)0733-9496(2006)132:3(129).
- Falkenmark, M., Wang-Erlandsson, L. and Rockström, J. 2019. Understanding of water resilience in the Anthropocene. *Journal of Hydrology* 2, 100009. doi: 10.1016/j.hydroa.2018.100009.
- Farley, K.A., Jobbágy, E.G. and Jackson, R.B. 2005. Effects of afforestation on water yield: A global synthesis with implications for policy. *Global Change Biology* 11(10), pp. 1565–1576. doi: 10.1111/j.1365-2486.2005.01011.x.
- Feng, X. et al. 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nature Climate Change* 6(11), pp. 1019–1022. doi: 10.1038/nclimate3092.
- Filoso, S., Bezerra, M.O., Weiss, K.C.B. and Palmer, M.A. 2017. Impacts of forest restoration on water yield: A systematic review. *PLoS ONE* 12(8), e0183210. doi: 10.1371/journal.pone.0183210.
- Findell, K.L. and Eltahir, E.A.B. 2003a. Atmospheric controls on soil moisture-boundary layer interactions. Part I: Framework development. *Journal of Hydrometeorology* 4(3), pp. 552–569. doi: [https://doi.org/10.1175/1525-7541\(2003\)004<0552:ACOSML>2.0.CO;2](https://doi.org/10.1175/1525-7541(2003)004<0552:ACOSML>2.0.CO;2).
- Findell, K.L. and Eltahir, E.A.B. 2003b. Atmospheric controls on soil moisture-boundary layer interactions. Part II: Feedbacks within the continental United States. *Journal of Hydrometeorology* 4, pp. 570–583. doi: [https://doi.org/10.1175/1525-7541\(2003\)004%3C0570:ACOSML%3E2.0.CO;2](https://doi.org/10.1175/1525-7541(2003)004%3C0570:ACOSML%3E2.0.CO;2).
- Findell, K.L. and Eltahir, E.A.B. 2003c. Atmospheric controls on soil moisture-boundary layer interactions: Three-dimensional wind effects. *Journal of Geophysical Research: Atmospheres* 108(8). doi: <https://doi.org/10.1029/2001JD001515>.

- Findell, K.L., Keys, P.W., van der Ent, R.J., Lintner, B.R., Berg, A. and Krasting, J.P. 2019. Rising temperatures increase importance of oceanic evaporation as a source for continental precipitation. *Journal of Climate* 32(22), pp. 7713–7726. doi: 10.1175/JCLI-D-19-0145.1.
- Findlater, K., Kozak, R. and Hagerman, S. 2022. Difficult climate-adaptive decisions in forests as complex social–ecological systems. *Proceedings of the National Academy of Sciences* 119(4), e2108326119. doi: 10.1073/pnas.2108326119.
- Forzieri, G., Alkama, R., Miralles, D.G. and Cescatti, A. 2017. Satellites reveal contrasting responses of regional climate to the widespread greening of Earth. *Science* 356, pp. 1180–1184. doi: <https://doi.org/10.1126/science.aal1727>.
- Fraedrich, K. and Kleidon, A. 1999. A green planet versus a desert world: Estimating the effect of vegetation extremes on the atmosphere. *Journal of Climate* 12, pp. 3156–3163. doi: [https://doi.org/10.1175/1520-0442\(1999\)012%3C3156:AGPVAD%3E2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012%3C3156:AGPVAD%3E2.0.CO;2).
- Fraser, E.D.G., Simelton, E., Termansen, M., Gosling, S.N. and South, A. 2013. “Vulnerability hotspots”: Integrating socio-economic and hydrological models to identify where cereal production may decline in the future due to climate change induced drought. *Agricultural and Forest Meteorology* 170, pp. 195–205. doi: 10.1016/j.agrformet.2012.04.008.
- Froehlich, K., Kralik, M., Papesch, W., Rank, D., Scheifinger, H. and Stichler, W. 2008. Deuterium excess in precipitation of Alpine regions - Moisture recycling. *Isotopes in Environmental and Health Studies* 44(1), pp. 61–70. doi: 10.1080/10256010801887208.
- Galleguillos, M., Gimeno, F., Puelma, C., Zambrano-Bigiarini, M., Lara, A. and Rojas, M. 2021. Disentangling the effect of future land use strategies and climate change on streamflow in a Mediterranean catchment dominated by tree plantations. *Journal of Hydrology* 595, 126047. doi: 10.1016/j.jhydrol.2021.126047.
- Gao, J., Barzel, B. and Barabási, A.-L. 2016. Universal resilience patterns in complex networks. *Nature* 530(7590), pp. 307–312. doi: 10.1038/nature16948.
- Gao, Y., Chen, F., Miguez-Macho, G. and Li, X. 2020. Understanding precipitation recycling over the Tibetan Plateau using tracer analysis with WRF. *Climate Dynamics* 55(9–10), pp. 2921–2937. doi: 10.1007/s00382-020-05426-9.
- Ghodsvalli, M., Krishnamurthy, S. and de Vries, B. 2019. Review of transdisciplinary approaches to food-water-energy nexus: A guide towards sustainable development. *Environmental Science and Policy* 101, pp. 266–278. doi: 10.1016/j.envsci.2019.09.003.
- Gibbard, S., Caldeira, K., Bala, G., Phillips, T.J. and Wickett, M. 2005. Climate effects of global land cover change. *Geophysical Research Letters* 32(23), pp. 1–4. doi: 10.1029/2005GL024550.

- Gimeno, L. et al. 2021. The residence time of water vapour in the atmosphere. *Nature Reviews Earth and Environment* 2(8), pp. 558–569. doi: 10.1038/s43017-021-00181-9.
- Gleeson, T. et al. 2020. Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resources Research* 56(4), e2019WR024957. doi: 10.1029/2019WR024957.
- Goessling, H.F. and Reick, C.H. 2013. On the “well-mixed” assumption and numerical 2-D tracing of atmospheric moisture. *Atmospheric Chemistry and Physics* 13(11), pp. 5567–5585. doi: 10.5194/acp-13-5567-2013.
- Gómez-Hernández, M., Drumond, A., Gimeno, L. and Garcia-Herrera, R. 2013. Variability of moisture sources in the Mediterranean region during the period 1980–2000. *Water Resources Research* 49(10), pp. 6781–6794. doi: 10.1002/wrcr.20538.
- Griscom, B.W. et al. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America* 114(44), pp. 11645–11650. doi: 10.1073/pnas.1710465114.
- Griscom, B.W. et al. 2020. National mitigation potential from natural climate solutions in the tropics. *Philosophical Transactions of the Royal Society B: Biological Sciences* 375(1794), 20190126. doi: 10.1098/rstb.2019.0126.
- Harrington, T.S., Nusbaumer, J. and Skinner, C.B. 2023. The contribution of local and remote transpiration, ground evaporation, and canopy evaporation to precipitation across North America. *Journal of Geophysical Research: Atmospheres* 128(7), e2022JD037290. doi: 10.1029/2022JD037290.
- He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J. and Bryan, B.A. 2021. Future global urban water scarcity and potential solutions. *Nature Communications* 12(1), 4667. doi: 10.1038/s41467-021-25026-3.
- Heck, V., Gerten, D., Lucht, W. and Boysen, L.R. 2016. Is extensive terrestrial carbon dioxide removal a ‘green’ form of geoengineering? A global modelling study. *Global and Planetary Change* 137, pp. 123–130. doi: 10.1016/j.gloplacha.2015.12.008.
- Van Heerwaarden, C.C. and Teuling, A.J. 2014. Disentangling the response of forest and grassland energy exchange to heatwaves under idealized land-atmosphere coupling. *Biogeosciences* 11(21), pp. 6159–6171. doi: 10.5194/bg-11-6159-2014.
- van Heerwaarden, C.C., Vilà-Guerau de Arellano, J., Gounou, A., Guichard, F. and Couvreur, F. 2010. Understanding the daily cycle of evapotranspiration: A method to quantify the influence of forcings and feedbacks. *Journal of Hydrometeorology* 11(6), pp. 1405–1422. doi: 10.1175/2010JHM1272.1.
- Hersbach, H. et al. 2020. The ERA5 global reanalysis. *Quarterly Journal of Royal Meteorological Society* 146(730), pp. 1999–2049. doi: 10.1002/qj.3803.
- De Hertog, S.J. et al. 2024. Effects of idealized land cover and land management changes on the atmospheric water cycle. *Earth System Dynamics* 15(2), pp. 265–291. doi: 10.5194/esd-15-265-2024.

- Hoek van Dijke, A.J. et al. 2022. Shifts in regional water availability due to global tree restoration. *Nature Geoscience* 15, pp. 363–368. doi: 10.1038/s41561-022-00935-0.
- Holgate, C.M., Evans, J.P., Dijk, I.J.M.V., Pitman, J. and Virgilio, G.D.I. 2020. Australian precipitation recycling and evaporative source regions. *Journal of Climate* 33(20), pp. 8721–8735. doi: 10.1175/JCLI-D-19-0926.1.
- Hou, Y., Wei, X., Zhang, M., Creed, I.F., McNulty, S.G. and Ferraz, S.F.B. 2023. A global synthesis of hydrological sensitivities to deforestation and forestation. *Forest Ecology and Management* 529. doi: 10.1016/j.foreco.2022.120718.
- Hua, F. et al. 2022. The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. *Science* 376(6595), pp. 839–844. doi: 10.1126/science.abl4649.
- Huang, J., Guan, X. and Ji, F. 2012. Enhanced cold-season warming in semi-arid regions. *Atmospheric Chemistry and Physics* 12(12), pp. 5391–5398. doi: 10.5194/acp-12-5391-2012.
- Huang, X. and Swain, D.L. 2022. Climate change is increasing the risk of a California megaflood. *Science* 8, 995. doi: <https://doi.org/10.1126/sciadv.abq0995>.
- Iftekhhar, M.S., Polyakov, M., Ansell, D., Gibson, F. and Kay, G.M. 2017. How economics can further the success of ecological restoration. *Conservation Biology* 31(2), pp. 261–268. doi: 10.1111/cobi.12778.
- Insua-Costa, D. and Miguez-Macho, G. 2018. A new moisture tagging capability in the Weather Research and Forecasting model: formulation, validation and application to the 2014 Great Lake-effect snowstorm. *Earth System Dynamics* 9(1), pp. 167–185. doi: 10.5194/esd-9-167-2018.
- Insua-Costa, D., Senande-Rivera, M., Llasat, M.C. and Miguez-Macho, G. 2022. The central role of forests in the 2021 European floods. *Environmental Research Letters* 17(6), 064053. doi: 10.1088/1748-9326/ac6f6b.
- Intergovernmental Panel on Climate Change (IPCC). 2023a. *Climate Change 2021 – The Physical Science Basis*. Cambridge University Press. doi: 10.1017/9781009157896.
- Intergovernmental Panel on Climate Change (IPCC) ed. 2023b. *Climate Change 2022 - Mitigation of Climate Change*. Cambridge University Press. doi: 10.1017/9781009157926.
- Jach, L., Warrach-Sagi, K., Ingwersen, J., Kaas, E. and Wulfmeyer, V. 2020. Land cover impacts on land-atmosphere coupling strength in climate simulations with WRF over Europe. *Journal of Geophysical Research: Atmospheres* 125(18), e2019JD031989. doi: 10.1029/2019JD031989.
- Jackson, R.B. et al. 2005. Atmospheric science: Trading water for carbon with biological carbon sequestration. *Science* 310(5756), pp. 1944–1947. doi: 10.1126/science.1119282.
- Jackson, R.B. et al. 2008. Protecting climate with forests. *Environmental Research Letters* 3(4), 044006. doi: 10.1088/1748-9326/3/4/044006.

- Jana, S., Rajagopalan, B., Alexander, M.A. and Ray, A.J. 2018. Understanding the dominant sources and tracks of moisture for summer rainfall in the southwest United States. *Journal of Geophysical Research: Atmospheres* 123(10), pp. 4850–4870. doi: 10.1029/2017JD027652.
- Jarvis, P.G. 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philosophical transactions of the Royal Society of London* 273(927), pp. 593–610. doi: <https://doi.org/10.1098/rstb.1976.0035>.
- Jones, A., Haywood, J. and Boucher, O. 2009. Climate impacts of geoengineering marine stratocumulus clouds. *Journal of Geophysical Research: Atmospheres* 114(D10). doi: 10.1029/2008JD011450.
- de Jong, L., De Bruin, S., Knoop, J. and van Vliet, J. 2021. Understanding land-use change conflict: a systematic review of case studies. *Journal of Land Use Science* 16(3), pp. 223–239. doi: 10.1080/1747423X.2021.1933226.
- de Jonge, L.W., Jacobsen, O.H. and Moldrup, P. 1999. Soil water repellency: Effects of water content, temperature, and particle size. *Soil Science Society of America Journal* 63(3), pp. 437–442. doi: 10.2136/sssaj1999.03615995006300030003x.
- Juang, J.Y. et al. 2007. Hydrologic and atmospheric controls on initiation of convective precipitation events. *Water Resources Research* 43(3). doi: 10.1029/2006WR004954.
- Jung, M. et al. 2021. Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nature Ecology & Evolution* 5(11), pp. 1499–1509. doi: 10.1038/s41559-021-01528-7.
- Kaplan, J.O., Krumhardt, K.M. and Zimmermann, N. 2009. The prehistoric and preindustrial deforestation of Europe. *Quaternary Science Reviews* 28(27–28), pp. 3016–3034. doi: 10.1016/j.quascirev.2009.09.028.
- Keeley, J.E., Bond, W.J., Bradstock, R.A., Pausas, J.G. and Rundel, P.W. 2011. *Fire in Mediterranean ecosystems: Ecology, evolution and management*. Cambridge University Press.
- Kéfi, S., Rietkerk, M., Alados, C.L., Pueyo, Y., Papanastasis, V.P., ElAich, A. and De Ruiter, P.C. 2007. Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. *Nature* 449(7159), pp. 213–217. doi: 10.1038/nature06111.
- Keith, D.W. 2000. Geoengineering the climate: History and prospect. *Annual Review of Energy and the Environment* 25(1), pp. 245–284. doi: 10.1146/annurev.energy.25.1.245.
- Keune, J. and Miralles, D.G. 2019. A precipitation recycling network to assess freshwater vulnerability: Challenging the watershed convention. *Water Resources Research* 55(11), pp. 9947–9961. doi: 10.1029/2019WR025310.
- Keune, J., Schumacher, D.L. and Miralles, D.G. 2022. A unified framework to estimate the origins of atmospheric moisture and heat using Lagrangian models. *Geoscientific Model Development* 15(5), pp. 1875–1898. doi: 10.5194/gmd-15-1875-2022.

- Keys, P.W., Barnes, E.A., van der Ent, R.J. and Gordon, L.J. 2014. Variability of moisture recycling using a precipitationshed framework. *Hydrology and Earth System Science* 18(10), pp. 3937–3950. doi: 10.5194/hess-18-3937-2014.
- Keys, P.W., Van der Ent, R.J., Gordon, L.J., Hoff, H., Nikoli, R. and Savenije, H.H.G. 2012. Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences* 9(2), pp. 733–746. doi: 10.5194/bg-9-733-2012.
- Keys, P.W., Porkka, M., Wang-Erlandsson, L., Fetzer, I., Gleeson, T. and Gordon, L.J. 2019. Invisible water security: Moisture recycling and water resilience. *Water Security* 8, pp. 57–89. doi: 10.1016/j.wasec.2019.100046.
- Keys, P.W., Wang-Erlandsson, L. and Gordon, L.J. 2016. Revealing invisible Water: Moisture recycling as an ecosystem service. *PLoS ONE* 11(3), e0151993. doi: 10.1371/journal.pone.0151993.
- Keys, P.W., Wang-Erlandsson, L., Gordon, L.J., Galaz, V. and Ebbesson, J. 2017. Approaching moisture recycling governance. *Global Environmental Change* 45, pp. 15–23. doi: 10.1016/j.gloenvcha.2017.04.007.
- King, J.A., Weber, J., Lawrence, P., Roe, S., Swann, A.L.S. and Val Martin, M. 2024. Global and regional hydrological impacts of global forest expansion. *Biogeosciences* 21(17), pp. 3883–3902. doi: 10.5194/bg-21-3883-2024.
- Klein Goldewijk, K., Beusen, A., Van Dreht, G. and De Vos, M. 2011. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecology and Biogeography* 20(1), pp. 73–86. doi: 10.1111/j.1466-8238.2010.00587.x.
- Knox, R., Bisht, G., Wang, J. and Bras, R. 2011. Precipitation variability over the forest-to-nonforest transition in Southwestern Amazonia. *Journal of Climate* 24(9), pp. 2368–2377. doi: 10.1175/2010JCLI3815.1.
- Konapala, G., Mishra, A.K., Wada, Y. and Mann, M.E. 2020. Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nature Communications* 11(1), 3044. doi: 10.1038/s41467-020-16757-w.
- Konings, A.G., Dekker, S.C., Rietkerk, M. and Katul, G.G. 2011. Drought sensitivity of patterned vegetation determined by rainfall-land surface feedbacks. *Journal of Geophysical Research: Biogeosciences* 116(4), pp. 1–15. doi: 10.1029/2011JG001748.
- Krönke, J., Wunderling, N., Winkelmann, R., Staal, A., Stumpf, B., Tuinenburg, O.A. and Donges, J.F. 2020. Dynamics of tipping cascades on complex networks. *Physical Review E* 101(4), 042311. doi: 10.1103/PhysRevE.101.042311.
- Laguë, M.M. and Swann, A.L.S. 2016. Progressive midlatitude afforestation: Impacts on clouds, global energy transport, and precipitation. *Journal of Climate* 29(15), pp. 5561–5573. doi: 10.1175/JCLI-D-15-0748.1.
- Latham, J. et al. 2012. Marine cloud brightening. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370(1974), pp. 4217–4262. doi: 10.1098/rsta.2012.0086.

- Lawrence, D. and Vandecar, K. 2015. Effects of tropical deforestation on climate and agriculture. *Nature Climate Change* 5(1), pp. 27–36. doi: 10.1038/nclimate2430.
- Lawrence, M.G., Williams, S., Nanz, P. and Renn, O. 2022. Characteristics, potentials, and challenges of transdisciplinary research. *One Earth* 5(1), pp. 44–61. doi: 10.1016/j.oneear.2021.12.010.
- Layton, K. and Ellison, D. 2016. Induced precipitation recycling (IPR): A proposed concept for increasing precipitation through natural vegetation feedback mechanisms. *Ecological Engineering* 91, pp. 553–565. doi: 10.1016/j.ecoleng.2016.02.031.
- van der Leeuw, S. 2020. *Social sustainability, past and future*. Cambridge University Press.
- Lehmann, P., Merlin, O., Gentine, P. and Or, D. 2018. Soil texture effects on surface resistance to bare-soil evaporation. *Geophysical Research Letters* 45(19), pp. 10398–10405. doi: 10.1029/2018GL078803.
- Leifeld, J. and Menichetti, L. 2018. The underappreciated potential of peatlands in global climate change mitigation strategies /704/47/4113 /704/106/47 article. *Nature Communications* 9(1), 1071. doi: 10.1038/s41467-018-03406-6.
- Leijnse, M., F P Bierkens, M., H M Gommans, K., Lin, D., Tait, A. and Wanders, N. 2024. Key drivers and pressures of global water scarcity hotspots. *Environmental Research Letters* 19(5), 054035. doi: 10.1088/1748-9326/ad3c54.
- Lettau, H., K., L. and Molion, L.C.B. 1979. Amazonia's hydrologic cycle and the role of atmospheric recycling in assessing deforestation effects. *Monthly Weather Reviews* 107, pp. 227–238. doi: [https://doi.org/10.1175/1520-0493\(1979\)107%3C0227:AHCA TR%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1979)107%3C0227:AHCA TR%3E2.0.CO;2).
- Leutwyler, D., Imamovic, A. and Schär, C. 2021. The continental-scale soil moisture-precipitation feedback in Europe with parameterized and explicit convection. *Journal of Climate* 34, pp. 5303–5320. doi: 10.1175/JCLI-D-20.
- Lewis, L.L., Wheeler, C.E., Mitchard, E.T.A. and Koch, A. 2019. Regenerate natural forests to store carbon. *Nature* 568, pp. 25–28. doi: <https://doi.org/10.1038/d41586-019-01026-8>.
- Li, Y. et al. 2023. Contribution of Tibetan Plateau ecosystems to local and remote precipitation through moisture recycling. *Global Change Biology* 29(3), pp. 702–718. doi: 10.1111/gcb.16495.
- Lian, X. et al. 2022. Biophysical impacts of northern vegetation changes on seasonal warming patterns. *Nature Communications* 13(1), 3925. doi: 10.1038/s41467-022-31671-z.
- Liang, W. et al. 2015. Quantifying the impacts of climate change and ecological restoration on streamflow changes based on a Budyko hydrological model in China's Loess Plateau. *Water Resources Research* 51(8), pp. 6500–6519. doi: 10.1002/2014WR016589.
- Liberato, M.L.R., Ramos, A.M., Trigo, R.M., Trigo, I.F., Durán-Quesada, A.M., Nieto, R. and Gimeno, L. 2012. Moisture sources and large-scale dynamics associated with a flash flood event. *Geophysical Monograph Series* 200, pp. 111–126. doi: 10.1029/2012GM001244.

- Link, A., Van Der Ent, R., Berger, M., Eisner, S. and Finkbeiner, M. 2020. The fate of land evaporation - A global dataset. *Earth System Science Data* 12(3), pp. 1897–1912. doi: 10.5194/essd-12-1897-2020.
- Lionello, P. et al. 2006. The Mediterranean climate: An overview of the main characteristics and issues. *Developments in Earth and Environmental Sciences* 4(C), pp. 1–26. doi: 10.1016/S1571-9197(06)80003-0.
- Liu, W., Zhang, Q., Li, C., Xu, L. and Xiao, W. 2022. The influence of soil moisture on convective activity: a review. *Theoretical and Applied Climatology* 149(1–2), pp. 221–232. doi: 10.1007/s00704-022-04046-z.
- Liu, Y. et al. 2023. Revisiting biophysical impacts of greening on precipitation over the Loess Plateau of China using WRF with water vapor tracers. *Geophysical Research Letters* 50(8), e2023GL102809. doi: 10.1029/2023GL102809.
- Liu, Y.-Y., Slotine, J.-J. and Barabási, A.-L. 2011. Controllability of complex networks. *Nature* 473(7346), pp. 167–173. doi: 10.1038/nature10011.
- Löfqvist, S. et al. 2023. How social considerations improve the equity and effectiveness of ecosystem restoration. *BioScience* 73(2), pp. 134–148. doi: 10.1093/biosci/biac099.
- Lotsch, A., Friedl, M.A., Anderson, B.T. and Tucker, C.J. 2003. Coupled vegetation-precipitation variability observed from satellite and climate records. *Geophysical Research Letters* 30(14). doi: 10.1029/2003GL017506.
- Lu, J., Carbone, G.J. and Grego, J.M. 2019. Uncertainty and hotspots in 21st century projections of agricultural drought from CMIP5 models. *Scientific Reports* 9(1), pp. 1–12. doi: 10.1038/s41598-019-41196-z.
- Luo, X., Ge, J., Guo, W., Fan, L., Chen, C., Liu, Y.U. and Yang, L. 2022. The biophysical impacts of deforestation on precipitation: results from the CMIP6 model intercomparison. *Journal of climate* 35(11), pp. 3293–3311. doi: 10.1175/JCLI-D-21.
- Makarieva, A.M. et al. 2023. The role of ecosystem transpiration in creating alternate moisture regimes by influencing atmospheric moisture convergence. *Global Change Biology* 29(9), pp. 2536–2556. doi: 10.1111/gcb.16644.
- Makarieva, A.M., Gorshkov, V.G. and Li, B. 2006. Conservation of water cycle on land via restoration of natural closed-canopy forests: implications for regional landscape planning. *Ecological Research* 21(6), pp. 897–906. doi: 10.1007/s11284-006-0036-6.
- Marey-Pérez, M.F. and Rodríguez-Vicente, V. 2011. Factors determining forest management by farmers in northwest Spain: Application of discriminant analysis. *Forest Policy and Economics* 13(5), pp. 318–327. doi: 10.1016/j.forpol.2011.03.008.
- Marshall, A.R. et al. 2023. Fifteen essential science advances needed for effective restoration of the world's forest landscapes. *Philosophical Transactions of the Royal Society B: Biological Sciences* 378(1867). doi: 10.1098/rstb.2021.0065.

- Materia, S. et al. 2022. Summer temperature response to extreme soil water conditions in the Mediterranean transitional climate regime. *Climate Dynamics* 58(7–8), pp. 1943–1963. doi: 10.1007/s00382-021-05815-8.
- Mayor, Á. G, Bautista, S., Bellot, J. 2009. Factors and interactions controlling, infiltration, runoff, and soil loss at the microscale in a patchy Mediterranean semiarid landscape. *Earth Surface Processes and Landforms* 34, pp. 1702–1711. doi: 10.1002/esp.1875.
- Meaza, H., Abera, W. and Nyssen, J. 2022. Impacts of catchment restoration on water availability and drought resilience in Ethiopia: A meta-analysis. *Land Degradation and Development* 33(4), pp. 547–564. doi: 10.1002/ldr.4125.
- Meehl, G.A. and Tebaldi, C. 2004. More Intense, More Frequent, and Longer Lasting Heat Waves in the 21st Century. *Science* 305(5686), pp. 994–997. doi: 10.1126/science.1098704.
- van Meerveld, H.J., Jones, J.P.G., Ghimire, C.P., Zwartendijk, B.W., Lahitiana, J., Ravelona, M. and Mulligan, M. 2021. Forest regeneration can positively contribute to local hydrological ecosystem services: Implications for forest landscape restoration. *Journal of Applied Ecology* 58(4), pp. 755–765. doi: 10.1111/1365-2664.13836.
- Meier, R., Schwaab, J., Seneviratne, S.I., Sprenger, M., Lewis, E. and Davin, E.L. 2021. Empirical estimate of forestation-induced precipitation changes in Europe. *Nature Geoscience* 14(7), pp. 473–478. doi: 10.1038/s41561-021-00773-6.
- Mekonnen, M.M. and Hoekstra, A.Y. 2016. Sustainability: Four billion people facing severe water scarcity. *Science Advances* 2(2). doi: 10.1126/sciadv.1500323.
- Millán, M.M. 2014. Extreme hydrometeorological events and climate change predictions in Europe. *Journal of Hydrology* 518, pp. 206–224. doi: 10.1016/j.jhydrol.2013.12.041.
- Miller, P.C., Poole, D.K. and Miller, P.M. 1983. The Influence of annual precipitation, topography, and vegetative cover on soil moisture and summer drought in southern California. *Oecologia* 56, pp. 385–391. doi: <https://doi.org/10.1007/bf00379717>.
- Mimeau, L., Trambly, Y., Brocca, L., Massari, C., Camici, S. and Finaud-Guyot, P. 2021. Modeling the response of soil moisture to climate variability in the Mediterranean region. *Hydrology and Earth System Sciences* 25(2), pp. 653–669. doi: 10.5194/hess-25-653-2021.
- Minx, J.C. et al. 2018. Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters* 13(6), 063001. doi: 10.1088/1748-9326/aabf9b.
- Miralles, D.G., Gentile, P., Seneviratne, S.I. and Teuling, A.J. 2019. Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. *Annals of the New York Academy of Sciences* 1436(1), pp. 19–35. doi: 10.1111/nyas.13912.

- Miralles, D.G., Teuling, A.J., Van Heerwaarden, C.C. and De Arellano, J.V.G. 2014. Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nature Geoscience* 7(5), pp. 345–349. doi: 10.1038/ngeo2141.
- Mitman, G., Armiero, M. and Emmett, R. 2018. *Future Remains*. University of Chicago Press. doi: 10.7208/chicago/9780226508825.001.0001.
- Miyamoto, Y., Kajikawa, Y., Yoshida, R., Yamaura, T., Yashiro, H. and Tomita, H. 2013. Deep moist atmospheric convection in a subkilometer global simulation. *Geophysical Research Letters* 40(18), pp. 4922–4926. doi: 10.1002/grl.50944.
- Mo, L. et al. 2023. Integrated global assessment of the natural forest carbon potential. *Nature* 624(7990), pp. 92–101. doi: 10.1038/s41586-023-06723-z.
- Moirano, R., Sánchez, M.A. and Štěpánek, L. 2020. Creative interdisciplinary collaboration: A systematic literature review. *Thinking Skills and Creativity* 35, 100626. doi: 10.1016/j.tsc.2019.100626.
- Molden, D. 2007. *A Comprehensive Assessment of Water Management in Agriculture; Summary*.
- Monin, A.S. and Obukhov, A.M. 1954. Basic laws of turbulent mixing in the surface layer of the atmosphere. *Tr. Akad. Nauk SSSR Geophiz. Inst* 24(151), pp. 163–187.
- Monteith, J.L. 1965. Evaporation and environment. *In Symposia of the society for experimental biology* 19, pp. 205–234.
- Muñoz-Sabater, J. et al. 2021. ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data* 13(9), pp. 4349–4383. doi: 10.5194/essd-13-4349-2021.
- Murakami, S., Tsuboyama, Y., Shimizu, T., Fujieda, M. and Noguchi, S. 2000. Variation of evapotranspiration with stand age and climate in a small Japanese forested catchment. *Journal of Hydrology* 227(1–4), pp. 114–127. doi: 10.1016/S0022-1694(99)00175-4.
- Nair, U.S., Wu, Y., Kala, J., Lyons, T.J., Pielke, R.A. and Hacker, J.M. 2011. The role of land use change on the development and evolution of the west coast trough, convective clouds, and precipitation in southwest Australia. *Journal of Geophysical Research Atmospheres* 116(7). doi: 10.1029/2010JD014950.
- NASA. 2009. *Distance to the nearest coast*. Available at: <https://oceancolor.gsfc.nasa.gov/docs/distfromcoast/> [Accessed: 8 November 2021].
- National Research Council. 1979. *Carbon dioxide and climate: A scientific assessment*. Washington D.C.
- Naudts, K., Chen, Y., McGrath, M.J., Ryder, J., Valade, A., Otto, J. and Luyssaert, S. 2016. Europe's forest management did not mitigate climate warming. *Science* 351(6273), pp. 597–600. doi: 10.1126/science.aad7270.
- Nepstad, D.C. et al. 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature* 372(6507), pp. 666–669. doi: 10.1038/372666a0.

- Newman, M. 2018. *Networks*. second. Oxford University Press.
- Nobre, C.A., Sellers, P.J. and Shukla J. 1991. Amazonian deforestation and regional climate change. *Journal of Climate* 4(10), pp. 957–988. doi: [https://doi.org/10.1175/1520-0442\(1991\)004%3C0957:ADARCC%3E2.0.CO;2](https://doi.org/10.1175/1520-0442(1991)004%3C0957:ADARCC%3E2.0.CO;2).
- Noce, S., Collalti, A. and Santini, M. 2017. Likelihood of changes in forest species suitability, distribution, and diversity under future climate: The case of Southern Europe. *Ecology and Evolution* 7(22), pp. 9358–9375. doi: 10.1002/ece3.3427.
- Noilhan, J. and Mahfouf, J.-F. 1996. The ISBA land surface parameterisation scheme. *Global and Planetary Change* 13(4), pp. 145–159. doi: 10.1016/0921-8181(95)00043-7i.
- Noual, G., Brunet, Y., Le Moigne, P. and Lac, C. 2023. Simulating the effects of regional forest cover and windthrow-induced cover changes on mid-latitude boundary-layer clouds. *Journal of Geophysical Research: Atmospheres* (2015), pp. 1–35. doi: 10.1029/2023jd038477.
- O'Connor, J.C., Dekker, S.C., Staal, A., Tuinenburg, O.A., Rebel, K.T. and Santos, M.J. 2021a. Forests buffer against variations in precipitation. *Global Change Biology* 27(19), pp. 4686–4696. doi: 10.1111/gcb.15763.
- O'Connor, J.C., Santos, M.J., Dekker, S.C., Rebel, K.T. and Tuinenburg, O.A. 2021b. Atmospheric moisture contribution to the growing season in the Amazon arc of deforestation. *Environmental Research Letters* 16(8), 084026. doi: 10.1088/1748-9326/ac12f0.
- Octavia, D. et al. 2023. Smart agroforestry for sustaining soil fertility and community livelihood. *Forest Science and Technology* 19(4), pp. 315–328. doi: 10.1080/21580103.2023.2269970.
- OECD. 2022. *Tackling policy challenges through public sector innovation: A strategic portfolio approach*. Paris: OECD Publishing. doi: 10.1787/052b06b7-en.
- Oki, T. and Kanae, S. 2006. Global hydrological cycles and world water resources. *Science* 313(5790), pp. 1068–1072. doi: <https://doi.org/10.1126/science.1128845>.
- Panchal, P., Preece, C., Peñuelas, J. and Giri, J. 2022. Soil carbon sequestration by root exudates. *Trends in Plant Science* 27(8), pp. 749–757. doi: 10.1016/j.tplants.2022.04.009.
- Pascual, U. et al. 2014. Social equity matters in payments for ecosystem services. *BioScience* 64(11), pp. 1027–1036. doi: 10.1093/biosci/biu146.
- Peel, M.C., Finlayson, B.L. and McMahon, T.A. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences* 11(5), pp. 1633–1644. doi: 10.5194/hess-11-1633-2007.
- Peng, C. et al. 2023. Global spatiotemporal trend of satellite-based soil moisture and its influencing factors in the early 21st century. *Remote Sensing of Environment* 291, 113569. doi: 10.1016/j.rse.2023.113569.
- Peñuelas, J. and Staudt, M. 2010. BVOCs and global change. *Trends in Plant Science* 15(3), pp. 133–144. doi: 10.1016/j.tplants.2009.12.005.

- Pfahl, S. and Sodemann, H. 2014. What controls deuterium excess in global precipitation? *Climate of the Past* 10(2), pp. 771–781. doi: 10.5194/cp-10-771-2014.
- Pielke, S. 2001. Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Reviews of Geophysics* 39(2), pp. 151–177. doi: 10.1029/1999RG000072.
- Pierret, A., Maeght, J.L., Clément, C., Montoroi, J.P., Hartmann, C. and Gonkhamdee, S. 2016. Understanding deep roots and their functions in ecosystems: An advocacy for more unconventional research. *Annals of Botany* 118(4), pp. 621–635. doi: 10.1093/aob/mcw130.
- Pineo, H. et al. 2021. A new transdisciplinary research model to investigate and improve the health of the public. *Health Promotion International* 36(2), pp. 481–492. doi: 10.1093/heapro/daaa125.
- Pingping, H., Xue, S., Li, P. and Zhanbin, L. 2013. Effect of vegetation cover types on soil infiltration under simulating rainfall. *Nature Environment and Pollution Technology* 12(2), pp. 193–198.
- Pires, G.F. 2023. The forest is not yet lost. *Nature Climate Change* 13(7), pp. 606–607. doi: 10.1038/s41558-023-01707-3.
- Pokhrel, Y. et al. 2021. Global terrestrial water storage and drought severity under climate change. *Nature Climate Change* 11(3), pp. 226–233. doi: 10.1038/s41558-020-00972-w.
- Poorter, L. et al. 2016. Biomass resilience of Neotropical secondary forests. *Nature* 530(7589), pp. 211–214. doi: 10.1038/nature16512.
- Portmann, R., Beyerle, U., Davin, E., Fischer, E.M., De Hertog, S. and Schemm, S. 2022. Global forestation and deforestation affect remote climate via adjusted atmosphere and ocean circulation. *Nature Communications* 13(1), 5569. doi: 10.1038/s41467-022-33279-9.
- Pörtner, H.O. et al. 2022. *Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.
- Posada-Marín, J., Salazar, J., Rulli, M.C., Wang-Erlandsson, L. and Jaramillo, F. 2024. Upwind moisture supply increases risk to water security. *Nature Water*, pp. 875–888. doi: 10.1038/s44221-024-00291-w.
- Powlen, K.A. and Jones, K.W. 2019. Identifying the determinants of and barriers to landowner participation in reforestation in Costa Rica. *Land Use Policy* 84, pp. 216–225. doi: 10.1016/j.landusepol.2019.02.021.
- Pranindita, A., Wang-Erlandsson, L., Fetzer, I. and Teuling, A.J. 2022. Moisture recycling and the potential role of forests as moisture source during European heatwaves. *Climate Dynamics* 58(1–2), pp. 609–624. doi: 10.1007/s00382-021-05921-7.
- Raimi, K.T. 2021. Public perceptions of geoengineering. *Current opinion in psychology* 42, pp. 66–70. doi: 10.1016/j.copsyc.2021.03.012.

- Rasmijn, L.M., Van Der Schrier, G., Bintanja, R., Barkmeijer, J., Sterl, A. and Hazeleger, W. 2018. Future equivalent of 2010 Russian heatwave intensified by weakening soil moisture constraints. *Nature Climate Change* 8(5), pp. 381–385. doi: 10.1038/s41558-018-0114-0.
- Richards, F. and Arkin, P. 1998. On the relationship between satellite-observed cloud cover and precipitation. *Monthly Weather Reviews* 109(5), pp. 1081–1093.
- Rios-Entenza, A., Soares, P.M.M., Trigo, R.M., Cardoso, R.M. and Miguez-Macho, G. 2014. Moisture recycling in the Iberian peninsula from a regional climate simulation: Spatiotemporal analysis and impact on the precipitation regime. *Journal of Geophysical Research* 119(10), pp. 5895–5912. doi: 10.1002/2013JD021274.
- Roberts, N. et al. 2012. Palaeolimnological evidence for an east-west climate see-saw in the Mediterranean since AD 900. *Global and Planetary Change* 84–85, pp. 23–34. doi: 10.1016/j.gloplacha.2011.11.002.
- Rockström, J., Mazzucato, M., Andersen, L.S., Fahrländer, S.F. and Gerten, D. 2023. Why we need a new economics of water as a common good. *Nature* 615(7954), pp. 794–797. doi: 10.1038/d41586-023-00800-z.
- Roe, G.H. 2005. Orographic precipitation. *Annual Review of Earth and Planetary Sciences* 33, pp. 645–671. doi: 10.1146/annurev.earth.33.092203.122541.
- Rohatyn, S., Yakir, D., Rotenberg, E. and Carmel, Y. 2022. Limited climate change mitigation potential through forestation of the vast dryland regions. *Science* 377(6613), pp. 1436–1439. doi: 10.1126/science.abm9684.
- Rombach, S., Wagner-Ahlf, C., Riekhof, M.C., and Oppelt, N. 2024. Transdisciplinary research in marine science: What's the added value of involving stakeholders? *Transdisciplinary Journal of Engineering and Science* 15, pp. 297–318. doi: 10.22545/2024/00257.
- Ruijsch, J., Teuling, A.J., Duveiller, G. and Hutjes, R.W.A. 2024. The local cooling potential of land restoration in Africa. *Communications Earth & Environment* 5(1), 495. doi: 10.1038/s43247-024-01650-x.
- Di Sacco, A. et al. 2021. Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. *Global Change Biology* 27(7), pp. 1328–1348. doi: 10.1111/gcb.15498.
- Salati, E., Dall'Olio, A., Matsui, E. and Gat, J.R. 1979. Recycling of water in the Amazon Basin: An isotopic study. *Water Resources Research* 15(5), pp. 1250–1258. doi: 10.1029/WR015i005p01250.
- Salmon, J.M., Friedl, M.A., Frohling, S., Wisser, D. and Douglas, E.M. 2015. Global rain-fed, irrigated, and paddy croplands: A new high resolution map derived from remote sensing, crop inventories and climate data. *International Journal of Applied Earth Observation and Geoinformation* 38, pp. 321–334. doi: 10.1016/j.jag.2015.01.014.

- Sapkota, R.P., Stahl, P.D. and Rijal, K. 2018. Restoration governance: An integrated approach towards sustainably restoring degraded ecosystems. *Environmental Development* 27, pp. 83–94. doi: 10.1016/j.envdev.2018.07.001.
- Savenije, H.H.G. 1995. New definitions for moisture recycling and the relationship with land-use changes in the Sahel. *Journal of Hydrology* 167(1–4), pp. 57–78. doi: 10.1016/0022-1694(94)02632-L.
- Savenije, H.H.G. 2018. Intercepted by lichens. *Nature Geoscience* 11(8), pp. 548–549. doi: 10.1038/s41561-018-0202-9.
- Scheff, J. and Frierson, D. 2012. Twenty-First-Century multimodel subtropical precipitation declines are mostly midlatitude shifts. *Journal of Climate* 25(12), pp. 4330–4347. doi: 10.1175/JCLI-D-11-00393.1.
- Schewe, J. et al. 2014. Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America* 111(9), pp. 3245–3250. doi: 10.1073/pnas.1222460110.
- Schicker, I., Radanovics, S. and Seibert, P. 2010. Origin and transport of mediterranean moisture and air. *Atmospheric Chemistry and Physics* 10(11), pp. 5089–5105. doi: 10.5194/acp-10-5089-2010.
- Seager, R., Osborn, T.J., Kushnir, Y., Simpson, I.R., Nakamura, J. and Liu, H. 2019. Climate variability and change of mediterranean-type climates. *Journal of Climate* 32(10), pp. 2887–2915. doi: 10.1175/JCLI-D-18-0472.1.
- Seckler, D., Barker, R. and Amarasinghe, U. 1999. Water Scarcity in the Twenty-first Century. *International Journal of Water Resources Development* 15(1–2), pp. 29–42. doi: 10.1080/07900629948916.
- Seeley, J.T. and Roms, D.M. 2015. Why does tropical convective available potential energy (CAPE) increase with warming? *Geophysical Research Letters* 42(23), pp. 10429–10437. doi: 10.1002/2015GL066199.
- Seneviratne, S.I. et al. 2010. Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews* 99(3–4), pp. 125–161. doi: 10.1016/j.earscirev.2010.02.004.
- Shahidian, S., Serralheiro, R., Serrano, J., Teixeira, J., Haie, N. and Santos, F. 2012. Hargreaves and other reduced- set methods for calculating evapotranspiration. In: *Evapotranspiration - remote sensing and modeling*. pp. 59–80. doi: 10.5772/18059.
- Shao, R., Zhang, B., Su, T., Long, B., Cheng, L., Xue, Y. and Yang, W. 2019. Estimating the increase in regional evaporative water consumption as a result of vegetation restoration over the Loess Plateau, China. *Journal of Geophysical Research: Atmospheres* 124(22), pp. 11783–11802. doi: 10.1029/2019JD031295.
- Shaw, T.A. et al. 2016. Storm track processes and the opposing influences of climate change. *Nature Geoscience* 9(9), pp. 656–664. doi: 10.1038/ngeo2783.

- Shaw, T.A. 2019. Mechanisms of future predicted changes in the zonal mean mid-latitude circulation. *Current Climate Change Reports* 5(4), pp. 345–357. doi: 10.1007/s40641-019-00145-8.
- Sheil, D. et al. 2019. Forest restoration: Transformative trees. *Science* 366(6463), pp. 316–317. doi: 10.1126/science.aay7309.
- Shukla, J., Nobre, C. and Sellers, P. 1990. Amazon deforestation and climate change. *Science* 247(4948), pp. 1322–1325. doi: 10.1126/science.247.4948.1322.
- Smith, C., Baker, J.C.A. and Spracklen, D. V. 2023. Tropical deforestation causes large reductions in observed precipitation. *Nature* 615(7951), pp. 270–275. doi: 10.1038/s41586-022-05690-1.
- Sodemann, H. 2020. Beyond turnover time: Constraining the lifetime distribution of water vapor from simple and complex approaches. *Journal of Atmospheric Science* 77(2), pp. 413–433. doi: 10.1175/JAS-D-18-0336.1.
- Sodemann, H., Schwierz, C. and Wernli, H. 2008. Interannual variability of Greenland winter precipitation sources: Lagrangian moisture diagnostic and North Atlantic Oscillation influence. *Journal of Geophysical Research Atmospheres* 113(3). doi: 10.1029/2007JD008503.
- Soerianegara, I. and Mansuri. 1994. Factors which determine the success of regreening in Gunung Kidul, Central Java. *Journal of Tropical Forest Science* 7(1), pp. 64–75.
- Spracklen, D. V., Arnold, S.R. and Taylor, C.M. 2012. Observations of increased tropical rainfall preceded by air passage over forests. *Nature* 489(7415), pp. 282–285. doi: 10.1038/nature11390.
- Spracklen, D.V., Baker, J.C.A., Garcia-Carreras, L. and Marsham, J.H. 2018. The effects of tropical vegetation on rainfall. *Annual Review of Environment and Resources* 43(1), pp. 193–218. doi: 10.1146/annurev-environ-102017-030136.
- Staal, A. et al. 2018. Forest-rainfall cascades buffer against drought across the Amazon. *Nature Climate Change* 8(6), pp. 539–543. doi: 10.1038/s41558-018-0177-y.
- Staal, A. et al. 2020a. Hysteresis of tropical forests in the 21st century. *Nature Communications* 11(1), 4978. doi: 10.1038/s41467-020-18728-7.
- Staal, A. 2022. Plants water the planet. *Nature Geoscience* 15(12), pp. 958–959. doi: 10.1038/s41561-022-01086-y.
- Staal, A., Flores, B.M., Aguiar, A.P.D., Bosmans, J.H.C., Fetzer, I. and Tuinenburg, O.A. 2020b. Feedback between drought and deforestation in the Amazon. *Environmental Research Letters* 15(4), 044024. doi: 10.1088/1748-9326/ab738e.
- Staal, A., Koren, G., Tejada, G. and Gatti, L. V. 2023. Moisture origins of the Amazon carbon source region. *Environmental Research Letters* 18(4), 044027. doi: 10.1088/1748-9326/acc676.
- Staal, A., Meijer, P., Nyasulu, M.K., Tuinenburg, O.A. and Dekker, S.C. 2025. Global terrestrial moisture recycling in Shared Socioeconomic Pathways. *Earth System Dynamics* 16(1), pp. 215–238. doi: 10.5194/esd-16-215-2025.

- Staal, A., Theeuwes, J.J.E., Wang-Erlandsson, L., Wunderling, N. and Dekker, S.C. 2024. Targeted rainfall enhancement as an objective of forestation. *Global Change Biology* 30(1), e17096. doi: 10.1111/gcb.17096.
- Steffen, W. et al. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223), pp. 1–29. doi: 10.1126/science.1259855.
- Steffen, W., Grinevald, J., Crutzen, P. and McNeill, J. 2011. The anthropocene: Conceptual and historical perspectives. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369(1938), pp. 842–867. doi: 10.1098/rsta.2010.0327.
- Sterling, S.M., Ducharme, A. and Polcher, J. 2013. The impact of global land-cover change on the terrestrial water cycle. *Nature Climate Change* 3(4), pp. 385–390. doi: 10.1038/nclimate1690.
- Stohl, A., Forster, C., Frank, A., Seibert, P. and Wotawa, G. 2005. Technical note: The Lagrangian particle dispersion model FLEXPART version 6.2. *Atmospheric Chemistry and Physics* 5(9), pp. 2461–2474. doi: 10.5194/acp-5-2461-2005.
- Stokols, D., Misra, S., Moser, R.P., Hall, K.L. and Taylor, B.K. 2008. The ecology of team science: Understanding contextual influences on transdisciplinary collaboration. *American Journal of Preventive Medicine* 35. doi: 10.1016/j.amepre.2008.05.003.
- Strassburg, B.B.N. et al. 2020. Global priority areas for ecosystem restoration. *Nature* 586(7831), pp. 724–729. doi: 10.1038/s41586-020-2784-9.
- Stull, R.B. 1988. *An introduction to boundary layer meteorology*. 1st ed. Kluwer academic publishers.
- Sun, J., Li, G., Zhang, Y., Qin, W. and Wang, M. 2022. Identification of priority areas for afforestation in the Loess Plateau region of China. *Ecological Indicators* 140, 108998. doi: 10.1016/j.ecolind.2022.108998.
- Taylor, C.M., de Jeu, R.A.M., Guichard, F., Harris, P.P. and Dorigo, W.A. 2012. Afternoon rain more likely over drier soils. *Nature* 489, pp. 423–426. doi: 10.1038/nature11377.
- Tedesco, A.M. et al. 2023. The role of incentive mechanisms in promoting forest restoration. *Philosophical Transactions of the Royal Society B: Biological Sciences* 378(1867). doi: 10.1098/rstb.2021.0088.
- Tennekes, H. 1973. A model for the dynamics of the inversion above a convective boundary layer. *Journal of Atmospheric sciences* 30(4), pp. 558–567. doi: [https://doi.org/10.1175/1520-0469\(1973\)030%3C0558:AMFTDO%3E2.0.CO;2](https://doi.org/10.1175/1520-0469(1973)030%3C0558:AMFTDO%3E2.0.CO;2).
- Tennekes, H. and Driedonks, A.G.M. 1981. Basic entrainment equations for the atmospheric boundary layer. *Boundary-Layer Meteorology* 20, pp. 515–531. doi: <https://doi.org/10.1007/BF00122299>.
- Teuling, A.J. et al. 2010. Contrasting response of European forest and grassland energy exchange to heatwaves. *Nature Geoscience* 3(10), pp. 722–727. doi: 10.1038/ngeo950.

- Teuling, A.J. 2018. A hot future for European droughts. *Nature Climate Change* 8(5), pp. 364–365. doi: 10.1038/s41558-018-0154-5.
- Theeuwen, J., Dekker, S., Hamelers, B. and Staal, A. 2024a. Atmospheric moisture recycling in Mediterranean-type climate regions across the world [Data set]. doi: 10.5281/zenodo.13868473.
- Theeuwen, J.J.E., Dekker, S.C., Hamelers, B.V.M. and Staal, A. 2024b. Ecohydrological variables underlie local moisture recycling in Mediterranean-type climates. *Journal of Geophysical Research: Biogeosciences* 129(10), e2024JG008286. doi: 10.1029/2024JG008286.
- Theeuwen, J.J.E., Staal, A., Tuinenburg, O.A., Hamelers, B.V.M. and Dekker, S.C. 2023a. Local moisture recycling across the globe. *Hydrology and Earth System Sciences* 27, pp. 1457–1476. doi: <https://doi.org/10.5194/hess-27-1457-2023>.
- Theeuwen, J.J.E., Staal, A., Tuinenburg, O.A., Hamelers, B.V.M. and Dekker, S.C. 2023b. Local moisture recycling across the globe [Data set]. doi: 10.5281/zenodo.7684640.
- Tian, L., Zhang, B., Chen, S., Wang, X. and Ma, X. 2022. Large-scale afforestation enhances precipitation by intensifying the atmospheric water cycle over the Chinese loess plateau. *Journal of Geophysical Research : Atmospheres* 127, e2022JD036738. doi: 10.1029/2022JD036738.
- Tóth, G. et al. 2008. *Soils of the European Union*. doi: DOI10.2788/87029.
- Trenberth, K.E. 1999. Atmospheric moisture recycling: Role of advection and local evaporation. *Journal of Climate* 12(5 II), pp. 1368–1381. doi: 10.1175/1520-0442(1999)012<1368:amrroa>2.0.co;2.
- Treppiedi, D., Cipolla, G. and Noto, L.V. 2023. Convective precipitation over a Mediterranean area: From identification to trend analysis starting from high-resolution rain gauges data. *International Journal of Climatology* 43(1), pp. 293–313. doi: 10.1002/joc.7758.
- Tuinenburg, O.A., Bosmans, J.H.C. and Staal, A. 2022. The global potential of forest restoration for drought mitigation. *Environmental Research Letters* 17(3), 034045. doi: 10.1088/1748-9326/ac55b8.
- Tuinenburg, O.A., Hutjes, R.W.A. and Kabat, P. 2012. The fate of evaporated water from the Ganges basin. *Journal of Geophysical Research : Atmospheres* 117(1), pp. 1–17. doi: 10.1029/2011JD016221.
- Tuinenburg, O.A. and Staal, A. 2020. Tracking the global flows of atmospheric moisture and associated uncertainties. *Hydrology and Earth System Sciences* 24(5), pp. 2419–2435. doi: 10.5194/hess-24-2419-2020.
- Tuinenburg, O.A., Theeuwen, J.J.E. and Staal, A. 2020a. Global evaporation to precipitation flows obtained with Lagrangian atmospheric moisture tracking [Data set]. doi: 10.1594/PANGAEA.912710.
- Tuinenburg, O.A., Theeuwen, J.J.E. and Staal, A. 2020b. High-resolution global atmospheric moisture connections from evaporation to precipitation. *Earth System Science Data* 12(4), pp. 3177–3188. doi: 10.5194/essd-12-3177-2020.

- United Nations. 2019. *The United Nations world water development report 2019: leaving no one behind*.
- Vautard, R., Cattiaux, J., Yiou, P., Thépaut, J.N. and Ciais, P. 2010. Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nature Geoscience* 3(11), pp. 756–761. doi: 10.1038/ngeo979.
- Vecchi, G.A., Soden, B.J., Wittenberg, A.T., Held, I.M., Leetmaa, A. and Harrison, M.J. 2006. Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature* 441(1), pp. 73–76. doi: 10.1038/nature04744.
- Veldman, J.W. et al. 2015a. Tyranny of trees in grassy biomes. *Science* 347(6221), pp. 484–485. doi: 10.1126/science.347.6221.484-c.
- Veldman, J.W. et al. 2015b. Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *BioScience* 65(10), pp. 1011–1018. doi: 10.1093/biosci/biv118.
- Veldman, J.W. et al. 2019. Comment on “The global tree restoration potential.” *Science* 366(6463). doi: 10.1126/science.aay7976.
- Vereecken, H. et al. 2022. Soil hydrology in the Earth system. *Nature Reviews Earth and Environment* 3(9), pp. 573–587. doi: 10.1038/s43017-022-00324-6.
- Vilà-Guerau de Arellano, J. et al. 2023. Advancing understanding of land–atmosphere interactions by breaking discipline and scale barriers. *Annals of the New York Academy of Sciences* 1522(1), pp. 74–97. doi: 10.1111/nyas.14956.
- Vilà-Guerau de Arellano, J., Gioli, B., Miglietta, F., Jonker, H.J.J., Baltink, H.K., Hutjes, R.W.A. and Holtslag, A.A.M. 2004. Entrainment process of carbon dioxide in the atmospheric boundary layer. *Journal of Geophysical Research Atmospheres* 109(18). doi: 10.1029/2004JD004725.
- Vilà-Guerau de Arellano, J., van Heerwaarden, C.C., van Stratum, B.J.H. and van den Dries, K. 2015. *Atmospheric Boundary Layer*. Cambridge University Press. Available at: <https://www.cambridge.org/core/product/identifier/9781316117422/type/book>.
- Wagner-Ahlf, C. 2022. *Strategies of stakeholder engagement: Mapping and analysis of approaches and strategies within the SEA-EU Alliance*.
- Wallace, J.M. and Hobbs, P. V. 2006. *Atmospheric science: an introductory survey*. 2nd ed. Elsevier.
- Wang, C. and Yang, K. 2022. Changes in the moisture contribution over global arid regions. *Climate Dynamics* (14), pp. 1–15. doi: 10.1007/s00382-022-06600-x.
- Wang-Erlandsson, L. et al. 2022. A planetary boundary for green water. *Nature Reviews Earth and Environment* 3, pp. 380–392. doi: 10.1038/s43017-022-00287-8.
- Wang-Erlandsson, L., Van der Ent, R.J., Gordon, L.J. and Savenije, H.H.G. 2014. Contrasting roles of interception and transpiration in the hydrological cycle - Part 1: Temporal characteristics over land. *Earth System Dynamics* 5(2), pp. 441–469. doi: 10.5194/esd-5-441-2014.

- Wang-Erlandsson, L., Fetzer, I., Keys, P.W., van der Ent, R.J., Savenije, H.H.G. and Gordon, L.J. 2018. Remote land use impacts on river flows through atmospheric teleconnections. *Hydrology and Earth System Sciences* 22(8), pp. 4311–4328. doi: 10.5194/hess-22-4311-2018.
- Weng, W., Luedeke, M.K.B., Zemp, D.C., Lakes, T. and Kropp, J.P. 2018. Aerial and surface rivers: downwind impacts on water availability from land use changes in Amazonia. *Hydrology and Earth System Sciences* 22(1), pp. 911–927. doi: 10.5194/hess-22-911-2018.
- West, J.B., Bowen, G.J., Dawson, T.E. and Tu, K.P. 2010. *Isoscapes: Understanding movement, pattern, and process on Earth through isotope mapping*. Springer. doi: 10.1007/978-90-481-3354-3.
- Wetsus. 2021. *Wetsus business plan 2021 - 2032*.
- Te Wierik, S.A. et al. 2022. The contribution of transpiration to precipitation over African watersheds. *Water Resources Research* 58(11), e2021WR031721. doi: 10.1029/2021WR031721.
- te Wierik, S.A., Cammeraat, E.L.H., Gupta, J. and Artzy-Randrup, Y.A. 2021. Reviewing the impact of land use and land-use change on moisture recycling and precipitation patterns. *Water Resources Research* 57(7), e2020WR029234. doi: 10.1029/2020WR029234.
- Te Wierik, S.A., Gupta, J., Cammeraat, E.L.H. and Artzy-Randrup, Y.A. 2020. The need for green and atmospheric water governance. *Wiley Interdisciplinary Reviews: Water* 7(2), e1406. doi: 10.1002/wat2.1406.
- Williams, E. and Renno, N. 1993. An analysis of the conditional instability of the tropical atmosphere. *Monthly Weather Review* 121(1), pp. 21–35. doi: [https://doi.org/10.1175/1520-0493\(1993\)121%3C0021:AAOTCI%3E2.0.CO;2](https://doi.org/10.1175/1520-0493(1993)121%3C0021:AAOTCI%3E2.0.CO;2).
- Winckler, J., Reick, C.H. and Pongratz, J. 2017. Robust identification of local biogeophysical effects of land-cover change in a global climate model. *Journal of Climate* 30(3), pp. 1159–1176. doi: 10.1175/JCLI-D-16-0067.1.
- van Woesik, F., van Steenberg, F., Sambalino, F., de Boek, H.J., Pace Ricci, J.M. and Bastiaanssen, W. 2023. *Managing the Local Climate*. Practical Action Publishing. doi: 10.3362/9781788532266.
- Wouters, H. et al. 2019. Atmospheric boundary layer dynamics from balloon soundings worldwide: CLASS4GL v1.0. *Geoscientific Model Development* 12(5), pp. 2139–2153. doi: 10.5194/gmd-12-2139-2019.
- Wright, J.S. et al. 2017. Rainforest-initiated wet season onset over the southern Amazon. *Proceedings of the National Academy of Sciences* 114(32), pp. 8481–8486. doi: 10.1073/pnas.1621516114.
- Wunderling, N. et al. 2021. Modelling nonlinear dynamics of interacting tipping elements on complex networks: the PyCascades package. *The European Physical Journal Special Topics* 230(14–15), pp. 3163–3176. doi: 10.1140/epjs/s11734-021-00155-4.

- Wunderling, N. et al. 2022a. Recurrent droughts increase risk of cascading tipping events by outpacing adaptive capacities in the Amazon rainforest. *Proceedings of the National Academy of Sciences* 119(32). doi: 10.1073/pnas.2120777119.
- Wunderling, N., Stumpf, B., Krönke, J., Staal, A., Tuinenburg, O.A., Winkelmann, R. and Donges, J.F. 2020. How motifs condition critical thresholds for tipping cascades in complex networks: Linking micro- to macro-scales. *Chaos: An Interdisciplinary Journal of Nonlinear Science* 30(4). doi: 10.1063/1.5142827.
- Wunderling, N., Wolf, F., Tuinenburg, O.A. and Staal, A. 2022b. Network motifs shape distinct functioning of Earth's moisture recycling hubs. *Nature Communications* 13(1), 6574. doi: 10.1038/s41467-022-34229-1.
- Xi, Y. et al. 2022. Trade-off between tree planting and wetland conservation in China. *Nature Communications* 13(1), 1967. doi: 10.1038/s41467-022-29616-7.
- Xu, R. et al. 2022. Contrasting impacts of forests on cloud cover based on satellite observations. *Nature Communications* 13(1), 670. doi: 10.1038/s41467-022-28161-7.
- Yang, Y. et al. 2023. Evapotranspiration on a greening Earth. *Nature Reviews Earth and Environment* 4(9), pp. 626–641. doi: 10.1038/s43017-023-00464-3.
- Yang, Y. et al. 2024. Climate change exacerbates the environmental impacts of agriculture. *Science* 385(6713), 123568. doi: 10.1126/science.adn3747.
- Yang, Z. and Dominguez, F. 2019. Investigating land surface effects on the moisture transport over South America with a moisture tagging model. *Journal of Climate* 32(19), pp. 6627–6644. doi: 10.1175/JCLI-D-18-0700.1.
- Yin, J., Albertson, J.D., Rigby, J.R. and Porporato, A. 2015. Land and atmospheric controls on initiation and intensity of moist convection: CAPE dynamics and LCL crossings. *Water Resources Research* 51(10), pp. 8476–8493. doi: 10.1002/2015WR017286.
- Zampieri, M., Luong, T.M., Ashok, K., Dasari, H.P., Pistocchi, A. and Hoteit, I. 2024. Leveraging atmospheric moisture recycling in Saudi Arabia and neighboring countries for irrigation and afforestation planning. *Regional Environmental Change* 24(3), 124. doi: 10.1007/s10113-024-02284-7.
- Zemp, D.C. et al. 2014a. On the importance of cascading moisture recycling in South America. *Atmospheric Chemistry and Physics* 14(23), pp. 13337–13359. doi: 10.5194/acp-14-13337-2014.
- Zemp, D.C., Wiedermann, M., Kurths, J., Rammig, A. and Donges, J.F. 2014b. Node-weighted measures for complex networks with directed and weighted edges for studying continental moisture recycling. *EPL (Europhysics Letters)* 107(5), 58005. doi: 10.1209/0295-5075/107/58005.
- Zhang, B., Tian, L., Yang, Y. and He, X. 2022a. Revegetation does not decrease water yield in the Loess Plateau of China. *Geophysical Research Letters* 49(9), e2022GL098025. doi: 10.1029/2022GL098025.

- Zhang, L., Dawes, W.R. and Walker, G.R. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* 37(3), pp. 701–708. doi: 10.1029/2000WR900325.
- Zhang, X., Yi, H., Xue, F., Bruijnzeel, L.A., Cheng, Z. and Liu, B. 2022b. Stability and variability of long-term streamflow and its components in watersheds under vegetation restoration on the Chinese Loess Plateau. *Hydrological Processes* 36(4), e14543. doi: 10.1002/hyp.14543.
- Zhang, Y., Niu, J., Yu, X., Zhu, W. and Du, X. 2015a. Effects of fine root length density and root biomass on soil preferential flow in forest ecosystems. *Forest Systems* 24(1), e012. doi: 10.5424/fs/2015241-06048.
- Zhang, Y. wang, Wang, K. bo, Wang, J., Liu, C. and Shangguan, Z. ping. 2021. Changes in soil water holding capacity and water availability following vegetation restoration on the Chinese Loess Plateau. *Scientific Reports* 11(1), pp. 1–11. doi: 10.1038/s41598-021-88914-0.
- Zhang, Z., Moore, J.C., Huisinigh, D. and Zhao, Y. 2015b. Review of geoengineering approaches to mitigating climate change. *Journal of Cleaner Production* 103, pp. 898–907. doi: 10.1016/j.jclepro.2014.09.076.
- Zhao, M., A, G., Zhang, J., Velicogna, I., Liang, C. and Li, Z. 2020. Ecological restoration impact on total terrestrial water storage. *Nature Sustainability* 4(1), pp. 56–62. doi: 10.1038/s41893-020-00600-7.
- Zhou, F. et al. 2020. Deceleration of China's human water use and its key drivers. *Proceedings of the National Academy of Sciences* 117(14), pp. 7702–7711. doi: 10.1073/pnas.1909902117.
- Zurbenko, I. and Luo, M. 2015. Surface humidity changes in different temporal scales. *American Journal of Climate Change* 04(03), pp. 226–238. doi: 10.4236/ajcc.2015.43018.

Summary

Climate change and land-use change contribute to water scarcity worldwide. Mediterranean-type climate regions specifically, are prone to drying and are identified as climate change hotspots (Ali et al. 2022). Across the globe, there are five major Mediterranean-type climate regions, south-west US, the region surrounding the Mediterranean Sea: the Mediterranean Basin, central Chile, the Cape region of South Africa, and south-west Australia. To mitigate climate change, forestation initiatives are realized for carbon sequestration. However, the hydrological effects of these initiatives remain unclear. Whereas some studies report that enhanced evapotranspiration due to an increase in vegetation results in local drying (Zhang et al. 2001; Brown et al. 2005), other studies suggest that they may enhance rainfall and contribute to increased water availability (Tian et al. 2022; Cao et al. 2024). It remains unclear whether greening may contribute to enhanced water availability in Mediterranean-type climate regions.

Terrestrial moisture recycling describes the return of evaporated water as precipitation over land. Therefore, this metric provides insight into to what extent evapotranspiration contributes to precipitation over land. To understand whether an increase in evapotranspiration contributes to an increase in local rainfall, it is necessary to gain more insights into local moisture recycling, i.e., the return of evaporated water as precipitation locally. So far, moisture recycling has not been systematically studied on a local scale and it remains unclear how it is affected by vegetation.

Moisture recycling can be studied with atmospheric moisture-tracking models. Such models track water vapor, from evaporation source to precipitation sink, to define atmospheric moisture flows. In Chapter 2, the output from a moisture-tracking model is used to quantify local evaporation recycling across the globe. The local evaporation recycling ratio describes the fraction of evaporated water that returns as rainfall within a distance of 0.5° , ca. 50km, from its source. On average, 1%-2% of evaporated water recycles locally across the globe. Local evaporation recycling peaks over relatively wet areas, i.e., with high precipitation, and over mountainous regions. Updrafts in air, due to convection, the general atmospheric circulation and the orographic lift seem to enhance local evaporation recycling.

In Chapter 3, the local precipitation recycling ratio is quantified for the five major Mediterranean-type climate regions worldwide, building on the methodology introduced in Chapter 2. The local precipitation recycling ratio is defined as the fraction of precipitation that originates within ca. 50km from where it precipitates. Similar to local evaporation recycling, on average, 1%-2% of precipitation recycles locally in Mediterranean-type climate regions. Both local evaporation and

precipitation recycling correlate to ecohydrological variables (i.e., directly related to the hydrological cycle or vegetation). However, whereas local evaporation recycling correlates positively to precipitation and is higher in relatively wet regions, local precipitation recycling correlates negatively with precipitation and is higher in relatively dry regions. Finally, different variables that are related to vegetation correlate positively with both local evaporation and precipitation recycling, suggesting that an increase in vegetation may strengthen the local water cycle.

The data that were used to study local evaporation and precipitation recycling in Chapters 2 and 3 do not allow to experiment with land-use changes, and therefore, cannot be used to analyse how vegetation affects the underlying dynamics of local rainfall. In Chapter 4, a process-based model is used to simulate the impact of forestation on the development of the atmospheric boundary layer in the Mediterranean Basin. The development of this layer provides insight into the potential for convective precipitation to occur, which is a typical type of precipitation during summer as it depends on strong solar heating. In the Mediterranean Basin, a land cover change from bare soil to forest seems to have a cooling and wetting effect in regions with relatively high soil moisture content, and a warming and drying effect in regions with relatively low soil moisture content. Furthermore, an increase in soil moisture seems to increase the possibility for convective precipitation to occur. However, this is not necessarily the case as in some regions an increase in soil moisture seems to have a negative impact on the potential for convective precipitation. In addition to the relatively wet regions, forestation may have a positive influence on convective precipitation in coastal regions, over mountains, and in close proximity to regions that already show a possibility of convective precipitation over bare soil.

In addition to enhancing local rainfall, forestation may also enhance rainfall downwind. Chapter 5 discusses that the effects of forestation on rainfall downwind are relevant and significant. Additionally, this chapter describes the processes that underlie rainfall enhancement downwind and it describes the models and data that are currently available and can be used to make an assessment of the hydrological effects of forestation. To improve our understanding of the hydrological effects of forestation in a changing environment, it is crucial to better understand how changes in vegetation and climate affect the atmospheric dynamics and moisture flows. Nevertheless, this chapter underlines that the available tools allow to take into account targeted rainfall enhancement in the planning of forestation initiatives.

Solely a complete understanding of the hydrological effects of forestation will not be sufficient to realize regreening initiatives that contribute to more precipitation. Chapter 6 assesses how the integration of various natural sciences and the

collaboration with stakeholders can be beneficial to create societal impact. The integration of various scientific disciplines contributes to creative solutions and the active involvement of stakeholders promotes effective communication of research outputs as it allows stakeholders to more easily acquire and apply new knowledge. In addition, in the future, regreening initiatives from stakeholders will provide opportunities to test research outputs. This assessment provides insight into the scientific and societal challenges related to rainfall enhancement through regreening, which helps to evaluate and redirect the research focus to eventually achieve the intended impact. Finally, this chapter indicates that to enhance the societal impact of research activities, outputs should be easily accessible, understandable and applicable, in addition to being freely available.

To realize a sustainable restoration project that does not contribute to local drying, a full assessment of its hydrological effects is necessary. The data and models that are applied in this thesis can be used to strategically plan restoration initiatives that aim at rainfall enhancement. Chapter 7 discusses such an engineering approach and how it could be optimized. Important aspects to address include the uncertainty of the models and data, and incorporating a socio-economic impact assessment. Additionally, this chapter presents a solution that may help to realize rainfall enhancement in arid regions. Finally, this chapter ends with an outlook that describes the importance of adopting a transdisciplinary research approach to realize natural water production through regreening.

Samenvatting

Wereldwijd heeft de mens invloed op het klimaat. De uitstoot van broeikasgassen, die warmte vasthouden, zorgt voor een wereldwijde opwarming. De manier waarop we ons land indelen heeft lokale effecten op het klimaat. Zo kan houtkap bijvoorbeeld invloed hebben op perioden van droogte, hittegolven, en overstromingen. Door klimaatverandering is er wereldwijd een toename in watertekorten. Met name gebieden met een mediterraan klimaat zijn gevoelig voor uitdroging en zijn daarom hotspots voor klimaatverandering (Ali et al. 2022). Over de hele wereld zijn er vijf grote gebieden met een mediterraan klimaat: het zuidwesten van de Verenigde Staten, de regio rond de Middellandse Zee, centraal Chili, de Kaapregio van Zuid-Afrika en het zuidwesten van Australië.

Omdat bossen CO₂, een bekend broeikasgas, opvangen, wordt herbebossing gezien als een van de oplossingen om klimaatverandering tegen te gaan. Maar bossen hebben niet alleen invloed op de CO₂ in de lucht, ze hebben ook invloed op de uitwisseling van water tussen de lucht en het land. Om te groeien en gezond te blijven nemen bomen water op uit de grond. Dit water geven ze vervolgens als waterdamp af aan de lucht. Zo helpen bossen het water van het land naar de lucht te verplaatsen. Net als zweten bij mensen zorgt dit voor verkoeling, wat er bijvoorbeeld voor kan zorgen dat hittegolven minder extreem worden.

De waterdamp die de bomen vrijlaten in de lucht zal vervolgens ook voor regen zorgen. Het water kan uitregenen op dezelfde plek als waar deze bomen staan maar het is ook mogelijk dat de wind de waterdamp wegblaast en die op een andere plek uitregent. Als bomen water opnemen uit de grond en dit water vervolgens niet terugkeert als regen op dezelfde plek kan dat voor verdroging zorgen. Maar, als echter genoeg waterdamp uitregent boven deze bomen kan het droogte juist verminderen. In deze scriptie wordt de invloed van planten en bossen, ook wel vegetatie, op de uitwisseling van waterdamp tussen het land en de lucht bestudeerd. Het doel van deze scriptie is om te begrijpen hoe bomen kunnen bijdragen aan meer regen om droogte te verminderen. Hieronder worden de achtergrond en uitkomsten van dit proefschrift in meer detail samengevat.

Het totale effect van het aanplanten van bomen op de watercyclus is onduidelijk. De watercyclus beschrijft de uitwisseling van water tussen de atmosfeer, het land en oceanen. Sommige studies laten zien dat een toename in vegetatie leidt tot lokale uitdroging door meer verdamping (Zhang et al. 2001; Brown et al. 2005) en andere studies suggereren dat bebossing kan bijdragen aan meer regen en daarmee een grotere waterbeschikbaarheid (Tian et al. 2022; Cao et al. 2024). Ook voor gebieden met een mediterraan klimaat is het onduidelijk wat bebossing doet met de waterbeschikbaarheid.

Verdampt water dat terugkeert als regen over land wordt beschreven met vochtrecycling. Vochtrecycling geeft inzicht in welke mate verdamping in een specifiek gebied bijdraagt aan regen over land. Om te begrijpen of een toename in verdamping bijdraagt aan een toename in lokale regenval, is het nodig om meer inzicht te krijgen in lokale vochtrecycling: de terugkeer van verdampt vocht als lokale neerslag. Tot nu toe is vochtrecycling niet systematisch op een lokale schaal bestudeerd en is het onduidelijk hoe lokale vochtrecycling wordt beïnvloed door vegetatie.

Vochtrecycling kan worden bestudeerd met atmosferische vocht-trackingmodellen. Dergelijke modellen volgen waterdamp van verdampingsbron tot het punt waar het uitregent. Dit maakt het mogelijk atmosferische vochtstromen te identificeren. In Hoofdstuk 2 wordt de output van een trackingmodel gebruikt om lokale verdampingsrecycling te kwantificeren voor de hele wereld. De lokale verdampingsrecyclingratio beschrijft de fractie van het verdampte water die terugkeert als neerslag binnen een afstand van 0.5° (ca. 50km) van de bron. In de wereld recyclet gemiddeld 1% tot 2% van verdampt water lokaal. Daarnaast is de lokale verdampingsrecycling hoger dan gemiddeld in relatief natte gebieden met veel neerslag, en in bergachtige gebieden. Opwaartse luchtstroming ten gevolge van lokale opwarming van de lucht, de grootschalige atmosferische circulatie en de luchtstroom over bergen lijken de lokale verdampingsrecycling te verbeteren.

In Hoofdstuk 3 wordt de fractie van neerslag die afkomstig is binnen een straal van ca. 50km waar het uitregent gekwantificeerd. Dit is de lokale neerslagrecyclingratio. In Hoofdstuk 3 wordt voortgebouwd op de methodologie die in Hoofdstuk 2 is geïntroduceerd en ingezoomd op de vijf grootste mediterrane gebieden wereldwijd. Net als bij lokale verdampingsrecycling, wordt gemiddeld 1% tot 2% van de neerslag lokaal gerecycled in de mediterrane klimaatregio's. Zowel lokale verdamping- als neerslagrecycling correleren met onderdelen van de watercyclus. Lokale verdampingsrecycling correleert positief met neerslag en is hoger in relatief natte regio's. Lokale neerslagrecycling correleert negatief met neerslag en is hoger in relatief droge gebieden. Deze tegenstrijdige resultaten zijn het resultaat van de afhankelijkheid van neerslagrecycling van de toevoer van extern vocht. Verdampingsrecycling is per definitie niet afhankelijk van de toevoer van extern vocht. Ten slotte, de hoeveelheid vegetatie correleert positief met zowel lokale verdampings- als neerslagrecycling, wat suggereert dat een toename in vegetatie de lokale watercyclus zou kunnen versterken.

De data die in de hoofdstukken 2 en 3 zijn gebruikt om lokale verdampings- en neerslagrecycling te bestuderen, maken het niet direct mogelijk om te experimenteren met veranderingen in landgebruik. Daarom kunnen deze data op

zichzelf niet gebruikt worden om te onderzoeken hoe vegetatie de onderliggende processen van lokale regenval beïnvloedt. In Hoofdstuk 4 wordt een model gebruikt om de impact van bebossing op de ontwikkeling van de atmosferische grenslaag in het Middellandse Zeegebied te simuleren. De atmosferische grenslaag is de onderste laag van de atmosfeer en wordt beïnvloed door landgebruik. De ontwikkeling van deze laag gedurende de dag geeft inzicht in de mogelijkheid voor convectieve regenval. Dit type regen komt vaak voor in de zomer en zal daarom vanaf nu worden aangeduid als zomerregenval. In het Middellandse Zeegebied lijkt een verandering van kale grond naar bos een verkoelend en vernattend effect te hebben in regio's met een relatief hoog bodemvochtgehalte. De verandering van kale grond naar bos lijkt een opwarmend en uitdrogend effect te hebben in regio's met een relatief laag bodemvochtgehalte. Daarnaast lijkt een toename van het bodemvocht de kans op zomerregenval te vergroten. Dit laatste is echter niet noodzakelijkerwijs het geval, aangezien in sommige regio's een toename van het bodemvocht een negatieve invloed lijkt te hebben op zomerregenval. Naast de relatief natte regio's kan bebossing een positieve invloed op zomerregenval hebben in kustgebieden, boven bergen en in de buurt van plekken waar boven kale grond al kans op zomerregenval is.

Een toename in verdamping door bebossing kan ook regionaal bijdragen aan meer regenval wanneer het verdampte vocht meegenomen wordt door de wind en het verderop gelegen (d.w.z., benedenwinds) uitregent. Hoofdstuk 5 laat zien dat bebossing een relevante en significante impact heeft op regen benedenwinds. Daarnaast beschrijft dit hoofdstuk de processen die een toename in neerslag benedenwinds mogelijk maken, en bespreekt het de modellen en gegevens die momenteel beschikbaar zijn om de effecten van bebossing op regen te bestuderen. Om de effecten van bebossing in een veranderend klimaat beter te begrijpen is het cruciaal om beter te bevatten hoe deze veranderingen het weer en de vochtstromen in de atmosfeer beïnvloeden. Desalniettemin wordt in dit hoofdstuk benadrukt dat beschikbare tools het momenteel mogelijk maken om bij de planning van bebossingsinitiatieven rekening te houden met gerichte verbetering van regenval.

Een beter begrip van het effect van bebossing op regen alleen zal niet genoeg zijn om vergroeningsinitiatieven die bijdragen aan meer regen te realiseren. Hoofdstuk 6 beschrijft hoe de integratie van verschillende natuurwetenschappen en samenwerking met stakeholders nuttig kan zijn om maatschappelijke impact te creëren. Hierbij ligt de nadruk specifiek op vergroening voor natuurlijke waterproductie. De integratie van verschillende wetenschappelijke disciplines draagt bij aan het vinden van creatieve oplossingen. Daarnaast bevordert de actieve betrokkenheid van stakeholders een effectieve communicatie van onderzoeksresultaten omdat het stakeholders in staat stelt nieuwe kennis

gemakkelijker te verwerven en toe te passen. Bovendien zullen in de toekomst vergroeningsinitiatieven van stakeholders waarschijnlijk mogelijkheden bieden om onderzoeksresultaten te testen. Verder biedt dit hoofdstuk inzicht in de wetenschappelijke en maatschappelijke uitdagingen met betrekking tot vergroening. Dit inzicht kan bijdragen aan de evaluatie en optimalisatie van dit onderzoek om uiteindelijk de beoogde impact te bereiken. Ten slotte beschrijft dit hoofdstuk dat, om de impact van het onderzoek te vergroten, de uitkomsten en resultaten van het onderzoek toegankelijk, begrijpelijk en toepasbaar moeten zijn naast dat ze vrij beschikbaar moeten zijn.

Om een inschatting te maken waar vergroening niet bijdraagt aan lokale verdroging, is het nodig om de invloed van vergroening op regen in kaart te brengen. De gegevens en modellen die in dit proefschrift worden toegepast, kunnen helpen om vergroeningsinitiatieven die gericht zijn op meer regen strategisch te plannen. Hoofdstuk 7 bespreekt een dergelijke technologische aanpak. Om deze aanpak te verbeteren moet er meer onderzoek gedaan worden naar de onzekerheid van de modellen en gegevens. Daarnaast is het belangrijk om een inschatting te maken van de invloed van vergroeningsprojecten op de economie en samenleving en dit mee te nemen in de planning. Tot slot geeft dit hoofdstuk een vooruitblik die het belang van de samenwerking tussen wetenschappers van verschillende vakgebieden en belanghebbenden onderstreept om uiteindelijk natuurlijke waterproductie door vergroening te realiseren.

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During my PhD I got several opportunities to supervise, and teach students. I am grateful for the inspiring interactions I had with them. Their enthusiasm and curiosity

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About the author

Jolanda Theeuwen was born on October 10, 1994, in Duiven, the Netherlands. She pursued a Bachelor's degree in Chemistry at the Radboud University in Nijmegen, graduating in 2016. Her academic journey then led her to Wageningen University & Research, where she pursued a Master's degree in Earth & Environment with a specialization in Air Quality & Meteorology and a minor in Hydrology, graduating in 2019.

Jolanda began her PhD research in 2019. This was a collaborative project between Wetsus in Leeuwarden, and the Copernicus Institute for Sustainable Development at Utrecht University. At Wetsus, she was part of the Natural Water Production research theme, working alongside industry partners to develop innovative solutions to water scarcity in arid and semi-arid regions. Her research focused on understanding the exchange of water between land and atmosphere, and exploring the effects of greening on this exchange. The outputs of this project are presented in this thesis. During her PhD, Jolanda was actively involved in outreach activities and teaching, sharing her passion for science, climate, and sustainability.

In 2023, Jolanda became the theme coordinator for the Natural Water Production research theme at Wetsus. Following the completion of her PhD research, she continues to work at Wetsus, contributing to sustainable water technologies as the theme coordinator for the Natural Water Production research theme.

List of publications

- Cropper, S., Solander, K., Newman, B.D., Tuinenburg, O.A., Staal, A., Theeuwes, J.J.E., & Xu, C. (2021). Comparing deuterium excess to large-scale precipitation recycling models in the tropics. *npj Climate and Atmospheric Science*, 4(1), 60.
- Hoek van Dijke, A. J., Herold, M., Mallick, K., Benedict, I., Machwitz, M., Schlerf, M., Pranindita, A., Theeuwes, J.J.E., Bastin, J.F., Teuling, A.J. (2022). Shifts in regional water availability due to global tree restoration. *Nature Geoscience*, 15(5), 363-368.
- Staal, A., Theeuwes, J. J.E., Wang-Erlandsson, L., Wunderling, N., & Dekker, S. C. (2024). Targeted rainfall enhancement as an objective of forestation. *Global Change Biology*, 30(1), e17096.
- Theeuwes, J.J.E., Staal, A., Tuinenburg, O.A., Hamelers, H.V.M., & Dekker, S.C. (2023). Local moisture recycling across the globe. *Hydrology and Earth System Sciences*, 27(7), 1457-1476.
- Theeuwes, J.J.E., Dekker, S.C., Hamelers, H.V.M., & Staal, A. (2024). Ecohydrological variables underlie local moisture recycling in Mediterranean-type climates. *Journal of Geophysical Research: Biogeosciences*, 129(10), e2024JG008286.
- Tuinenburg, O.A., Theeuwes, J.J.E., & Staal, A. (2020). High-resolution global atmospheric moisture connections from evaporation to precipitation. *Earth System Science Data*, 12(4), 3177-3188.

Datasets

- Theeuwes, J. Staal, A., Tuinenburg, O., Hamelers, B., & Dekker, S. (2023). Local moisture recycling across the globe [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.7684640>
- Theeuwes, J., Dekker, S., Hamelers, B., & Staal, A. (2024). Atmospheric moisture recycling in Mediterranean-type climate regions across the world [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.13868473>
- Theeuwes, J., Warnau, S., Benedict, I., Dekker, S., Hamelers, H., van Heerwaarden, C., & Staal, A. (2025). Atmospheric boundary layer development over bare soil and forest in the Mediterranean Basin [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.14716230>
- Tuinenburg, O., Theeuwes, J., & Staal, A. (2020): Global evaporation to precipitation flows obtained with Lagrangian atmospheric moisture tracking [dataset]. PANGAEA, <https://doi.org/10.1594/PANGAEA.912710>



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Selection of Oral Presentations

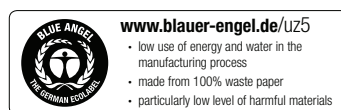
- o *Enhancing the local water cycle in Mediterranean areas: The role of satellite data in regreening.* Wetsus Congress 2021, 4-5 October 2021, Leeuwarden, The Netherlands
- o *Using local moisture recycling to assess the impact of regreening on the local water cycle in five Mediterranean regions.* EGU, 23-27 May 2022, Vienna, Austria
- o *Atmospheric moisture recycling as a key to successful regreening.* European Water Technology Week 2022, 19-21 September 2022, Leeuwarden, The Netherlands
- o *Local moisture recycling across the globe.* EGU, 22-28 April 2023, Vienna Austria

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