Stockholm University

Moisture recycling in forest-agricultural systems

An interdisciplinary view within and across scales

Agnes Pranindita

Doctoral Thesis in Sustainability Science at Stockholm University, Sweden 2026

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An interdisciplinary view within and across scales

Agnes Pranindita

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Abstract

Moisture recycling is a hydrological process that captures the journey of water particles in the atmosphere - starting with terrestrial and oceanic evaporation, continuing with their windborne transport, and ending with precipitation back on land and ocean. Land cover affects the amount of recycled precipitation, and hence the ways we, as humans, use, manage, and govern land concern moisture recycling. Moisture recycling is scarcely managed and governed currently, despite being increasingly recognized as an important process in the biosphere, supporting our society. Moisture recycling is one of the many processes entangling forests and agriculture at various scales, as part of forest-agricultural social-ecological systems. Forests have the potential for securing precipitation for downwind agriculture, although the understanding of this process within the broader forest-agricultural systems remains limited and improving this understanding requires an interdisciplinary approach. As our biophysical understanding of moisture recycling progresses, a question arises: how can we use the knowledge of moisture recycling to guide our activities on land that safeguard forests and agriculture synergistically? The thesis attempts to answer this question by applying a social-ecological systems perspective and an interdisciplinary approach to investigate the interdependence between forests and agriculture through moisture recycling. By applying the forest-agricultural systems context and beyond, the thesis further assesses the need to govern moisture recycling as a mediating process in social-ecological systems. Five papers in this thesis cover different scales of social-ecological processes entangling forests and agriculture. **Paper I** analyzes moisture recycling at the national scale, to conceptualize its interconnection with forests, agricultural production, and crop trade across countries globally. **Paper II** focuses on the regional scale dynamics of moisture recycling and the role of forests as moisture sources during heatwaves in Europe. **Paper III** zooms in on the local scale to detect changes in local forests and shifting cultivation practices as a result of social-ecological pressures on land in the Democratic Republic of Congo. **Paper IV** complements **Paper III** with an investigation into the moisture recycling process connecting local forests with local agricultural practices. Finally, **Paper V** uses a futuring exercise to imagine the governance of moisture recycling as economic goods at diverse scales. Together, these papers suggest that forests support downwind agricultural production through the provision of precipitation within and across scales. This relationship is reciprocal, considering that forests are also influenced by the state of downwind agriculture through social dynamics. Accordingly, moisture recycling unravels a new way of interdependence between forests and agriculture. This thesis advances the moisture recycling knowledge beyond its biophysical aspects, and prompts us to reflect on what governing moisture recycling in the future would entail.

Keywords: *moisture recycling, forests, agriculture, social-ecological systems, interdisciplinary.*

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To Manie and Pada,
and my guardian angels,
for paving the way
that led me *here*.

Abstract

Moisture recycling is a hydrological process that captures the journey of water particles in the atmosphere - starting with terrestrial and oceanic evaporation, continuing with their windborne transport, and ending with precipitation back on land and ocean. Land cover affects the amount of recycled precipitation, and hence the ways we, as humans, use, manage, and govern land concern moisture recycling. Moisture recycling is scarcely managed and governed currently, despite being increasingly recognized as an important process in the biosphere, supporting our society. Moisture recycling is one of the many processes entangling forests and agriculture at various scales, as part of forest-agricultural social-ecological systems. Forests have the potential for securing precipitation for downwind agriculture, although the understanding of this process within the broader forest-agricultural systems remains limited and improving this understanding requires an interdisciplinary approach. As our biophysical understanding of moisture recycling progresses, a question arises: how can we use the knowledge of moisture recycling to guide our activities on land that safeguard forests and agriculture synergistically? The thesis attempts to answer this question by applying a social-ecological systems perspective and an interdisciplinary approach to investigate the interdependence between forests and agriculture through moisture recycling. By applying the forest-agricultural systems context and beyond, the thesis further assesses the need to govern moisture recycling as a mediating process in social-ecological systems. Five papers in this thesis cover different scales of social-ecological processes entangling forests and agriculture. **Paper I** analyzes moisture recycling at the national scale, to conceptualize its interconnection with forests, agricultural production, and crop trade across countries globally. **Paper II** focuses on the regional scale dynamics of moisture recycling and the role of forests as moisture sources during heatwaves in Europe. **Paper III** zooms in on the local scale to detect changes in local forests and shifting cultivation practices as a result of social-ecological pressures on land in the Democratic Republic of Congo. **Paper IV** complements **Paper III** with an investigation into the moisture recycling process connecting local forests with local agricultural practices. Finally, **Paper V** uses a futuring exercise to imagine the governance of moisture recycling as economic goods at diverse scales. Together, these papers suggest that forests support downwind agricultural production through the provision of precipitation within and across scales. This relationship is reciprocal, considering that forests are also influenced by the state of downwind agriculture through social dynamics. Accordingly, moisture recycling unravels a new way of interdependence between forests and agriculture. This thesis advances the moisture recycling knowledge beyond its biophysical aspects, and prompts us to reflect on what governing moisture recycling in the future would entail.

Keywords: *moisture recycling, forests, agriculture, social-ecological systems, interdisciplinary*

Sammanfattning

Fuktåtercirkulering är en hydrologisk process som följer vattenpartiklarnas resa i atmosfären, från avdunstning över land och hav, via vindburen transport, till nederbörd tillbaka över land och hav. Markanvändningen och marktäcket påverkar mängden återcirkulerad nederbörd, och därmed hur vi som människor använder och förvaltar mark i relation till fuktåtercirkulering. Trots att fuktåtercirkulering i allt högre grad erkänns som en viktig process i biosfären som stödjer viktiga samhällsfunktioner, fuktåtercirkulering förvaltas i dagsläget endast i begränsad omfattning. Fuktåtercirkulering är en av flera processer som på olika sätt sammanbinder skogar och jordbruk inom ramen för skogs-jordbruksrelaterade social-ekologiska system. Skogar har potential att bidra till nederbörd som är avgörande för jordbruk nedströms. Samtidigt är förståelsen av denna process, och dess roll i bredare skogs-jordbrukssystem, fortfarande begränsad. För att fördjupa denna förståelse krävs ett tvärvetenskapligt angreppssätt som integrerar biofysiska och samhällsvetenskapliga perspektiv. I takt med att den biofysiska kunskapen om fuktåtercirkulering utvecklats aktualiseras frågan: hur kan denna kunskap användas för att förvalta markrelaterade aktiviteter på ett sätt som både stärker skyddet av skogar och främjar ett hållbart jordbruk? Denna avhandling försöker besvara denna fråga genom att tillämpa ett social-ekologiskt systemperspektiv och ett tvärvetenskapligt angreppssätt för att undersöka det ömsesidiga beroendet mellan skogar och jordbruk via fuktåtercirkulering. Grundat i ett skogs-jordbrukssystemperspektiv synliggör avhandlingen behovet av att förvalta fuktåtercirkulering som en förmedlande process i social-ekologiska system. De fem artiklarna i avhandlingen behandlar olika nivåer av social-ekologiska processer som sammanbinder skogar och jordbruk. **Artikel I** analyserar fuktåtercirkulering på nationell nivå och syftar till att konceptualisera sambanden mellan skogar, jordbruksproduktion och internationell handel med grödor. **Artikel II** fokuserar på regionala dynamiker i fuktåtercirkulering, med särskild betoning på skogars roll som fuktkällor under värmeböljor i Europa. **Artikel III** undersöker lokala processer och analyserar förändringar i lokala skogar samt skiftande odlingsmetoder till följd av social-ekologiska påfrestningar på markanvändningen i Demokratiska Republiken Kongo. **Artikel IV** bygger vidare på **Artikel III** genom att närmare analysera fuktåtercirkuleringsprocessen som länkar samman lokala skogar och lokala jordbruksmetoder. Slutligen använder **Artikel V** en framtidsinriktad analys för att utforska hur fuktåtercirkulering skulle kunna styras som ekonomiska nyttigheter på olika geografiska nivåer. Tillsammans visar artiklarna i denna avhandling att skogar stödjer jordbruksproduktion nedströms genom att tillhandahålla nederbörd inom och mellan olika nivåer. Detta samband är ömsesidigt, eftersom skogar också påverkas av tillståndet i det nedströms jordbruket genom sociala dynamiker i omvänd riktning. Därmed bidar ett fokus på fuktåtercirkulering ett nytt sätt att förstå det ömsesidiga beroendet mellan skogar och jordbruk. Avhandlingen för kunskapen om fuktåtercirkulering bortom dess biofysiska aspekter och uppmanar till reflektion kring vad en framtida förvaltningen av fuktåtercirkulering kan innebära.

Nyckelord: *fuktåtercirkulering, skogar, jordbruk, socioekologiska system, tvärvetenskaplig*

Samenvatting

De recycling van vocht, beker bekend onder de Engelse term ’moisture recycling’, is een hydrologisch proces dat de reis van waterdeeltjes in de atmosfeer weergeeft - beginnend met verdamping van het landoppervlak en de oceanen, gevolgd door transport door de wind en eindigend met neerslag terug op het land en in de oceanen. Landbedekking beïnvloedt de hoeveelheid gerecyclede neerslag, en daarom zijn de manieren waarop wij als mensen land gebruiken, beheren en besturen van belang voor moisture recycling. Moisture recycling wordt momenteel nauwelijks beheerd en gereguleerd, ondanks dat het steeds meer wordt erkend als een belangrijk proces in de biosfeer dat onze samenleving ondersteunt. Moisture recycling is een van de vele processen die bossen en landbouw op verschillende schaalniveaus met elkaar verweven, als onderdeel van de sociaal-ecologische systemen van bosbouw en landbouw. Bossen hebben het potentieel om neerslag voor landbouwgebieden benedenwinds te verzekeren, hoewel het begrip van dit proces binnen de bredere bosbouw- en landbouwsystemen nog beperkt is en een interdisciplinaire aanpak vereist om dit begrip te verbeteren. Naarmate ons biofysisch begrip van moisture recycling vordert, rijst de vraag: hoe kunnen we de kennis over moisture recycling gebruiken om onze activiteiten op het land te sturen die bossen en landbouw op synergetische wijze beschermen? Het proefschrift probeert deze vraag te beantwoorden door een sociaal-ecologisch systeemperspectief en een interdisciplinaire benadering toe te passen om de onderlinge afhankelijkheid tussen bossen en landbouw door middel van moisture recycling te onderzoeken. Door de context van bosbouw-landbouwsystemen en daarbuiten toe te passen, beoordeelt het proefschrift verder de noodzaak om moisture recycling te reguleren als een bemiddelend proces in sociaal-ecologische systemen. Vijf artikelen in dit proefschrift behandelen verschillende schalen van sociaal-ecologische processen waarbij bossen en landbouw met elkaar verweven zijn. **Artikel I** analyseert moisture recycling op nationale schaal, om de onderlinge verbanden met bossen, landbouwproductie en handel in gewassen tussen landen wereldwijd te conceptualiseren. **Artikel II** richt zich op de dynamiek van moisture recycling op regionale schaal en de rol van bossen als vochtbronnen tijdens hittegolven in Europa. **Artikel III** zoomt in op de lokale schaal om veranderingen in lokale bossen en verschuivende landbouwpraktijken als gevolg van sociaal-ecologische druk op land in de Democratische Republiek Congo te detecteren. **Artikel IV** vult **Artikel III** aan met een onderzoek naar het moisture recycling proces dat lokale bossen met lokale landbouwpraktijken verbindt. Ten slotte maakt **Artikel V** gebruik van een toekomstverkenning om zich een beeld te vormen van het beheer van moisture recycling als economisch goed op verschillende schaalniveaus. Samen suggereren deze artikelen dat bossen de landbouwproductie benedenwinds ondersteunen door het leveren van neerslag binnen en tussen schaalniveaus. Deze relatie is wederzijds, aangezien bossen ook worden beïnvloed door de toestand van de landbouw benedenwinds via sociale dynamiek. Moisture recycling onthult dus een nieuwe vorm van onderlinge afhankelijkheid tussen bossen en landbouw. Dit proefschrift gaat verder de gebruikelijkbiofysische focus op moisture recycling en zet ons aan tot nadenken over wat het beheer van moisture recycling in de toekomst zou inhouden.

Trefwoorden: *moisture recycling, bossen, landbouw, sociaal-ecologische systemen, interdisciplinair*

Abstrak

Daur ulang kelembapan merupakan suatu proses hidrologis yang mecakup perjalanan partikel air di atmosfer - diawali dari penguapan terestrial dan oseanik, dilanjutkan dengan transportasi oleh angin, dan diakhiri dengan presipitasi kembali ke daratan maupun lautan. Tutupan lahan mempengaruhi besarnya presipitasi yang mengalami daur ulang; sehingga cara manusia menggunakan, mengelola, dan mengatur lahan berimplikasi terhadap daur ulang kelembapan. Daur ulang kelembapan saat ini hanya dikelola dan diatur secara terbatas, meskipun semakin diakui sebagai proses penting dalam biosfer yang menopang kehidupan masyarakat. Daur ulang kelembapan merupakan salah satu dari berbagai proses yang mengaitkan hutan dan pertanian pada beragam skala, sebagai bagian dari sistem sosial-ekologis hutan–pertanian. Hutan memiliki potensi untuk menjamin ketersediaan presipitasi bagi pertanian di wilayah hilir angin. Namun demikian, pemahaman mengenai proses ini dalam konteks sistem hutan–pertanian yang lebih luas masih terbatas, dan peningkatan pemahaman tersebut memerlukan pendekatan interdisipliner. Seiring dengan berkembangnya pemahaman biofisika mengenai daur ulang kelembapan, muncul pertanyaan mendasar: bagaimana pengetahuan tentang daur ulang kelembapan dapat dimanfaatkan untuk memandu aktivitas manusia pada lahan guna melindungi hutan dan pertanian secara sinergis? Disertasi ini berupaya untuk menjawab pertanyaan tersebut dengan menerapkan perspektif sistem sosial-ekologis serta pendekatan interdisipliner untuk mengkaji ketergantungan antara hutan dan pertanian melalui daur ulang kelembapan. Melalui konteks sistem hutan–pertanian dan lainnya, disertasi ini juga menelaah kebutuhan tata kelola daur ulang kelembapan sebagai suatu proses mediasi dalam sistem sosial-ekologis. Lima makalah dalam disertasi ini mencakup berbagai skala proses sosial-ekologis yang mengaitkan hutan dan pertanian. **Makalah I** menganalisa daur ulang kelembapan pada skala nasional untuk mengonseptualisasikan keterkaitannya dengan hutan, produksi pertanian, dan perdagangan pertanian antar negara secara global. **Makalah II** bertuju pada dinamika daur ulang kelembapan pada skala regional, serta peran hutan sebagai sumber kelembapan pada saat terjadi gelombang panas di Eropa. **Makalah III** mempersempit analisis ke skala lokal dengan mengidentifikasi perubahan pada hutan lokal dan praktik perladangan berpindah sebagai akibat dari tekanan sosial-ekologis terhadap lahan di Republik Demokratik Kongo. **Makalah IV** melengkapi **Makalah III** melalui kajian terhadap proses daur ulang kelembapan yang menghubungkan hutan lokal dengan praktik pertanian lokal. Terakhir, **Makalah V** mengeksplorasi skenario masa depan untuk membayangkan tata kelola daur ulang kelembapan sebagai benda ekonomi pada berbagai skala. Secara keseluruhan, kelima makalah tersebut menunjukkan bahwa hutan mendukung produksi pertanian di wilayah hilir angin melalui penyediaan presipitasi, baik di dalam maupun lintas skala. Hubungan ini bersifat timbal balik, mengingat hutan juga dipengaruhi oleh kondisi pertanian di wilayah hilir melalui dinamika sosial. Daur ulang kelembapan mengungkap bentuk baru hubungan saling ketergantungan antara hutan dan pertanian. Disertasi ini memperluas pemahaman daur ulang kelembapan melampaui aspek biofisikanya, serta mendorong refleksi mengenai tata kelola daur ulang kelembapan di masa mendatang.

Kata kunci: *daur ulang kelembapan, hutan, pertanian, sistem sosial-ekologis, interdisipliner*

List of papers

Paper I **Pranindita, A.**, Teuling, A.J., Fetzer, I., Wang-Erlandsson, L. Forests support global crop supply through atmospheric moisture transport. 2025. *Nature Water* 3, 1243–1255. https://doi.org/10.1038/s44221-025-00518-4

Paper II **Pranindita, A.**, Wang-Erlandsson, L., Fetzer, I., Teuling, A.J., 2022. Moisture recycling and the potential role of forests as moisture source during European heatwaves. *Climate Dynamics* 58, 609–624. https://doi.org/10.1007/s00382-021-05921-7

Paper III **Pranindita, A.**, Koh, N.S., Crépin, A-S., Tyukavina, A., Potapov, P., Bongwele, E., Amani, P.L., Worden, S.R., Keys, P., Zipper, S., Ordway, E., Wong, G., Teuling, A.J., Fetzer, I., Wang-Erlandsson, L. Shifting cultivation livelihoods under social-ecological pressures in the Democratic Republic of Congo. *Manuscript.*

Paper IV **Pranindita, A.**, Staal., A., Bakels, L., Worden, S.R., Fetzer, I., Koh, N.S., Crépin, A-S., Keys, P., Zipper, S., Ordway, E., Teuling, A.J., Wang-Erlandsson, L. Dependence of shifting cultivation practices on precipitation from changing forests in the Democratic Republic of Congo. *Manuscript*.

Paper V Keys, P.W., Wang-Erlandsson, L., Moore, M.-L., **Pranindita, A.**, Stenzel, F., Varis, O., Warrier, R., Wong, R.B., D'Odorico, P., Folke, C., 2024. The dry sky: Future scenarios for humanity's modification of the atmospheric water cycle. *Global Sustainability* 7, e11. https://doi.org/10.1017/sus.2024.9

Contributions

In **Paper I-IV**, I developed the idea, designed the methodology, gathered the data, conducted the analysis, interpreted the results, created the visualizations, wrote and edited the manuscripts. In **Paper I**, I was supported by co-authors in designing the methodology, interpreting the results, and editing the manuscript. In **Paper II**, I also ran the moisture tracking model, and got support from co-authors in developing the idea, designing the methodology, interpreting the results, and editing the manuscript. In **Paper III**, I was supported by co-authors in designing the methodology, gathering the data, interpreting the results, and editing the manuscript. In **Paper IV**, A.S. and L.B. ran the moisture tracking models, and I was supported by co-authors in developing the methodology, interpreting the results, and editing the manuscript. In **Paper V**, I participated in the workshops, wrote a story, and edited the manuscript. The rest of the work in **Paper V** was mainly conducted by P.W.K., with the support from other co-authors.

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Report

FAO, SEI, CI & TNC. 2025. Climate and ecosystem service benefits of forests and trees for agriculture. *Rome, Stockholm, and Arlington*. https://doi.org/10.4060/cd7599en (*contributing author of Chapter 3*)

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Introduction

Moisture recycling is a process in which moisture from land and oceanic surfaces evaporates, travels downwind, and falls back as precipitation on land surfaces and the ocean locally and elsewhere (van der Ent et al., 2010). Moisture flows from upwind regions, namely 'moisture source', to downwind regions, namely 'moisture sink'. Over the past decades, the biophysical aspect of moisture recycling has been increasingly understood, and efforts to intervene in this process have been gradually implemented. Some examples of the interventions include the direct manipulation of atmospheric water[1] through cloud seeding (see 'Governing moisture recycling in social-ecological systems' under 'Theoretical underpinning' for more explanation on cloud seeding) (Rivera et al., 2020) and the indirect implementation of payment for ecosystem services or water licenses on atmospheric water (Jacobson, 2003; Kauffman et al., 2014). However, the consequences of such interventions on atmospheric water, climate, and society at large remain poorly scrutinized. Meanwhile, moisture recycling has the potential to connect different sectors in our society, such as forests and agriculture (Lawrence and Vandecar, 2015). Forests supply precipitation to downwind agriculture through moisture recycling (Commar et al., 2023; Leite-Filho et al., 2021, 2019; Nyasulu et al., 2024; Oliveira et al., 2013; Sierra et al., 2023). Moisture recycling might create a synergy between forests, agriculture, and climate; while forests safeguard precipitation for agriculture that is increasingly threatened by climate change, they also mitigate climate change. One question arises: How can we use the knowledge of moisture recycling to guide our activities on land that safeguard both forests and agriculture? This thesis addresses this broad question by investigating moisture recycling as a process that enables the interdependence between forests and agriculture. Here, I explain my entry point to the thesis and the knowledge gaps.

Forests and agriculture are interdependent

Forests and agriculture are two sectors in our society that are interdependent at various spatial scales. An overview of non-exhaustive processes connecting forests and agriculture is provided in Figure 1 (lower panel). In this thesis, 'interdependence between forests and agriculture' is defined as mutual influence between forests and agriculture, with the state of forests affecting the state of agriculture, and vice versa. The type of interdependence between forests and agriculture varies at different scales, such as between local forests and local farms, forested countries and crop-producing countries, as well as regional forests and regional agriculture (Figure 1, middle panel). At the local scale, forests are important for agriculture and food security of local communities. Forests provide nutritional wild foods (Ickowitz et al., 2022), prevent erosion (Borrelli et al., 2017), enhance water infiltration and soil moisture (Bargués-Tobella et al., 2020), maintain conducive working environment through their evaporative cooling effects (Ellison et al., 2024), and are sources of products and activities for diversifying livelihoods

[1] Atmospheric water refers to the type of water that is contained in the atmosphere, as compared to surface water, groundwater, and soil water that are stored in the ground.

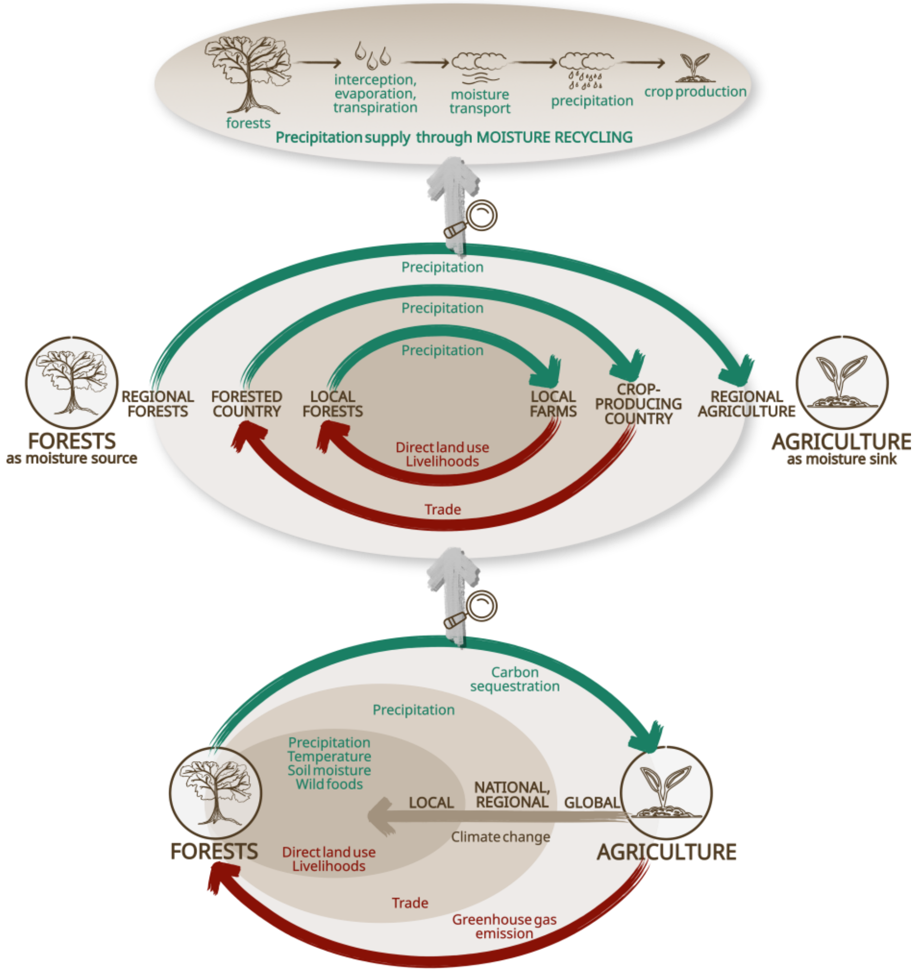

Figure 1- Interdependence between forests and agriculture. (Lower panel) Overview of non-exhaustive bi-directional processes creating interdependence between forests and agriculture within and across the local, national, regional, and global scales. The green texts and arrows signify how forests could affect agriculture within one scale, the red texts and arrows show how agriculture could affect forests in reverse within one scale, while the brown arrows illustrate the cross-scale processes between forests and agriculture. (Middle panel) Zooming in on to some processes that are covered in this thesis, including the supply of precipitation from forests to agriculture at various scales, and the direct land use, livelihoods, and agricultural trade that affect forests. (Upper panel) Further zooming in on the moisture recycling process enabling the supply of precipitation from forests to downwind agriculture, starting from interception, evaporation, and transpiration from forests, to moisture transport, and finally precipitation on agricultural regions.

(Reed et al., 2017). Forests are also located in areas where precipitation is recycled locally (Theeuwen et al., 2023). Forests have the potential to be a reliable moisture source through the abundance of evaporation via interception and transpiration[2] (Schlesinger

[2] Interception is evaporation of precipitated water that falls on the surface of vegetation, among other things, such as on leave surfaces. Interception typically occurs directly after precipitation, preventing water to reach the soil. Transpiration is evaporation that occurs through the stomata of vegetation, as part of the photosynthetic exchange of carbon and water with the atmosphere.

and Jasechko, 2014; Wang-Erlandsson et al., 2014) (Figure 1, upper panel), more access to water through deeper roots (Filoso et al., 2017; Zhang et al., 2001), and high available energy absorbed through lower surface albedo[3] (Bonan, 2008). Forests also affect cloud cover (Luo et al., 2024; Xu et al., 2022) and help create a convective condition given their high surface roughness[4] that enhances atmospheric turbulence and triggers precipitation (Eiras-Barca et al., 2020). Despite the benefits and services that forests provide to agriculture locally, forests have been historically cleared for increasing our food producing capacity through agricultural expansion (Gibbs et al., 2010; Ramankutty and Foley, 1999). Until recently, over 80% of deforestation in the tropical regions still takes place for the creation of new agricultural lands (Curtis et al., 2018; Gibbs et al., 2010; West et al., 2025).

At the regional scale, forests also play an important role in moisture recycling that maintain the resilience of ecosystem and support downwind agriculture. For instance, the Amazon forests in the Brazilian territory supply up to one-third of annual precipitation to the rest of the Amazon located in Peru, Ecuador, Colombia and Bolivia (Flores et al., 2024a). Reduction of westward moisture inflow from the Atlantic ocean during the dry season leads to cascading self-amplification of drought and forest loss in 10-13% of the Amazon basin (Zemp et al., 2017). Less precipitation in eastern Amazon forests nonlinearly decreases the forest resilience, reduces forest cover and evaporation, and cascades into lowered precipitation downwind where the cycle repeats westward affecting the entire Amazon basin (Staal et al., 2018; Zemp et al., 2017). Furthermore, the amount of precipitation determines the state of forests. For instance, the Amazon forests are stable beyond a certain threshold of annual precipitation that ranges in different studies from 1800 to 2500 mm, although this is not based on an exhaustive list of papers on this topic (Flores et al., 2024b; Staal et al., 2018; Staver et al., 2011). These studies estimate that the Amazon forests become unstable below this threshold and could exist in two alternative stable states, with high and low tree cover (Flores et al., 2024b; Staal et al., 2020a; Staver et al., 2011). Deforestation that leads to significant reduction in precipitation regionally might thus lead to a regime shift that changes the state of forests. Another example of regional moisture recycling is in the Congo Basin, where 23 to 68% of annual precipitation is estimated to be recycled within the regions (Bakels et al., 2025; Baker and Spracklen, 2022; Dyer et al., 2017; Nyasulu et al., 2024; Pokam et al., 2012; Sorí et al., 2017; te Wierik et al., 2022). Meanwhile, forests are affected remotely by agriculture through crop demand and trade. The trade network of agricultural products increased in complexity in the past decades, which renders a country or region dependent on another exporting country or region (Burkholz and Schweitzer, 2019). Demands for agricultural crops in the importing regions drive agricultural expansion into forests and water appropriation in the exporting regions (Henders et al., 2015; Lathuillière et al., 2025). For instance, over 120,000 hectares of deforestation in Brazil were dedicated for export of beef to the European Union and soybean to China between 2000 and 2011 (Henders et al., 2015). Over 20% of water that was required for exports to China and the EU was sourced from Brazilian river basins that experienced water scarcity between 2015 and 2017 (Lathuillière et al., 2025).

Globally, forests play a key role in mitigating climate change, which is crucial for supporting agriculture and achieving food security. Net carbon sink of forests amounts to

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[3] Surface albedo is the measure of reflectivity of solar energy radiation from land surfaces. The lower the albedo, the more energy is absorbed.

[4] Surface roughness is a measure of land surfaces' textures in the vertical direction, influencing atmospheric turbulence. Ununiform surfaces, such as forest canopy, have high surface roughness.

around 1 petagram of carbon per year (Pg C per year) between 1990 and 2019, which is equivalent to approximately 15% of global annual fossil fuel emmission (Pan et al., 2024). Forests are also recognized as biodiversity hotspots that are important in the fight against climate change and for safeguarding the ecosystems (IPBES, 2019; Mittermeier et al., 2011). Anomalous precipitation patterns that are associated with climate change negatively affect agriculture as drought alone can cause over 8% losses of national agricultural production and yield (Kim et al., 2019; Lesk et al., 2016), while floods result in up to 4% changes in yield anomaly of the flooded areas (Han et al., 2024). Extreme precipitation events, such as droughts and floods, threaten agricultural production and are predicted to become more frequent and more intense in the coming decades (Gründemann et al., 2022; Jackson et al., 2021; Pokhrel et al., 2021). Forests and their carbon sequestration potential thus indirectly influences the risk of climate change on agriculture. Ironically, agriculture contitutes the biggest proportion of greenhouse gas emmission at 21% that contributes to climate change through the production of fertilizer and methane emmission (IPCC, 2018). The conversion of forests into agriculture also makes up around 20% of global greenhouse gas emisision (Gibbs et al., 2010; Gibbs and Herold, 2007). Reducing the risk of climate change on agriculture would require reconciling the need to deforest for new agricultural lands with forest preservation for maximizing other benefits to agriculture.

Moisture recycling entangles forests and agriculture

The body of literature concurring with the importance of forests for supplying moisture downwind and specifically to agriculture is growing. Forests generally buffer the variability of downwind precipitation through moisture recycling (O'Connor et al., 2021a). Accordingly, deforestation has negative effects on downwind precipitation (Baudena et al., 2021; Duku and Hein, 2021; Silveira et al., 2025; Smith et al., 2023). Between 2003 and 2017, it was observed that the effect on precipitation increased as the scale of deforestation increased and at a 200-km scale, around 0.25 mm per month of precipitation was lost for every 1 percentage point of deforestation (Smith et al., 2023). Deforestation also specifically affects downwind agriculture through reduced amount of precipitation, decreased agricultural productivity, as well as modified onset of rainy seasons (Commar et al., 2023; Lawrence and Vandecar, 2015; Leite-Filho et al., 2021, 2019; Oliveira et al., 2013; Sierra et al., 2023). In the Amazon, up to US$ 1 billion worth of agricultural losses could be incurred due to deforestation that reduces precipitation by up to 200 mm per year, depending on the extent of deforestation (Leite-Filho et al., 2021). Another study estimates that in the best scenario where environmental legislation is implemented in the Amazon, a 47% expansion in agricultural areas only results in 3% and 12% increase in pasture and soybean productivity, respectively, due to negative climate effects (Oliveira et al., 2013). Deforestation in the Amazon also leads to late onset of rainfall season, which creates more uncertainties for agricultural practices (Commar et al., 2023; Sierra et al., 2023). A weak environmental governance for the worst scenario of climate warming results in 30 to 40 days delay in rainfall onset, mainly due to changes in the energy balance and the synoptic-scale atmospheric circulation (Commar et al., 2023). In contrast to deforestation, forest restoration results in more water distributed to the atmosphere through transpiration that is precipitated locally and elsewhere. Transpiration leaves less water to be locally infiltrated into the soil, recharged into aquifers, and run-off into rivers (Brown et al., 2005; Farley et al., 2005). At the river basin scale, this chain of processes leads to reduced local water availability that could amplify already dry conditions for some basins (Hoek van Dijke et al., 2022). These evidence suggests that agriculture is likely to be affected by changes in upwind forest cover through moisture recycling.

Meanwhile, how agriculture affects upwind forests in return is less understood. The local and regional processes explained in the previous sub-section provide some examples on how forests can be affected by agricultural demands, such as deforestation driven by the food demand of local farmers and of distant food consumers through trade. However, these processes have only been partially linked to the moisture recycling process. As shown in the previous paragraph, deforestation is found to alter not only precipitation on agriculture, but also agricultural production and revenue (Commar et al., 2023; Lawrence and Vandecar, 2015; Leite-Filho et al., 2021, 2019; Oliveira et al., 2013; Sierra et al., 2023). In other studies, deviating precipitation on agriculture associated with agricultural production loss, such as drought and late rainfall onset, in turn leads to deforestation (Desbureaux and Damania, 2018; Gou et al., 2022; Leblois, 2021; Zaveri et al., 2020). In developing countries, up to 21% cropland expansion occurs within 1 to 3 years after anomalously low rainfall events that reduced agricultural productivity (Zaveri et al., 2020). In the African rainforests, forest disturbance correlates negatively with precipitation, with the highest forest disturbance coinciding with the driest months of the year (Gou et al., 2022). In West and Central Africa, deforestation increases by 15% in years with unusually short rainy seasons and this increase in deforestation reaches 20% in regions that are more remote with limited access to alternative food and income sources (Leblois, 2021). In Madagascar, farmers cope with drought by clearing forests for additional agricultural lands, amounting up to an 8% increase in deforestation (Desbureaux and Damania, 2018). This evidence suggests that forests are likely to be affected by changes in agriculture through decision making at the household level.

The reverse dependence of moisture source on moisture sink has been hypothesized as social dynamics in the moisture recycling social-ecological systems (MR-SES) framework (Keys and Wang-Erlandsson, 2018). In this framework, moisture source and moisture sink constitute social-ecological systems (SES) through moisture recycling and social dynamics (Keys and Wang-Erlandsson, 2018) (see 'Social-ecological systems' under 'Theoretical underpinning' for definition and theoretical explanations on SES). The MR-SES framework conceptualizes that while moisture sink is dependent unidirectionally on moisture source through moisture recycling, they are all the more entangled through bidirectional social dynamics, creating a feedback between moisture source and moisture sink (Keys and Wang-Erlandsson, 2018). In the MR-SES framework paper, the presence of social dynamics was investigated through social-ecological inequalities, by comparing socially-relevant indicators, such as land use, market influence, and child malnutrition between moisture source and moisture sink (Keys and Wang-Erlandsson, 2018). In this thesis, I apply the MR-SES framework as a conceptual model by contextualizing upwind forests as moisture source and downwind agriculture as moisture sink, with moisture recycling as the mediating process (Figure 1, middle panel). I define the social dynamics between forests and agriculture as the socio-economic processes and interactions pertaining to the ways humans use, manage, and govern land. Studies on moisture recycling in the past decades have mainly focused on the biophysical aspects of the process, with less exploration on the social dynamics.

Very few studies address moisture recycling as being embedded in SES. In one study, moisture recycling was treated as a process that drives moist convection over land, which is identified as a tipping element of SES in southwestern Amazon, along with soil function, livelihood strategy, and social cohesion (Froese et al., 2023). Moisture recycling has also been considered relevant for the resilience of SES at different levels, from catchment to the Earth system (Falkenmark et al., 2019; Gleeson et al., 2020; Keys et al., 2019). Regardless, most of these studies have been done conceptually and more empirical studies are needed to provide evidence of the pertinence of a feedback mediated by moisture recycling in SES. Empirical evidence on social-ecological feedback is more available for other types of water that are studied within the field of socio-hydrology for instance, among other fields. Some examples are the supply-demand cycles and reservoir effects that entangle physical, technical, and social processes in a feedback (Di Baldassarre et al., 2018). The supply-demand cycles refer to the offset of benefits of a reservoir through perceived stable water supply that increases water demand, while the reservoir effect takes place when the vulnerability of a local community to drought increases as they overly rely on reservoirs (Di Baldassarre et al., 2018). These feedback reveal that technical interventions in the water system trigger other socially-driven processes that counteract the benefits of the interventions. I view the level of understanding of feedback in these examples as a long-term objective of studying moisture recycling and social dynamics intertwined in SES.

In this thesis, I hypothesize that feedback in SES involving upwind forests and downwind agriculture connected by moisture recycling exists given the evidence on the relevant processes in other studies. For instance, deforestation of tropical forests leads to reduced precipitation downwind (Smith et al., 2023), while changing precipitation patterns on agriculture drives farmers to deforest more (Leblois, 2021). Both studies include the tropical regions and might refer to the mechanisms that are applicable within the same locality, however the knowledge that they produce is fragmented. A holistic understanding of similar systems consisting moisture recycling, forests, and agriculture that influence each other dynamically might reveal a new phenomenon. A reinforcing feedback loop may exist, as productivity gains expected from agricultural expansion may be hampered by modified precipitation patterns, less suitability to cultivate, and marginal agricultural productivity. Likewise, feedback between forests and agriculture can also exist at a larger scale when forests are important moisture sources regionally, while undergoing changes due to distant drivers, such as agricultural policies or trade, through telecoupling (Bruckner et al., 2015; Ordway et al., 2017; Sylvester et al., 2024). Such feedback would exacerbate the contemporary challenges the food systems already encounter, which points to the need for understanding moisture recycling using a SES perspective for identifying such feedback.

Moisture recycling, forests, and agriculture as a synergistic nexus

Forests and agriculture are commonly seen as competing sectors, as forests are typically cleared for agricultural expansion for increasing crop and food production. However, given the impetus to conserve forests globally for mitigating climate change and maintaining biodiversity, agricultural expansion is seen as one of the solutions that should be ruled out to achieve global food security (Erb et al., 2016; Mehrabi et al., 2018; Phalan et al., 2011; Queiroz et al., 2021). The combination of other solutions, from agricultural intensification, reducing food waste, shifting diets, to improving management practices on land and water (Brown & Funk, 2008; Foley et al., 2011; Godfray et al., 2010; West et al., 2014), have been proposed, but have failed to prevent deforestation for agricultural expansion altogether. Agricultural intensification for instance, has stagnated as yield trend improvements are only half as fast as required to double global crop production by 2050 (Gerber et al., 2024; Ray et al., 2013). Meanwhile, the rate of global agricultural expansion that replaces forest has nearly doubled in the first two decades of the century (Potapov et al., 2022b). This trend begs the question of whether or not ending deforestation for agricultural expansion could be achieved in the near future (Rudel et al., 2009). In addition, agricultural expansion is not only driven by the need to improve food production locally. Pressures to fulfill the demand of agricultural crops globally and the profitability of cultivating high-value commodities offer incentives for people to favor agricultural lands over forests (Meyfroidt, 2018). As opposed to the trade-offs between forests and agriculture, scholars have accumulated evidence on their synergies through ecosystem services, livelihoods, wild food provision, and other aspects (Ickowitz et al., 2022; Rasmussen et al., 2017; Reed et al., 2017). Moisture recycling is one of the climate-regulating ecosystem services put forward, with a potential to help synergize forests and agriculture (Keys et al., 2016). These emerging narratives on synergies counteract the competition between forests and agriculture and suggest that forests can be both a victim of and a solution for agriculture. As the food system challenges coincide with an ever-increasingly unpredictable climate, synergies between forests and agriculture to ensure forest and biodiversity protection, as well as food security, become urgent.

Meanwhile, the knowledge of moisture recycling is growing and the relevance of moisture recycling for our society is increasingly recognized in the literature and in policy discussions (Ellison et al., 2019; FAO et al., 2025). Governance of moisture recycling is scarce but scholars have envisioned it as either existing in its own or integrated into other policies (Keys et al., 2017; te Wierik et al., 2020). Other scholars have expressed the need to consider the climate-regulating benefits of moisture recycling in existing policies, such as for the forest conservation policy to take into account recycled precipitation as another benefit of forests beyond carbon (Ellison et al., 2024; FAO, 2018; van Noordwijk and Ellison, 2019). Regardless, a strategic entry point to existing or new governance mechanisms is needed to advance the governance of moisture recycling (Keys et al., 2017; te Wierik et al., 2020). Meanwhile, as the climate crisis becomes pressing, particularly as a risk for agriculture, mitigation pathways that target ecosystems important for moisture recycling, such as forests, gain momentum. Global, regional, and local agendas have been set to halt deforestation and forest degradation, as well as boost afforestation and reforestation ("Glasgow Leaders' Declaration on Forests and Land Use," 2021; "Kunming-Montreal Global Biodiversity Framework," 2024; "New York Declaration on Forests," 2022). With the potential role of forests in supplying precipitation to agriculture, moisture recycling governance may be synergized with forest governance to ensure that precipitation is safeguarded for agriculture. However, there seems to be a gap between what we now know about moisture recycling and where we are heading. Some questions are inescapable: Do we have enough knowledge of moisture recycling to prove its synergies with conserving forests? If yes, how can we use the knowledge of moisture recycling to imagine its governance that is aligned with forest governance and the aspiration for food security? What else do we need to know before engaging with moisture recycling governance?

Knowledge gaps

In summary, this research addresses three knowledge gaps. Firstly, although moisture recycling from forests is increasingly studied, the specific dependence of agriculture on forests through moisture recycling is still poorly understood. The nature of moisture recycling could render two regions to be dependent remotely and lead to cross-scale interactions between forests and agriculture that are yet to be explored. Secondly, our understanding of moisture recycling is dominated by the understanding of biophysical processes. There are only few studies that look at moisture recycling as a mediating process in a SES that involve social dynamics, with most of them being conceptual studies. Feedback between moisture source and moisture sink might thus be overlooked, despite their potential to have an explanatory power on a system's behavior. In the context of forest and agriculture connected by moisture recycling in SES, empirical evidence is required to reveal this hidden feedback. Thirdly, the knowledge of forests and agriculture interdependence is pursued in silos. More synergies need to be discovered to navigate the complex challenges of our society combining climate change, biodiversity crisis, and food insecurity. Understanding the role of moisture recycling as a process that connects forests and agriculture at different scales, entangling various social-ecological processes, could lead to insights for governing the nexus of forests, moisture recycling, and agriculture.

Aim and scope of the thesis

The objectives of this thesis are threefold. First, the thesis aims to quantify the dependence of agriculture on forests through moisture recycling in different contexts at different spatial and temporal scales. Second, the thesis investigates the pertinence of an interdependence between forests and downwind agriculture. Specifically, the thesis assesses whether the dependence of agriculture on upwind forests mediated by moisture recycling is reciprocal, in a way that forests also depend on downwind agriculture through various processes, such as trade and livelihoods. Third, the thesis aims at providing insights for potentially governing moisture recycling as part of SES that synergize forests, moisture recycling, and agriculture. In order to achieve these objectives, I pose the following research questions (RQ) in the thesis:

1. **To what extent does agriculture depend on moisture from upwind forests?**
2. **Does moisture recycling process mediate an interdependence between forests and agriculture? If yes, what type of interdependence exists and how does it operate?**
3. **What do the key insights from this thesis suggest regarding the need to govern moisture recycling as part of social-ecological systems?**

These RQs are addressed in four first-authored papers and one collaborative paper that comprise this PhD thesis, which are described in Table 1. The first RQ is addressed in **Papers I, II, and IV**, in which the moisture recycling ratios sourced from forests to agriculture were quantified. In this thesis, moisture recycling ratio is expressed as the ratio between either precipitation originated from a certain land areas over total precipitation within a region of interest, or evaporation from a region of interest that falls as precipitation on land over the total evaporation from that region. The use of either precipitation or evaporation for moisture recycling ratio depends on the moisture recycling tracking method (see ‘Moisture tracking modelling and analysis’ under ‘Methods’). Agriculture in the downwind regions of forests was only explicitly addressed in **Papers I and IV**, while in **Paper II**, agriculture was implicitly discussed as one of the sectors that were affected by heatwaves in Europe. The second RQ is raised in **Papers I, III, and IV**. All papers addressing RQ2 explore the reciprocity of the dependence between forests and agriculture. The third RQ is covered in **Papers I - V**, as they could offer insights for assessing the need for governing moisture recycling as part of SES in the future.

Social-ecological processes and their interactions at different spatial and temporal scales were studied in each paper (Table 1). In **Paper I**, the interdependence between forested countries and downwind producers and exporters of agricultural crops was investigated globally. In this paper, the connectivity between national and transboundary moisture and crop flows at monthly and annual scales was mapped out. In **Paper II**, the temporal dynamics of moisture recycling during heatwaves in Europe was investigated, and the role of forests in buffering the effects of precipitation deficit during these extreme events was assessed. In **Paper III**, the consequences of various social-ecological pressures on forests, with an emphasis on climate-induced changes in agriculture, were evaluated for three sub-regions in the Democratic Republic of the Congo

(DRC) during growing and non-growing seasons. Moisture recycling was not directly studied in **Paper III**, but the results of **Paper III** fed into **Paper IV**, in which moisture recycling was quantified. In **Paper IV**, the detected changes on forests upon social-ecological pressures identified in **Paper III** were linked to the moisture recycling process within each of the three sub-regions in the DRC at the annual and seasonal scales. The pertinence of a feedback between forests and agriculture was explored in this paper. Finally, in **Paper V**, moisture recycling governance was imagined through the creation of futuristic stories. Stories involve forests and agriculture from local to regional scales at various temporal scales, which are typically decadal.

Table 1- Overview of papers included in the PhD thesis. Social-ecological interactions of various processes at different spatial and temporal scales, involving moisture recycling, forests, and agriculture.

Paper (RQ)	**Social-ecological interactions**	**Social-ecological processes**	**Spatial (case study) /temporal scales**
I (1,2,3)	Forested countries supplying precipitation to downwind crop producers and exporters	Moisture recycling, agricultural crop production and trade	National (globally)/ Annual, monthly
II (1,3)	Moisture recycling dynamics during heatwaves, with buffering effect of forests	Moisture recycling, heatwaves, atmospheric circulation, evaporation	Regional (Europe)/ Periodic heatwaves
III (2,3)	Shifting cultivators' coping strategies to climate change and other social-ecological pressures on land	Pressures on land, shifting cultivation dynamics, rural livelihoods	Sub-national (DRC)/ Seasonal
IV (1,2,3)	Moisture recycling sustaining precipitation for shifting cultivation practices under land pressures	Moisture recycling, pressures on land, shifting cultivation dynamics, rural livelihoods	Sub-national (DRC)/ Seasonal
V (3)	Story-based scenarios on future modifications of atmospheric water as economic goods	Moisture recycling, regional climate, governance, weather manipulation	Regional (fictional regions)/ Decadal

Theoretical underpinning

This thesis is underpinned by four theoretical concepts: moisture recycling, land-atmosphere interactions over forests, social-ecological systems, and governing moisture recycling in social-ecological systems. After all theoretical concepts are explained, their combination for use in this thesis is summarized.

Moisture recycling

Discourses on the concept of moisture recycling date back to as early as the late 1800s (Eltahir and Bras, 1996). Scholars from the United States started hypothesizing about the contribution of land evaporation to precipitation based on local meteorological observations (Ives, 1936; Jensen, 1936). The role of evaporation from land surface for recycled precipitation was argued, from having the utmost importance locally (Holzman, 1937), to being less significant due to the inflow of atmospheric water and the air mass transport from beyond the local scale (Ives, 1936; Jensen, 1936), to being nearly dismissed as sources of precipitation have been shown to be dominated by water evaporated over the oceans (Benton et al., 1950; Holzman, 1937). One study stood out in the period by arguing that the proportion of precipitation that is originated from the ocean can be associated with the distance of the region from the ocean (Horton, 1943). This finding resonates well with the concept of moisture recycling that is understood today. Decades later, another study used empirical observations on the fraction of oxygen isotopes and concluded that evaporation from the densely vegetated Amazon leads to the recycling of moisture regionally, with spatial and temporal heterogeneities (Salati et al., 1979). Another study provides further evidence showing the tree roots in the Amazon, as deep as 10 meters, are key to maintaining evaporation flows throughout the year (Nepstad et al., 1994).

In the 1990s and 2000s, the focus shifted from discussing the role of land evaporation for recycling precipitation to attempts in estimating the moisture recycling ratio given the advancement of observational technologies and the sophistication of models. The moisture recycling process was framed as the 'continental precipitation multiplier', through which the water particles entering a land mass from the ocean would be amplified by the continental evaporation (Savenije, 1995). By early 2000s, the concept of 'regional moisture recycling' was well studied, which refers to the recycling rate of moisture within one region of interest (Bisselink and Dolman, 2009; Dirmeyer and Brubaker, 2007; Eltahir and Bras, 1996; van der Ent et al., 2010). The concept of 'precipitationsheds' was later introduced to delineate the broader areas from which precipitation in a region of interest originates (Keys et al., 2012). The precipitationsheds framing is inspired by the concept of watersheds, which are highly researched hydrological units that are delineated by the topographical connectivity of surface water and groundwater.

Furthermore, regional moisture recycling is distinguished from ‘advected moisture recycling’, in which the origin of precipitation or destination of evaporation is located outside the region of interest (van der Ent et al., 2010). The estimation of moisture recycling ratio was deemed problematic as it concerns scaling, where the moisture recycling ratio proportionally increases as the area of the study region increases (van der Ent & Savenije, 2011). The issue of scale made comparing the strength of moisture recycling between regions difficult (van der Ent & Savenije, 2011). To address this scaling issue, new spatial and temporal metrics that are not scale-dependent were proposed, namely the ‘length and time scales’, respectively (van der Ent & Savenije, 2011). With these metrics, comparison between regions can be made based on the distance and period of moisture transport over each region. For instance, the study finds that the length and time scales over deserts are larger than tropical and mountainous regions, revealing a weak regional moisture recycling process over deserts, given the lack of physical geography of mountains and of vegetation that could trigger convective precipitation (Theeuwen et al., 2025; Tuinenburg et al., 2020; van der Ent & Savenije, 2011). Nevertheless, the moisture recycling ratio remains the most commonly used metric to assess the importance of regional moisture recycling.

As ellaborated in the previous paragraphs, the knowledge of moisture recycling has evolved in the past decades, from being defined to being quantified. Recently, the development of knowledge of moisture recycling is leaning towards understanding it as a process of societal relevance. Moisture recycling is increasingly found to be important in supplying precipitation to global breadbaskets (Bagley et al., 2012), ecoregions (Miralles et al., 2016), rivers (Wang-Erlandsson et al., 2018), wetlands (Fahrländer et al., 2024), and megacities (Keys et al., 2018), among others. Moisture recycling highlights the importance of conserving forests and other critically important ecosystems as they contribute notably to long-term and periodical precipitation in their downwind areas (Keys et al., 2024; O’Connor et al., 2021a; Sheil, 2018; Tuinenburg et al., 2022). Moisture recycling also facilitates the propagation of other societally-relevant events, such as droughts and heatwaves that are intensified by upwind water deficit (Eiras-Barca et al., 2025; Schumacher et al., 2022, 2019). The use of the precipitationshed concept reveals the exposure of downwind regions to water insecurity risk due to the vulnerability of the upwind regions (Keys et al., 2019; Keys and Wang-Erlandsson, 2018; Posada-Marín et al., 2024). Nevertheless, while recent studies have progressively underlined the importance of moisture recycling in our society, interdisciplinary and transdiciplinary approaches for studying moisture recycling, involving various sectors in our society, are still scarce.

Application in this thesis I intend to broaden the application of moisture recycling knowledge with a systems approach to societally-relevant contexts in which forests supply moisture to downwind agriculture (see ’Social-ecological systems’ in this chapter). I hypothesize that forests are geographically well-connected to downwind agriculture from global to local scales, and thus would supply notable precipitation to agriculture. Accordingly, I expect that the precipitation supplied by forests to downwind agriculture would be crucial for agricultural production. In **Papers I, II, and IV**, I generally use the moisture recycling ratio as a measure to determine the importance of moisture recycling at different scales in this thesis. In **Papers III, IV, and V**, I study the topic interdisciplinarily, combining methods such as moisture recycling analysis, semi-structured interviews, remote sensing analysis, and story-based scenarios.

Land-atmosphere interactions over forests

Land-atmosphere interaction is the exchange of energy, water, carbon dioxide, and other trace gases between land and atmosphere (Wang and Dickinson, 2026). The amount of exchange in land-atmosphere interaction is influenced by biophysical properties of soil, vegetation, and the atmosphere, such as the soil water content, leaf area index, and vapor pressure deficit (Wang and Dickinson, 2026). In this thesis, I focus particularly on the exchange of energy and water that contributes to evaporation and precipitation on land sufaces, particularly concerning forests. The type of land from which water is evaporated has been understood as an important variable in determining the moisture recycling ratio. The body of literature on land-atmosphere interactions has been foundational for distinguishing how different land cover types influence the moisture recycling process. Evaporation that includes direct evaporation, interception, and transpiration are the determining processes of moisture recycling (van der Ent et al., 2014; Wang-Erlandsson et al., 2014). Land cover and land use change thus affects the intensity of moisture recycling through changes in evaporation.

Forests have distinctively conducive evaporative charateristics for moisture recycling, as compared to other land cover types, such as grassland and barren land (Paca et al., 2019; Yang et al., 2023). The plethora of available observations, remote sensing, and reanalysis products allow for the assessment of evaporative characteristics of forests. Here, some examples are given. At the local scale, observational stations, such as the FLUXNET sites[5], have provided reliable data to show that forests have more persistent evaporation over a long term after a water-deficit event, as compared to grasslands (Teuling et al., 2010; van Heerwaarden and Teuling, 2014). Paired catchment experiments at the local scale were also done to prove that afforestation increases evaporation, which alters the water balance of the catchment resulting in decreased streamflow (Brown et al., 2005; Farley et al., 2005). At the regional scale, remotely-sensed observations show that deforestation has significantly changed the climatic characteristics of a region by reducing evaporation while increasing land surface temperature, among other changes (Silveira et al., 2025). At the global scale, remotely-sensed and reanalysis products are used to calculate process-based evaporation rate with six different Budyko models (Hoek van Dijke et al., 2022). The study uniformly finds an increase of evaporation rate over afforested grasslands with spatially heterogenous effects on water availability in different catchments (Hoek van Dijke et al., 2022). Meanwhile, deforestation globally into barren land reduces evaporation and consequent recycled precipitation, suggesting that moisture recycling is vegetation-regulated (Keys et al., 2016). Regardless of the approach used, these studies show the general consensus that the loss of forests for a less vegetated type of land cover, such as savanna, grasslands, and barren lands, leads to decrease in evaporation, while the gain of forests results in an increase in evaporation (Brown et al., 2005; Farley et al., 2005; Hoek van Dijke et al., 2022; Liu et al., 2021; Silveira et al., 2025).

However, there are exceptions to the effect of forest changes on evaporation. For instance, the conversion of forest into rainfed agriculture typically reduces evaporation, while the conversion of forests into intensively irrigated croplands or open water increases evaporation (Sterling et al., 2013; Tuinenburg et al., 2012). These effects on evaporation are driven by the evaporative characteristics of the subsequent land cover

[5] At FLUXNET sites, observational stations were built to conduct direct measurements of fluxes of carbon, water, and energy between land and atmosphere, using the eddy covariance technique. There are over 1000 active and historical FLUXNET sites globally. More information can be found at www.fluxnet.org.

type and other processes that determine the exchange rate of water and energy between land and atmosphere (Bonan, 2008; Miralles et al., 2019; Sterling et al., 2013). Essentially, irradiated energy on land surfaces is partitioned into latent and sensible heat fluxes. Latent heat fluxes from land surfaces, commonly known as evaporation, are influenced by various factors, such as albedo, available energy, temperature, soil moisture, vegetational development stage, stomatal resistance, rooting depth, wind speed, humidity and vapor pressure deficit (Miralles et al., 2011; Wang-Erlandsson et al., 2014). Actual rate of evaporation from land surfaces is lower than or equal to their potential evaporation under certain climatic conditions due to constraints in water and energy (Budyko, 1974). A third constraint on the exchange efficiency of water and energy fluxes was proposed in one study, expressed by the wind speed and vapor pressure deficit variables (Jansen et al., 2023). In a case study in the Netherlands, it is the water availability that is mainly limiting evaporation from forests, as compared to the exchange efficiency and energy availability limitations that are dominant in open water and non-forested lands, respectively (Jansen et al., 2023). Open water especially has higher evaporation than other non-forested lands following deforestation due to the abundance of water, the lack of biological control, and the stored additional energy from summer to winter months (Jansen et al., 2023; Sterling et al., 2013).

In addition to evaporation, other processes influencing land-atmosphere interactions affect the convective conditions for precipitation over forests, such as the resistance to horizontal moisture advection and the turbulence due to surface roughness (Eiras-Barca et al., 2020; Khanna et al., 2017; Lawrence et al., 2022; Luo et al., 2024); the release of biogenic volatile organic compounds that help produce both warming ozone and cooling cloud-forming aerosols (Kulmala et al., 2004; Wang et al., 2021); as well as the balancing effect between increased reflected energy due to higher cloud cover, and lower albedo of forests allowing for higher absorption for shortwave radiation (Bonan, 2008; Duveiller et al., 2021; Ellison et al., 2024; Wang et al., 2009). The effect of changes of forests can also be expressed in the modification of the Bowen ratio, which is defined as as the ratio of temperature-changing sensible heat over evaporating latent heat (Froese et al., 2023). The Bowen ratio is a proxy variable for moist convection that increases as forests are cleared, creating a self-amplifying feedback mechanism where an increased Bowen ratio reduces moist convection over deforested areas, lowering vegetational primary production, and further reduces evaporation (Froese et al., 2023). Moreover, the size of deforested patches and the heterogeneity of landscapes following deforestation also play a role in resulting precipitation, with small deforested patches having less effect on the reduction of precipitation due to thermodynamic effects (Khanna et al., 2017; Lawrence and Vandecar, 2015). The dominance of moisture recycling in affecting precipitation against all these other processes is still poorly understood (Goessling and Reick, 2011). A holistic understanding of the effect of forest conversion to agriculture, particularly to inform management and governance in a certain region, would require the consideration of all these processes combined. However, these processes are not considered in the moisture recycling process by definition.

Application in this thesis I hypothesize that forest cover change would lead to changes in evaporation, which further affects the precipitation and the moisture recycling ratio in the downwind regions. To account for the moisture recycling process, I do not consider other processes than evaporation upon land cover change. In **Papers I, II, and IV**, I assume that the evaporation (change) from upwind forests is proportional to precipitation (change) on downwind agriculture, given that the atmospheric circulation and atmospheric water transport remain relatively stable over decades.

Social-ecological systems

SES are systems in which humans and nature interact reciprocally in complex, non-linear, dynamic, and unpredictable ways (Liu et al., 2007). SES are constituted by how the elements in the system relate and interact with each other, rather than by their individual properties (Berkes et al., 2008, 2000). SES are complex adaptive systems in which the ecological and social elements of the system are intertwined (see next paragraph for more details) (Biggs et al., 2021; Walker and Salt, 2012). SES are characterized by six organizing principles: they are constituted relationally, adaptive, dynamic, radically open, contextual, and complex with emergent behaviors (Preiser et al., 2018). Unpredictable behaviors might emerge in SES due to different characteristics of the system, such as non-linear dynamics, dominant feedback loops, or thresholds over which the systems would undergo a regime shift (Meadows, 2008; Preiser et al., 2018). The emergence of the systems' behavior means that we cannot study SES only from any single interaction in the system, but instead from the system as a whole. Upon changing conditions, the systems adapt and are self-organizing with no central element in control, creating a feedback process that in turn affects the elements and their interactions (Preiser et al., 2018). The function of the systems depends heavily on the context in which they are viewed (Preiser et al., 2018). While SES' boundaries contextually define what are inside the system, the systems remain radically open and are influenced by processes outside considered boundaries (Preiser et al., 2018).

Research on SES has been done at different gradients of entanglement between the ecological and social processes; from ecological processes being linked or coupled to social processes (Berkes et al., 2000), social and economic processes being embedded within the biosphere (Folke, 2016); to ecological and social processes being intertwined through intra-active and co-evolving characteristics (Folke et al., 2016; Schlüter et al., 2020). Intertwinedness of SES points to the inseparable and co-constitutive nature of social and ecological processes within the system in that it is not possible to describe the social processes of the system without referring to the ecological processes, and vice versa (Biggs et al., 2021). As such, social and ecological processes cannot exist independently within SES as it is their interaction that allows a social-ecological phenomenon into being (Folke et al., 2016; Schlüter et al., 2019). A social-ecological phenomenon is defined as an empirical observation in the real world that can be understood and explained (Schlüter et al., 2019). Due to the contextuality of SES, the SES framework is most commonly applied in place-based research that focuses on one spatial scale (de Vos et al., 2019). However, interactions between processes across different scales also characterize SES as they contribute to non-linear dynamics, emergent phenomena, and the complexity of the system (Scholes et al., 2013).

Application in this thesis As described in the 'Introduction', the MR-SES framework is used in this thesis as a conceptual model, consisting of forests as moisture sources and agriculture areas as moisture sinks that are connected by moisture recycling and social dynamics (Keys and Wang-Erlandsson, 2018) (Figure 2a). In the MR-SES framework, social dynamics were defined as 'social drivers, feedbacks, interactions, or other social features of a complex adaptive system' (page 832), and were represented as bi-directional social processes between moisture sources and sinks (Keys and Wang-Erlandsson, 2018) (red arrows in Figure 2a). As mentioned in the 'Introduction', here I define the social dynamics between forests and agriculture as the socio-economic processes and interactions pertaining to the ways humans use, manage, and govern land. I only consider the processes unidirectionally from agriculture to forests. The combination of moisture recycling and social dynamics entangling forests and agriculture in opposite directions is treated as an interdependence in this thesis, which is a good first step to understanding social-ecological feedback mediated by moisture recycling. Moreover, the MR-SES framework was proposed alongside MR-SES archetypes, in which the cross-scale interactions between social-ecological processes were conceptualized (Keys and Wang-Erlandsson, 2018). In this thesis, I adapted the MR-SES archetypes to the context of forests and agriculture (Figure 2b). In each paper, different processes of this MR-SES archetype are covered either explicitly or implicitly (see 'Summary of papers' section). Moisture recycling in SES is addressed implicitly in **Paper I** and explicitly in **Paper IV**.

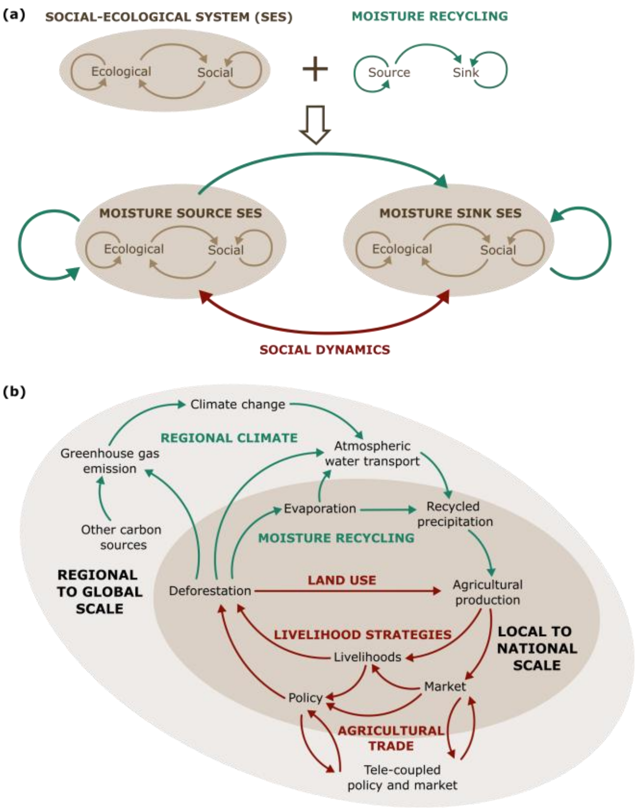

Figure 2 - (a) Conceptualization of moisture-recycling social-ecological systems (MR-SES) in Keys and Wang-Erlansson (2018). (b) Archetypes of MR-SES in Keys and Wang-Erlandsson (2018) adapted for its contextualizion through the forests and agriculture interdependence in this study.

Governing moisture recycling in social-ecological systems

Efforts to intervene with the atmospheric water flows have been implemented with uncertain effects on precipitation, such as through cloud seeding[6]. A couple of studies

[6] Cloud seeding is the addition of ice-nucleating particles, namely seeding agents, such as silver iodide, dry ice, and salt, into the atmosphere to initiate their interactions with clouds or super-cooled water droplets and ultimately modify the weather patterns. Cloud seeding can be used for precipitation enhancement, hail suppression, fog dissipation, and other purposes, with the use of ground-based generators, aircrafts, or rockets (Rivera et al., 2020). The first idea to modify the weather dates back to the late 19th century and the first experiment of cloud seeding took place in 1946 (Schaefer, 1968).

on cloud seeding for protecting agricultural crops by hail surpression show positive results in the reduction of hail energy and size (Dessens et al., 2016; Lu and Skidmore, 2025), with one study illustrating positive effects on crop yield and crop insurance loss (Knowles and Skidmore, 2021). However, reporting of positive results might be biased, as some reports were written by actors who benefit from the continuation of the cloud seeding projects (Dessens et al., 2016). Meanwhile, other studies found no significantly positive effect of cloud seeding on hail suppression (Gavrilov et al., 2013; Rivera et al., 2020). One study suggests that while cloud seeding managed to reduce hail size, there was no significant reduction of crop damages due to hail or drought and more association of crop damages with floods was observed instead (Lu and Skidmore, 2025). In addition, spillover effects, in which downwind crop productivity decreased, and uncertainty on the effect of seeding agents used in cloud seeding on public health and the environment, were also identified (Lu and Skidmore, 2025; Rivera et al., 2020). While cloud seeding has been implemented for over 60 years in some regions (Rivera et al., 2020), this evidence shows that atmospheric water has been modified without a holistic understanding of its benefits and effects on society and the environment. Changes in the atmospheric water balance, undetected health and environmental effects of seeding agents, and potential conflicts between enriched upwind regions while downwind regions are deprived of atmospheric water, can be speculated if unregulated and unmonitored cloud seeding technology continues to be implemented. This is one of the argued reasons why governance of atmospheric water is important and needed (te Wierik et al., 2020).

Currently, governance mechanisms on moisture recycling processes or atmospheric water are scarce. A review of regulatory, economic, and suasive environmental governance instruments on water found that while atmospheric water might be indirectly impacted by some of the 14 identified policy instruments, only two instruments specifically address atmospheric water (te Wierik, 2024). The first instrument is the Green Water Credit, which is a Payment for Ecosystem Service (PES) scheme in the Upper Tana Basin in Kenya (Kauffman et al., 2014). The scheme required downstream businesses to pay upstream farmers to prevent soil erosion at their farms (Kauffman et al., 2014). By doing so, they sustain soil evaporation rate and control streamflow, among other benefits (Kauffman et al., 2014). The second instrument is part of the South Africa's Water Policy, where investors of timber plantations were demanded to pay for licenses of water use due to the high evaporation rate of the timber species, which rendered water less available for other users (Jacobson, 2003; van Noordwijk et al., 2014). The rest of the policy instruments were targeted for surface and groundwater.

Merely expanding the governance of surface water and groundwater to atmospheric water would not suffice due to three reasons. First, the ways in which different regions are connected through atmospheric water are different than through surface water or groundwater. In the Green Water Credit example in Kenya, the payment scheme follows the upstream and downstream division of regions delineated by topography and its resulting surface water flow distribution within the basin (Kauffman et al., 2014). Such a division for regions connected by moisture recycling does not apply, as delineation of the precipitationshed is based on dynamic wind patterns that modify moisture recycling over seasons and across years (Navale and Karthikeyan, 2023; Zhong et al., 2022). Another study argues otherwise, suggesting that fluctuations of evaporation from namely 'core precipitationsheds' explain most of the variance in precipitationsheds and that core precipitationsheds minimally vary spatially (Keys et al., 2014). Regardless, as atmospheric circulation patterns are prone to changes in light of climate change (Shaw et al., 2024; Vautard et al., 2023), upwind and downwind regions of precipitationshed, analogous to upstream and downstream regions of surface watershed, may be more unpredictable in the future. Comparing precipitationsheds and watersheds also reveals distinctive risks for water security, stemming from the different management of upwind versus upstream regions, respectively (Posada-Marín et al., 2024).

Second, the spatio-temporal dynamics imposed by the wind patterns, among other biophysical processes relevant for moisture recycling, intersect with social dynamics that have not been explored empirically. Studies in Sub-Saharan Africa show that even with the best irrigation or water harvesting technology and infrastructural development, a thriving agricultural system could not be achieved without understanding the social dynamics in the regional and local contexts, such as the history of agricultural system and market access (Bjornlund et al., 2017; Mwamakamba et al., 2017; Piemontese et al., 2021). Agricultural intervention can lead to surprising regime shifts, with moisture recycling being the changing slow variable, such as the feedback between deforestation, recycled precipitation, drought, and agricultural fires in the Amazon, that may lead to the abrupt conversion of forests into savannas (Gordon et al., 2008; Staal et al., 2020b). Presently, too little is known about the feedback between moisture source and sink regions mediated by social dynamics and moisture recycling. Third, both spatio-temporal and social dynamics of moisture recycling, and of other types of water in general, challenge our current approaches in governing water. While river basins and watersheds are spatially and temporally connected across scales, their governance institutions operate on a geographically-bounded and closed system solely based on water flow distributions (Moore et al., 2024). These institutions lack 'fitness' to cope with complex and cross-scale water dynamics observed in the growing knowledge of Anthropocene water science, such as regime shift, telecoupling, and concurrent extreme events (Moore et al., 2024). For institutions to have the fitness needed to govern moisture recycling in the future, rethinking the current mode of governance of other water types is required, such as through introducing water-governing institutions with different capacities in responding to crisis, anticipating or adaptive, transforming, and incipiency (Moore et al., 2024).

Nevertheless, governance of moisture recycling can still draw on the existing governance of surface water and groundwater. Water can be governed directly, such as the application of water taxation (Kyei and Hassan, 2021), water subsidies (Gómez-Lobo and Contreras, 2003; Morales-Novelo et al., 2018), and water licenses (Le Maitre et al., 2002). Water can also be governed indirectly through the use of land for agriculture or protected areas. The Green Water Credit PES scheme explained above is an example of how indirectly upstream agricultural management of soil benefits the water availability for downstream communities (Kauffman et al., 2014). Likewise, the water licenses required for investing in South African timber plantation described above is also an example of an indirect atmospheric water governance (Jacobson, 2003). There are also concepts around agricultural interventions that address its indirect consequences on water, such as the accounting of 'water footprint' as impacts of agricultural practices on water resources (Hoekstra and Mekonnen, 2012; Mialyk et al., 2024; Tamea et al., 2021) and the comparability of the property rights approach of land grabbing to water, sometimes referred to as 'water grabbing' (Dell'Angelo et al., 2018; Rulli et al., 2013). Furthermore, the indirect governance of water can also be done through protecting certain ecosystems, such as the reduction of deforestation targets of the European Union's Regulation on Deforestation-free Products (EUDR) policy (Coenen et al., 2025; Johnston et al., 2025), Tropical Forests Forever Facility (TFFF) (TFFF, 2025), and the Reduce Deforestation and Degradation (REDD+) programs (Guizar-Coutiño et al., 2022; Theresia et al., 2025). Conserving forests indirectly benefits the regulation of the water cycle through moisture recycling.

Lastly, water can also be governed in a more integrated system that involves more sectors, such as the Integrated Water Resources Management (IWRM) (Al Radif, 1999), the Sustainable Land and Water Management (SLWM) (Kassie et al., 2015; Mangole et al., 2025), and the (Forests-)Food-Water-Energy-Nexus (Bazilian et al., 2011; Melo et al., 2021). All these different governance instruments and concepts could act as an entry point for governing moisture recycling. However, the question remains on the extent to which these instruments or concepts would be sufficient to address the governance of moisture recycling as a dominant process in SES. As a comparison, a framework of 'groundwater-connected systems' was proposed as an approach to view groundwater systems as SES with the pertinence of thresholds, feedback, nonlinear processes, and emergent phenomena, among others (Huggins et al., 2023). Similar to groundwater-connected systems, governing moisture recycling in SES requires an approach that is suited for dealing with the principles of SES; constituted relationally, adaptive, dynamic, radically open, contextual, and complex with emergent behaviors (Preiser et al., 2018).

Application in this thesis Sustainable Rural Livelihoods and Economic Goods frameworks were used to gain insights for governing moisture recycling in SES. The two frameworks capture the social dynamics of interest, which are the socio-economic processes and interactions through which lands are used, managed, and governed by humans. The Sustainable Rural Livelihoods framework was used in **Papers III and IV** (Scoones, 1998). The framework represents a system of livelihoods that constitutes four categories of social-ecological aspects, which are (1) contexts, conditions, and trends, (2) livelihood capital, (3) institutional structures and governance, (4) livelihood strategies, and (5) livelihoods outcomes. Sustainable livelihood is defined as a diverse web of activities that maintain one's ability to make a living without restraining the natural resource base (Scoones, 2009). In **Papers III and IV**, the framework was used to investigate the coping strategies of smallholder farmers practicing shifting cultivation to respond to climate change and other social-ecological pressures on land. The Economics Goods framework was used in **Paper V** (Kaul et al., 1999). Economics Goods framework distinguishes goods into four different types based on the rivalry and excludability of the goods. Rivalry exists when there is competition over the availability of the goods between different groups of society, whereas excludability is applicable when one group of society can exert control of the goods in a way that access by other groups are prevented (Kaul et al., 1999). In **Paper V**, atmospheric water is treated as either one of the four different types of economic goods: non-rival and non-excludable 'public goods'; non-rival but excludable 'club goods'; rival, but non-excludable 'common pool goods'; and rival and excludable 'private goods'. Story-based scenarios were created for each of the economic goods as a way to imagine the use and control of atmospheric water in the future.

Combining the theoretical concepts

Given the theoretical concepts explained above, a question that is relevant to this thesis is: why should we study moisture recycling as a dominant process in SES? I argue that understanding moisture recycling as embedded within SES would help guide the governance of the moisture recycling process. Governing moisture recycling in SES should be aimed at achieving the resilience of the system to a specific challenge and for certain actors. Resilience is defined as the ability of a system to resist, adapt, or transform itself to maintain its identity through function, structure, and feedbacks (Folke, 2016). In this thesis, I assume that the identity of SES that needs to be maintained is the ability to produce agricultural crops that meet societal demands at various spatial and temporal scales, while preserving forests and their climate-regulating services to agriculture through moisture recycling.

I draw inspirations from two case studies[7] on resilience thinking to motivate the integration of the theoretical concepts in this thesis. Both case studies look at the management of agricultural systems through the manipulation of water-related natural ecosystems. SES in both case studies were managed with reductionist “command-and-control” approaches[8] that resulted in the system’s low resilience to social and biophysical shocks (Walker and Salt, 2006). In the first case study, the Everglades in Florida, United States, was a constantly-changing landscape, comprising marshlands, swamps, and mangroves, that was influenced by decadal fire, drought, and freeze regimes to keep it in balance, low nutrient levels, and annual dry and wet seasons. Due to the rich nutrients in the soil recognized in the 1700s, the Everglades was optimized to deliver as much agricultural output through the draining of swamp for creating agricultural lands and the creation of levees to protect these lands from floods, mainly during wet seasons. The simplification of the agricultural part of the landscape transitioned the system from a sawgrass to a cattail dominated ecosystem that was less biodiverse and left the system vulnerable to storms, hurricanes, and droughts.

In the second case study, the Goulburn-Broke catchment in Victoria, Australia, was similarly modified from its natural state by the removal of deep-rooted native vegetation to create agricultural lands for horticulture and pasture, equipped with highly efficient irrigation systems that were fed by newly built dams. This human-driven ecological alteration increased the water table close to the surface, increasing the likelihood of water logging and bringing ancient salt that was stored in the subsoil upwards. By doing so, agriculture became constantly at a high risk of failure. The modified Goulburn-Broke catchment operated on a narrow window of water level, having to fulfill a minimum amount of water for agricultural production, while not exceeding a level with which salt was risen to the surface. In both case studies, the limited understanding of the complexity of the hydrological system led to decisions on land and water management that defeated the initial purpose of ensuring agricultural productivity. Such manipulations in both systems illustrate how humans prioritized control and efficiency for maximum agricultural output without regard of the social-ecological dynamics, complexity, and interconnectedness, only to ironically create an inefficient system with vulnerabilities to shocks in the long term. These case studies emphasize the necessity of the previously suggested approach to link ecological and social systems by grounding management practices in the ecological understanding of the system and relating them with the social mechanisms behind the practices (Berkes et al., 2000).

These case studies also demonstrate that an intervention on atmospheric water, such as through cloud seeding, without a holistic understanding of its effects within and across scales, should be avoided. The case studies also show the necessity to avoid reducing the forest-agricultural systems mediated by moisture recycling into a subset of hydrological processes that are influenced by land use. For instance, the use of cloud seeding as a means to secure local precipitation reduces the system into merely a few variables, with the most important being the size and and distribution of condensation

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[7] The two case studies explained in this section are taken from the book ”Resilience Thinking: Sustaining Ecosystems and People in a Changing World” (Walker and Salt, 2006).

[8] ”Command-and-control” approaches refer to the efficiency-driven management of a system by controlling and optimizing a narrow set of quantifiable parameters and marketable interests, as well as isolating these parameters and interests from the rest of the system (Walker and Salt, 2006). While ”command-and-control” management may lead to success and efficient production system for a good couple of decades, it is shown to limit adaptability in the long term and increase vulnerability to other shocks that were not initially targetted for control (Walker and Salt, 2006).

nuclei to enhance or trigger precipitation. Before implementing similar interventions, the effects on other aspects linked to the broader system, such as the atmospheric content and circulation, should be understood. In this thesis, the use of four theoretical concepts is intended for linking moisture recycling process with social dynamics concerning land use, management, and governance. The concept of land-atmosphere interactions over forests *grounds* the mechanisms in which certain land cover or land use types influence the water fluxes that feed into moisture recycling process. The moisture recycling process *enables* the entanglement between forests and agriculture in SES, termed as 'forest-agricultural system'. The SES perspective *provides the conceptual model* of the ways moisture recycling, forests, and agriculture interact within forest-agricultural systems. The governance of other types of water, such as that of marshland and groundwate aquifers in the case studies above, *inspires* the exploration of moisture recycling governance in forest-agricultural systems in the future. Figure 3 illustrates the integration of four theoretical concepts in this thesis.

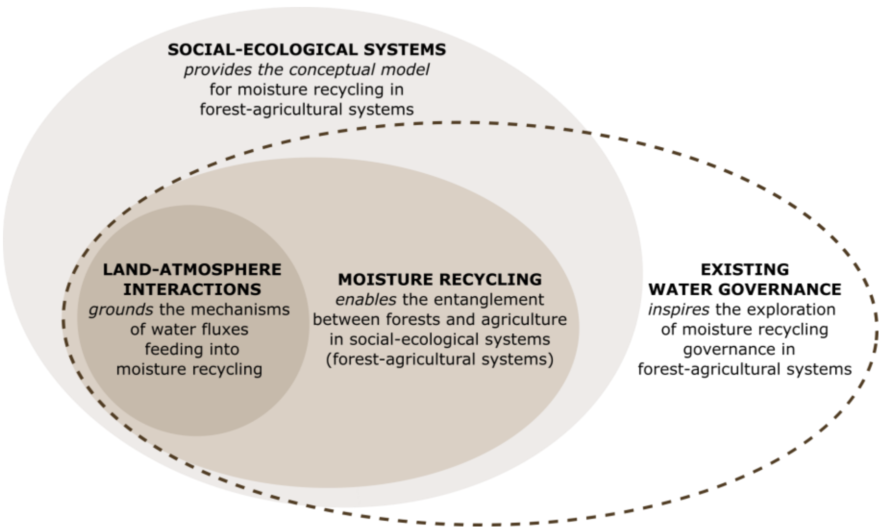

Figure 3 - Combining theoretical concepts on land-atmosphere interactions, moisture recycling, social-ecological systems, and water governance for this thesis.

Methods

This section describes the different data and methods used throughout the research. The methods are broadly categorized into moisture tracking modelling and analysis, spatial data and statistical analysis, thematic analysis, remote sensing analysis, and story-based scenarios.

<table>
<tr><th colspan="3">Paper I</th></tr>
<tr><td colspan="3">Data:</td></tr>
<tr><td colspan="2">Land cover classification
MODIS (Friedl et al., 2022)
MIRCA (Portmann et al., 2010)
SPAM (Lu et al., 2020)
Crop water requirements
WATNEEDS (Chiarelli et al., 2020)
Moisture trajectory
UTrack (Tuinenburg and Staal, 2020)</td><td>Evaporation, precipitation
ERA5 (Hersbach et al., 2020)
Country borders
GADM (GADM, 2025)
Croplands, crop production
M3 (Monfreda et al., 2008)
SPAM (Yu et al., 2020)
Agricultural crop trade
CWASI (Tamea et al., 2021)</td></tr>
<tr><td colspan="3">Methods:</td></tr>
<tr><td>Moisture tracking analysis</td><td>Spatial data analysis</td><td>Statistical analysis</td></tr>
<tr><th colspan="3">Paper II</th></tr>
<tr><td colspan="3">Data:</td></tr>
<tr><td colspan="2">Meteorological variables
E-OBS (Cornes et al., 2018)
ERA-Interim (Dee et al., 2011)</td><td>Land cover classification
MODIS (Friedl et al., 2010)</td></tr>
<tr><td colspan="3">Methods:</td></tr>
<tr><td>Moisture tracking modelling, analysis</td><td>Spatial data analysis</td><td>Statistical analysis</td></tr>
<tr><th colspan="3">Paper III</th></tr>
<tr><td colspan="3">Data:</td></tr>
<tr><td colspan="2">Forest cover
Primary forests (Turubanova et al., 2018)
Forest loss year (Hansen et al., 2013)
Tree cover height (Potapov et al., 2022a)
Pre-processed satellite imageries
ARD (Potapov et al., 2020)</td><td>Semi-structured interviews
Collected
Formal land use allocation
Forest Atlas (Forest Atlas, 2025)</td></tr>
<tr><td colspan="3">Methods:</td></tr>
<tr><td colspan="2">Thematic analysis
Remote sensing analysis</td><td>Spatial data analysis
Statistical analysis</td></tr>
</table>

Paper IV		
Data:		
<u>Forest cover</u> Primary forests (Turubanova et al., 2018) Forest loss year (Hansen et al., 2013) Tree cover height (Potapov et al., 2022a) **<u>Semi-structured interviews</u>** ***Collected***	<u>Meteorological variables</u> ERA5 (Hersbach et al., 2020) TRMM (Huffman et al., 2012) GLEAM (Miralles et al., 2011) GPCP (Adler et al., 2018)	
Methods:		
Moisture tracking modelling, analysis	Spatial data analysis	Statistical analysis
Paper V		
Data:		
<u>Literature data</u> *Collected*	<u>Workshop</u> *Collected*	
Methods:		
Computational text analysis[9]	Story-based scenarios	

Moisture tracking modelling and analysis

The Eulerien WAM-2layers model (van der Ent et al., 2010, 2013) and the Lagrangian UTrack model (Tuinenburg and Staal, 2020), were used in this thesis. For each applicable paper, the selection between the two models or the combination of them, was done based on the state-of-the-art model at the time the research was conducted and the suitability of the spatial scales for the research questions of interest (see explanations on the choice for each paper below). Both models used publicly available datasets on meteorological variables, such as evaporation, precipitation, wind speed, specific humidity, and surface pressure. The models represent one of the three main approaches that can be used to estimate moisture recycling ratio (Gimeno et al., 2020, 2012).

First, the numerical model is distinguished into two further types, which are the Lagrangian- and Eulerian-based models. In the Lagrangian-based model, moisture is tagged and followed through its atmospheric transport trajectory until it precipitates. Examples of Lagrangian models are the QIBT, FLEXPART, and the UTrack models (Dirmeyer and Brubaker, 2007; Stohl and James, 2004; Tuinenburg et al., 2020a). Whereas in the Eulerian-based model, the origin and destination of moisture are calculated on the basis of the water balance of all grid cells included in the region of interest. Examples of Eulerian models are WAM-2layers and RCM-Tag models (Kalverla et al., 2025; Knoche and Kunstmann, 2013; van der Ent et al., 2010). In these moisture tracking models, water particles can be tracked forward to map where upwind evaporation falls as precipitation, commonly referred to as 'evaporationshed', as well as backward to map where downwind precipitation originates, namely the 'precipitationshed'. Second, the bulk model is an analytical model that is process-based, using mathematical expressions based on the assumptions of minimal change of water storage over a long time scale and a well-mixed atmosphere (Burde and Zangvil, 2001). Third, the physical water vapour tracer makes use of isotopic fractionation of heavier hydrogen or deuterium (D) and oxygen (^{18}O) in observed water vapour and precipitation (Gimeno et al., 2020).

[9] Computational text analysis was fully performed by Patrick Keys, the lead author of Paper V. Hence, this method is not described in this thesis.

Physical water vapour tracer is an ideal physical observation against which analytical and numerical models can be validated (Gimeno et al., 2020, 2012). However, limited data availability and models constrain the universal use of physical water vapour tracer to validate modelling results (Gimeno et al., 2020, 2012).

Paper I used the UTrack model at the grid spatial resolution of 0.5°x0.5°, which was appropiate for classifying forest- and agriculture-dominated areas within a national boundary (see 'Spatial data and statistical analysis' below for more details). **Paper I** only used the output dataset of UTrack model, which consists of a four-dimensional dataset connecting source cells with sink cells globally between 2008 to 2017 (Tuinenburg et al., 2020b). The forward trajectory was used to map out the moisture flows between forested source cells and their downwind agricultural sink cells. The moisture flows were then aggregated at the national scale and the country-to-country moisture flows from forested countries to their downwind agricultural countries were estimated.

Paper II was conducted first among all the papers in this thesis, with WAM-2layers model at grid spatial resolution of 1.5°x1.5° using ERA-Interim as input data. WAM-2layers model was deemed suitable for the paper as more large-scale regional processes of moisture transport, focusing on the scale of a hypothesized anticyclonic blocking during heatwaves, could be observed with relatively low resolution. WAM-2layers model is also known to require low computing resources for global or regional studies. In **Paper II**, WAM-2layers model was used to backtrack precipitation that fell in three European regions during climatological summer and heatwaves. The heatwave periods were pre-selected based on interpolated ground-based observations of temperature and precipitation. The spatial coverage of precipitationsheds were mapped and distinguished as 'significant' and 'persistent' precipitationsheds. Significant precipitationshed, in the form of a polygon, includes upwind areas that contribute to the highest 70% of precipitation during the corresponding period (Keys et al., 2012). Whereas, persistent precipitationshed includes areas that contribute persistently to the top 70% of precipitation in either each year during climatological summer or each occurrence of heatwaves. The change of evaporation and of recycled evaporation from different land cover types between the climatologcial summer and heatwave periods was estimated.

By the time **Paper IV** was conducted, WAM-2layers model was updated for a spatial grid scale of 0.5°x0.5° and was coupled with ERA5 dataset, which was an update to ERA-Interim used in **Paper II** (Kalverla et al., 2025). Meanwhile, UTrack model was available at 0.25°x0.25° to be run with ERA5 (Tuinenburg and Staal, 2020). In **Paper IV**, both WAM-2layers model at 0.5°x0.5° and UTrack model at 0.25°x0.25° resolutions were used to track precipitation backward from three regions in the DRC. The models were run by Lucie Bakels and Arie Staal, respectively, as co-authors of the paper and the results were interpreted by me. The models were used to estimate the moisture recycling ratio within the three regions, which is the extent to which precipitation in each region is sourced by all areas within the region, including land and oceanic surfaces. Although, all regions were mostly covered by land. The moisture recycling ratio was investigated for both growing and non-growing seasons of agricultural crops grown within the region.

Spatial data and statistical analysis

In **Paper I**, we were interested in combining the various available datasets on forests, croplands, agricultural crop production and trade, and moisture recycling to estimate the dependence of global crop supply on forests. All input data were spatially distributed, except for the agricultural crop trade. The input cropland dataset was attributable to agricultural crop production in order to link forest cover with agricultural production. As the first step in the spatial data analysis, the land cover classification dataset was harmonized with the croplands dataset in order to produce one global map that distinguished areas dominated by forests from those dominated by agriculture. Agricultural areas located downwind of forests were then detected using the moisture trajectory dataset and the moisture flows between them were estimated both annually and monthly. The moisture flows were aggregated at national scale and were paired with agricultural crop trade. The pairing between moisture and crop flows was conceptualized into three types of dependence, which were circular transboundary flows, cascading transboundary flows, and cascading national flows. Descriptive statistics based on the superimposition of percentiles were used to map out the hotspots of crop producers and exporters that highly depend on moisture from forests. Linear regression was also used to compare the moisture recycling ratio estimation based on MIRCA/M3 datasets in the main analysis and SPAM dataset in the sensitivity analysis.

In **Paper II**, descriptive statistics were used to select heatwaves periods based criteria on precipitation deficit, severity of high temperature, consecutive days when low precipitation and high temperature were combined, and the minimum frequency of heatwave occurrence between 1979 and 2018. Spatial data analysis was used in **Paper II** to categorize the land cover type of moisture sources during climatological summers and heatwaves over three European regions. Land cover classification dataset was used and the classification was grouped into three broad categories, which included forests, other natural vegetation, and anthropogenic land covers, such as urban areas and croplands. The spatial data analysis was done following the moisture tracking analysis, from which the moisture sources of the studied European regions affected by heatwaves were mapped. The moisture sources that constitute the precipitationsheds were then overlaid with the three broad categories of land cover type, along with evaporation and its recycling ratio. The spatial data and statistical analysis resulted in the differences in moisture contribution from the three broad land cover types between climatological summer and heatwaves.

In **Paper III**, the characteristics of three regions within the DRC were compared using spatial data analysis. Data on primary forest cover, tree cover loss, and tree cover height were used to characterize the regions by the extent of primary forest loss and regrowing secondary forests. The trend of reduced fallow length was also estimated for each region based on 150 randomly selected samples for each region, within the areas that underwent primary forest loss between 2001 and 2023 (see 'Remote sensing analysis' below). The trends of fallow length were estimated using the statistical weighted least squares method for each region, in order to detect any changes in the shifting cultivation practices. **Paper IV** expands the analysis in **Paper III** by relating it with moisture recycling within the three regions of the DRC. **Paper IV** investigates the statistical significance of the difference in evaporation and precipitation between areas undergoing primary forest loss and without primary forest loss, using the Mann-Whitney U significance test- Furthermore, descriptive statistics were also used to compare the different tracking output between UTrack and WAM-2layers.

Thematic analysis

Thematic analysis is a method that facilitate meaning making of qualitative data. For **Paper III**, qualitative data were collected through semi-structured interviews with 25 participants. All the interviews were done online, except for one interview that was conducted in-person in Stockholm. The selection of participants was based on snowball sampling or convenience sampling that prioritised professionals who have worked on either forestry, agriculture, or the interface between them in the DRC. The main objective of the semi-structured interviews was to gain a systems-level understanding of the shifting cultivation livelihoods in the DRC and its dynamics upon social-ecological pressures on land, with an emphasis on climate-induced changes on agriculture. Given the objective of gaining a systems-level understanding, it was deemed important to obtain multiple perceptions of the system from different stakeholder groups. The stakeholder groups represented by the interview participants were academia, non-governmental organizations, independent consultants, international organizations, and local communities.

Participants from the local communities group include leaders of organizations whose works were dedicated for supporting agricultural practices by smallholder farmers and who also identified themselves as being part of the local communities. Smallholder farmers were not directly interviewed due to two reasons. First, the research questions of **Paper III** concern the overview of aspects influencing the dynamics and complexity of shifting cultivation livelihoods in the DRC at the systems level, rather than the decision making at the household or community level, such as on livelihood preferences. As such, I intended to interview participants who had knowledge of other processes beyond the household or community level, such as energy demand at the provicial level, or land use policies or migration at the national and regional levels. Second, interviewing smallholders farmers would need to be done in-person due to expectedly limited internet connection in remote rural areas. Conducting in-person interviews in the DRC in a non-extractive way would require time and resources for understanding the local contexts, as well as relationship building and collaboration with local partners. Resources were limited in this research.

The interviews were conducted in two rounds. The first round was aimed at the broad systems-level understanding and was conducted with 17 participants. The majority of the participants in the first round had expertise generally in the Congo Basin or the DRC, and the rest of the participants worked more specifically in either Central or Eastern DRC regions. The second round of interviews was conducted with the remaining 8 participants and aimed to get a more in-depth understanding of the shifting cultivation practices, partially by using semi-quantitative indicators. The participants in the second round interacted regularly and closely with smallholder farmers in their daily work in either the Central or Eastern DRC regions. The interview questions were based on the Sustainable Rural Livelihoods framework, with which we hypothesized that in order to cope with climate change and other social-ecological pressures, smallholder farmers tend to choose a livelihood strategy between agricultural intensification or extensification, livelihood diversification, or migration (Scoones, 1998). As suggested in the framework, these strategies were influenced by other aspects in the system, such as certain trends, capital, and institutions, which were discussed during both rounds of interviews based on the prompt from the participants. After all the interviews were completed, they were transcribed using the combination of an AI-based Whisper and Amberscript tools, which were later inspected manually. Both tools comply with the European Union General Data Protection Regulation (GDPR).

The thematic analysis was perfomed on the interview transcripts by qualitative coding in NVivo, in which I organized and analyzed the qualitative data into themes using an abductive approach. In this abductive approach, I initially coded the interviews deductively based on the different aspects proposed by the Sustainable Rural Livelihoods framework (Scoones, 1998), and then iteratively and inductively readjusted the themes based on emerging new themes recognized during coding (Braun and Clarke, 2006). Thematic analysis was used to explore the multiplicity of perceptions of the different participants on the social-ecological processes and interactions influencing the shifting cultivation practices in the DRC. These processes and interactions were then mapped into a Causal Loop Diagram (CLD), in order to qualitatively display the interconnectedness between the different elements in the system (Sterman, 2000). The thematic analysis in this thesis was done by combining the structured categorization of data into codes and the more latent interpretation of the data, resulting in the CLD and other findings (Boyatzis, 1998). Thematic analysis is a suitable method to bridge qualitative data with quantitative approach through systematically coding the data (Boyatzis, 1998).

Remote sensing analysis

Remote sensing data are commonly used to study land cover and land use patterns. Remote sensing data and analysis are especially suitable for regions where ground-based observations are limited, such as in the DRC, as the case study region of **Papers III and IV**. In **Paper III**, Landat satellite imageries were collected using the Analysis Ready Data (ARD) tool developed by the Global Land Analysis and Discovery (GLAD) lab at the University of Maryland, United States (Potapov et al., 2020). Firstly, sampling frames were chosen by excluding all primary forest areas that did not undergo forest losses between 2001 and 2023 in each region. Each sampling frame spans over a 2° x 2° region consisting of 8000 x 8000 pixels at a resolution of 28 x 28 meters at the Equator. Second, 150 sample points were randomly generated within the sampling frames of each region. For each sample point, 16-day composite of Landsat satellite imageries were extracted and the best composite was selected for each year between 2000 and 2023. Time series of indicators of shortwave radiation, red light absorption, water availability, and vegetation productivity were also generated for each sample throughout the whole study period to facilitate the assessment of shifting cultivation practices.

Third, each sample point was evaluated for signals that indicate clearings for agricultural plots. The combination between changes in the indicators listed in the previous paragraph, and visually-inspected changes in the composite and Landsat imageries, determine the clearing years of forests. Additional indicators were gathered from this last step, which include clearing year, active length, abandoned year, and fallow length before the sample was cleared again, if applicable. The loss of primary forests was also assessed, by eliminating all cells with primary forests (Turubanova et al., 2018) that have been lost each year (Hansen et al., 2013). The replacement of cleared forests with regrowing secondary forests were estimated using the tree cover height in each region in year 2005, 2010, 2015, and 2020 (Potapov et al., 2020). **Paper IV** used the results from the remote sensing analysis in **Paper III** to evaluate the hypothesized interdependence between forests and agriculture in SES. In order to do so, the remote sensing analysis output was matched with analysis of the moisture tracking modelling output and of hydrological variables upon forest cover loss in **Paper IV**.

Story-based scenarios

Developing story-based scenarios about the future is a method that has gained popularity in sustainability science. Story-based scenarios invoke creativity and give space for the participants to freely imagine alternative and tranformative pathways to addressing current societal challenges. In **Paper V**, story-based scenarios were developed as a way to imagine future pathways of anthropogenic governance of atmospheric water. I took part in the participatory worldbuilding and storytelling workshops that were aimed to equip a group of water scholars with futuring tools for developing the stories about the future modification of atmospheric water after 2050. The two workshops took place on the premise that atmospheric water could be treated as either one of four economic goods depending on its excludability and its rivalry between users (see 'Governing moisture recycling in social-ecological systems' under 'Theoretical underpinning' for more explanations). In the worldbuilding workshop, the Futures Wheels (Pereira et al., 2018), Three Horizon Framework (Sharpe et al., 2016), Probe Reality (Hall, 1976), and Make-It-Weird (Dator, 1993) exercises were conducted. Consecutively in the storytelling workshop, participants were given an exercise to create 'Story Beats' (Keys and Meyer, 2022). Both workhops built on the mapped literature themes for each economic goods, which were the results of methods conducted by Patrick Keys as the lead author of the paper, prior to the workshops. The prior methods included structured literature search, computational text analysis based on Latent Dirichlet allocation (Keys and Meyer, 2022), and mapping the keywords into themes classified into the different economic goods.

Summary of papers

In this section, the design and results of each paper are described in reference to its contribution to the overall thesis. Each paper represents different elements and processes of the conceptual framework of moisture recycling in SES (Figure 2b).

Paper I

Pranindita, A., Teuling, A.J., Fetzer, I., Wang-Erlandsson, L. Forests support global crop supply through atmospheric moisture transport. 2025. *Nature Water* 3, 1243–1255. https://doi.org/10.1038/s44221-025-00518-4

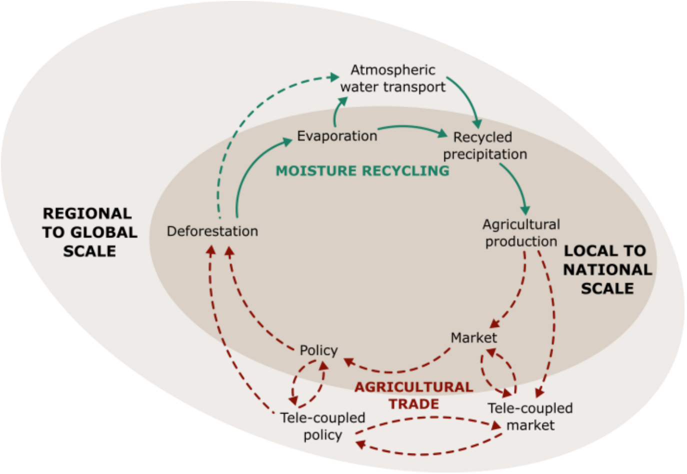

Figure 4 - Moisture recycling (green) and agricultural crop trade (red) were considered in Paper I. Processes were explicitly (solid lines) or implicitly (dotted lines) investigated.

Research questions In **Paper I**, we asked the questions: (1) How much precipitation do agricultural areas receive from upwind forests? (2) How much agricultural crop production and export are supported by precipitation from upwind forests? (3) To what extent does precipitation from upwind forests fulfill crop water requirements? (4) How do countries depend on each other through moisture recycling and crop trade?

Hypothesis Our hypothesis was that forests and agricultural areas would be well-connected through atmospheric water transport globally, which would underline the importance of forests for agriculture worldwide. We also hypothesized that a notable amount of global crop production and export would be supported by precipitation from upwind forests. However, we did not expect that precipitation from forests would fulfill crop water requirements.

Approach In **Paper I**, we used quantitative data analysis of land cover, moisture trajectory, crop water requirements, agricultural production, and trade datasets. First, we generated a global map distinguishing forests from remote agricultural areas categorized by country. We then tracked moisture flows forward from forested country to downwind country with agricultural areas. Second, we assessed the spatially-distributed precipitation from upwind forests against crop water requirements. Third, we paired the moisture flows across countries with traded crop flows to establish the interconnection between forested countries and crop-producing and -importing countries.

The study was done at the national, regional, and global scales. For the national scale, we investigated the interconnection between countries. For the regional scale, we looked at a cluster of countries that are prominent in their regions through moisture recycling, agricultural production, or agricultural export. For the global scale, we distinguished moisture supplied by the extratropical forests from that supplied by the tropical forests. We considered all countries that have either forests or agricultural areas, or both. Meanwhile, the global crop supply constitutes the crop production on agricultural areas in different countries and the distribution of produced crops across countries through agricultural trade. Since we were interested in studying the extent to which global crop supply was supported by upwind forests, we related moisture recycling with agricultural crop trade to represent social dynamics. Agricultural crop trade in this paper encompassed a set of processes involving market and policy at various levels that were covered only implicitly (Figure 4).

Key findings We find that the supply of precipitation from forests in other countries is more intensive than precipitation recycled within one country, amounting up to 630 mm and 250 mm of annual precipitation over downwind agricultural areas, respectively. Likewise, more countries are dependent on transboundary forests for supplying their agricultural areas with precipitation (155 countries), as compared to countries that depend on their own forests (105 countries). When considering all forested countries that have notable contribution of more than 5% of annual precipitation over downwind agricultural areas, we find that forests in Brazil, Peru, Bolivia, Democratic Republic of the Congo, Central African Republic, Russia, and Canada, support 18% of the global crop production and 30% of the global crop export accounted in the study.

We also conceptualized the dependence between forested countries, crop-producing, and crop-importing countries into three circular and cascade typologies (Figure 5). These typologies are (1) circular flows, where upwind forested countries are in turn dependent on crop production and export of their downwind countries, (2) transboundary cascading flows, where forested countries supply precipitation to downwind agricultural areas in other countries, who further export their crops elsewhere, and (3) nationally-recycled cascading flows, where forested countries recycle precipitation to agricultural areas within their national boundaries, on which crops are produced and exported further to other countries. Brazil appears to be a dominant country in all three typologies that cover the supply of precipitation and global crop supply nationally, regionally, and globally.

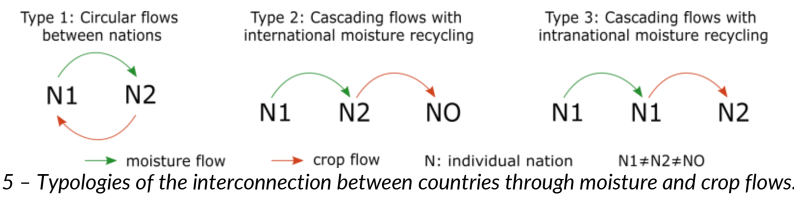

Figure 5 – Typologies of the interconnection between countries through moisture and crop flows.

Contribution to this thesis The findings in **Paper I** answer **RQ1** of this thesis through the quantitative estimation of the dependence of agriculture on moisture from upwind countries. The circular flow responds directly to **RQ2** of this thesis through establishing the two-way interdependence between forested countries and their downwind agricultural areas. The interdependence is applicable for Brazil, Paraguay, Uruguay, Argentina, and Bolivia in South America and Central African Republic and Cameroon in Africa. Three typologies also address **RQ3** by imagining the various contexts within which atmospheric water can be governed in synergy with forest conservation and food security.

Paper II

Pranindita, A., Wang-Erlandsson, L., Fetzer, I., Teuling, A.J. Moisture recycling and the potential role of forests as moisture source during European heatwaves. *Climate Dynamics* 58, 609–624. 2022. https://doi.org/10.1007/s00382-021-05921-7

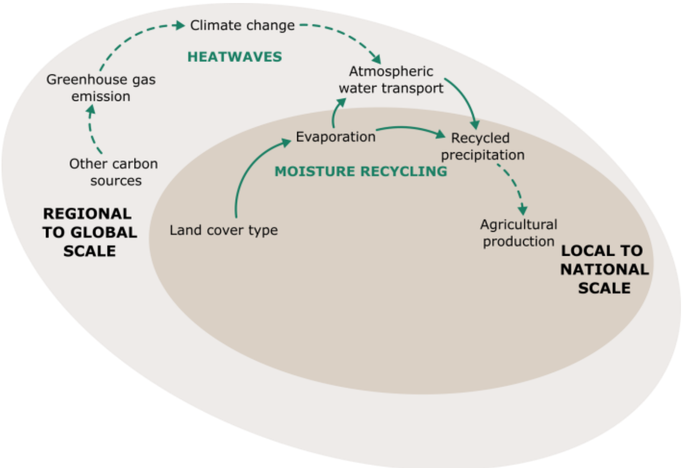

Figure 6 - Moisture recycling, heatwaves, and land cover type (green) were considered in Paper II. Processes were explicitly (solid lines) or implicitly (dotted lines) investigated.

Research questions In **Paper II**, we studied the moisture recycling patterns during heatwaves and the role of forests and other land cover types in supplying moisture during these events. We asked two questions: (1) Are there anomalies in moisture recycling patterns and moisture sources during heatwaves in Europe? (2) What is the role of different land cover types for regional moisture recycling?

Hypothesis Given previous knowledge on atmospheric blocking over Europe during heatwaves, we hypothesized that moisture supplied from the climatological summer sources, especially from the North Atlantic Ocean, would be disrupted or diverted away. We expected that this would reduce the precipitation during heatwaves overall and affect the recycling of precipitation in the region.

Approach In **Paper II**, three regions of Europe including Northern, Western, and Southern Europe, were selected as case study regions. We determined heatwave events in these regions between 1979 and 2018, based on consecutive days of high temperature and low precipitation. Precipitation that fell over the case study regions was then tracked backwards using the WAM-2layers moisture tracking model. The model output allowed the precipitationsheds of the study regions to be mapped out during both climatological summer and heatwaves. The precipitationsheds were finally superimposed with land cover types that distinguished forests from other natural vegetation and built areas. The distinction was done in order to compare the evaporation and moisture recycling patterns over the different land cover types during heatwaves. The study was conducted at the regional and periodic scales. Only the moisture recycling process was considered explicitly in the study (Figure 6). Social dynamics were not investigated in this study, however heatwaves were assumed to affect society negatively through, for instance crop failure and reduced labor productivity due to high temperature.

Key findings We find that specific local land surface processes, such as modified evaporation, can be as important as large-scale atmospheric circulation in supplying and transporting moisture during heatwaves. In Northern and Western Europe, terrestrial sources within and surrounding the regions buffer local impacts by supplying up to 10% of total precipitation during heatwaves that would otherwise be supplied by the North Atlantic Ocean. Atmospheric blocking disrupted the moisture transport evidently in Northern and Western Europe. In Southern Europe, increased evaporation from land surfaces was limited and the reversal of moisture flows from eastern continental Europe was less evident. This pattern in Southern Europe seems to show the dominance of land surface processes, where soil was drying and limiting evaporation as a result. Regardless, forests continued to recycle moisture within all regions during heatwaves, as compared to other land cover types.

Contribution to this thesis **Paper II** responds to **RQ1** by looking at the dependence of agriculture on forests more indirectly. The findings show that forests, as terrestrial instead of oceanic moisture sources, played an important role in buffering limited precipitation during heatwaves, which could further dampen the negative effects on agriculture. **Paper II** addresses **RQ3** by providing an evidence of the temporal dynamics of moisture recycling.

Paper III

Pranindita, A., Koh, N.S., Crépin, A-S., Tyukavina, A., Potapov, P., Bongwele, E., Amani, P.L., Worden, S.R., Keys, P., Zipper, S., Ordway, E., Wong, G., Teuling, A.J., Fetzer, I., Wang-Erlandsson, L. Shifting cultivation livelihoods under social-ecological pressures in the Democratic Republic of Congo. *Manuscript*.

Research questions In **Paper III**, we investigated forest cover changes in the past decades and related these changes with the shifting cultivation practices in the Democratic Republic of Congo (DRC). We asked the questions: (1) How have shifting cultivation practices within forested landscape changed in the past two decades? (2) How does climate change affect forests through the shifting cultivation practices and does it lead to deforestation? (3) What are the systemic enabling and hindering factors of deforestation as coping strategies to the changing climate?

Hypothesis We hypothesized that the shifting cultivation practices by smallholder farmers were greatly affected by climate change, resulting in loss of agricultural production. Our hypothesis is that smallholder farmers would add new agricultural plots by deforesting in order to compensate for climate-induced agricultural losses.

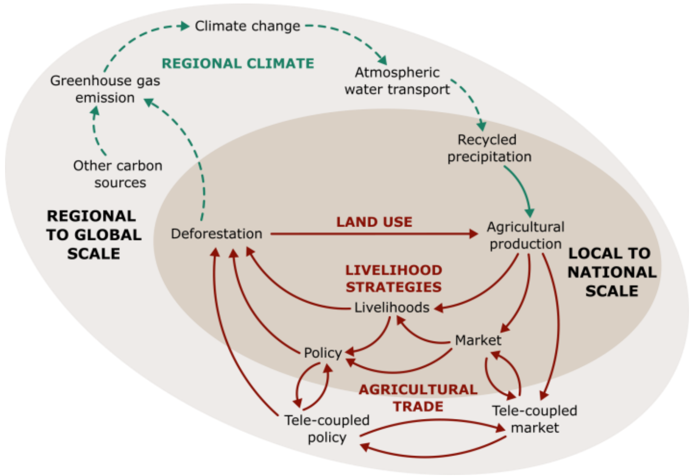

Figure 7 – Regional climate (green), as well as social dynamics (red) through land use, livelihood strategies, and agricultural trade were considered in Paper III. Processes were explicitly (solid lines) or implicitly (dotted lines) investigated.

Approach **Paper III** focuses particularly on the shifting cultivation practices that are prevalent in the DRC (Figure 7). Social dynamics were explored by focusing on changes in shifting cultivation practices under the changing climate and other social-ecological pressures. Sustainable Rural Livelihoods Framework (Scoones, 1998) was used for designing and analyzing the interviews, in order to capture geopolitical, socio-economic, and institutional factors that can help us understand the system. In contrast to the other papers, moisture recycling was not addressed in this paper. The results of **Paper III** on social dynamics were complemented with the moisture recycling process in **Paper IV**. We used a mixed-methods approach combining a qualitative analysis of 25 semi-structured interviews and a quantitative analysis of remote sensing data. The case study subregions are located in the Central, Eastern, and Southern DRC and each region represents different formal land use allocations, but with the forested landscapes in which shifting cultivation is being practiced by smallholder farmers. Remote sensing data were then extracted for each case study region. The semi-structured interviews were aimed at gaining a systems-level understanding of the forest-agricultural system in the DRC. Meanwhile, the remote sensing analysis were targeted for detecting changes in forests that pertain to the shifting cultivation practices.

Key findings The qualitative analysis of the interviews were used to make sense of the shifting cultivation dynamics observed in the remote sensing data. The remote sensing analysis shows an acceleration of the clearing of primary forests and a reduction in the fallow length between 2000 and 2023. We tried to unpack this while analyzing the interviews, by exploring climate change as a dominant pressure on agriculture that led to the accelerated changes in forest cover. However, the interview responses suggested that climate change is only one of seven identified social-ecological pressures in the system, including population growth, globalization, commercialization, conflict, urbanization, and land use and conservation policies. To cope with these pressures, smallholder farmers combined different forest-based livelihood strategies that eventually affected forest cover. The interview responses provided further nuances of the system, through the identification of enabling and hindering factors of deforestation as a coping strategy to the combined pressures . Regardless, findings from the interviews still point to the evidence of the changing climate and its negative effects on agriculture. Deforestation was stated as one of the coping strategies to climate-induced changes on agriculture by a few interview participants. Finally, a qualitative causal loop diagram (CLD) was produced to visualize the interactions between the social-ecological pressures and livelihood strategies in the DRC.

Contribution to the thesis These findings address **RQ2** by demonstrating that changes in the agricultural production affected forest cover between 2000 and 2023. Although, the attribution of climate change to this outcome was challenging given the complexity of the system, in which the different pressures and livelihood strategies are entangled. The findings reveal that social-ecological processes at the local to regional scales give rise to cross-scales interactions, which is characteristic of SES to be governed in **RQ3**.

Paper IV

Pranindita, A., Staal., A., Bakels, L., Worden, S.R., Fetzer, I., Koh, N.S., Crépin, A-S., Keys, P., Zipper, S., Ordway, E., Teuling, A.J., Wang-Erlandsson, L. Dependence of shifting cultivation practices on precipitation from changing forests in the Democratic Republic of Congo. *Manuscript*.

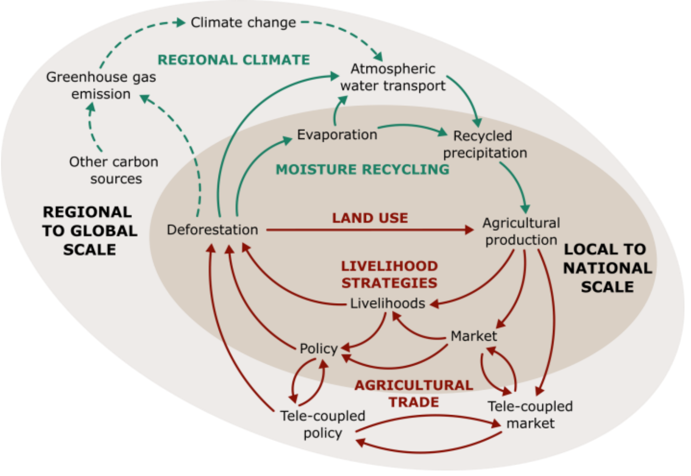

Figure 8 – Regional climate and moisture recycling (green), as well as social dynamics (red) through land use, livelihood strategies, and agricultural trade were considered in Paper IV. Processes were explicitly (solid lines) or implicitly (dotted lines) investigated.

Research questions The objective of **Paper IV** is to assess the moisture recycling capability of forests to sustain shifting cultivation practices in the DRC. **Paper IV** complements the results on the social dynamics in **Paper III** with the moisture recycling analysis. We asked the questions: (1) To what extent do forests in the DRC sustain precipitation over the shifting cultivation landscapes and across different seasons? (2) How do forest cover dynamics in each region influence hydrological processes important for moisture recycling?

Hypothesis We hypothesized that forests in the DRC recycle a notable amount of moisture over the shifting cultivation landscapes. We also expected that the accelerated loss of primary forests in the past decades would lead to changes in the hydrological aspects, particularly on evaporation and precipitation, that would eventually affect the shifting cultivation practices in the DRC.

Approach As suggested in the findings of **Paper III**, smallholder farmers modified their shifting cultivation practices by deforestation as one of the diversified coping strategies to climate-induced changes in agricultural production. We identify these findings as the social dynamics connecting downwind agriculture back to upwind forests within the DRC. In **Paper IV**, we complemented these findings with an analysis of the moisture recycling process over the case study regions (Figure 8). First, we analyzed and compared the output of UTrack and WAM-2layers moisture tracking models on the moisture recycling ratios in different seasons. Second, we investigated whether the different extents of forest cover loss led to significant changes in evaporation and precipitation, which are relevant for moisture recycling. We did this for both growing and non-growing seasons, as well as annually.

Key findings We find that peaks in the moisture recycling ratio based on UTrack model coincided with both boreal spring and fall growing seasons in Eastern and Southern DRC, and only in the fall growing season in Central DRC. The moisture recycling ratio ranges between 7-12%, 14-22%, and 6-12% during growing seasons in Central, Eastern, and Southern DRC, respectively. The precipitation amount in areas with different levels of deforestation was compared to areas without deforestation and differences were observed. Significant changes in evaporation were observed across the three regions, whereas significant changes in precipitation were only evident in Eastern DRC. While Eastern DRC has the highest rate of moisture recycling during the growing season, it seems to be affected most significantly and most severely by deforestation as compared to the other regions. Specifically, when forest cover remained below 40% by 2023 in Eastern DRC, evaporation and precipitation reduced by up to 34 and 59 mm per growing season month, respectively.

Contribution to this thesis The moisture recycling ratio in this study answers **RQ1** by quantifying dependence of agriculture on upwind forests at the local scale. **RQ2** is also addressed because of the social dynamics in **Paper III** that are included in **Paper IV**. The combination of the quantified dependence of agriculture and the social dynamics in the CLD create a contextualized SES involving forests and agriculture enabled by moisture recycling, which responds to **RQ3**.

Paper V

Keys, P.W., Wang-Erlandsson, L., Moore, M.-L., **Pranindita, A.**, Stenzel, F., Varis, O., Warrier, R., Wong, R.B., D'Odorico, P., Folke, C. The dry sky: future scenarios for humanity's modification of the atmospheric water cycle. *Global Sustainability* 7, e11. 2024. https://doi.org/10.1017/sus.2024.9

Research questions **Paper V** explores the future possibilities of anthropogenic modifications of the atmospheric water through storytelling. The objective of **Paper V** is to frame moisture recycling as a process that can be governed through the manipulation of atmospheric water as economics goods.

Hypothesis We hypothesized that using story-based scenarios would help reveal some assumptions about moisture recycling, its role in society, and alternative futures on its governance, imagined by the story creators.

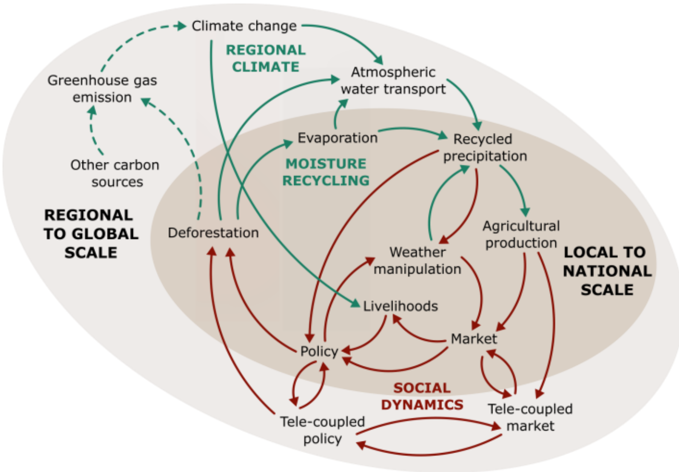

Figure 9 – Regional climate and moisture recycling (green), as well as social dynamics (red) were considered in Paper V. Processes were explicitly (solid lines) or implicitly (dotted lines) investigated.

Approach We applied the economic goods framework to distinguish atmospheric water as either a public good, club good, private good, or common pool good, based on its excludability and the rivalry between users. We created ten short stories representing all types of economic goods to illustrate the different pathways that atmospheric water can be managed and governed in the future. We did this by conducting structured literature search and computational text analysis, clustering keywords into topics for each economic goods based on the text analysis, followed by two workshops on worldbuilding and story-telling. This paper refers mainly to the regional and decadal scales. The paper captures both social and ecological processes combined in different contexts (Figure 9).

Key findings We find that future scenarios can be useful for imagining where atmospheric water governance could be headed in the future and for building the anticipatory capacity for implausible or impossible social, technological, and physical changes. The stories developed a world where atmopsheric water could be manipulated for societal benefits with some stories explicitly addressing forest conservation and securing precipitation for agriculture. Some stories reveal that even with the best technological interventions on the biophysical aspect of moisture recycling, surprising social responses could prevent society to fully benefit from them. These stories contain the breaking of solidarity, rules, and trust between different members of society. Interestingly, the majority of the stories were developed exclusively from each other by different co-authors, yet they present similar trajectory of societal responses to governance.

Contribution to the thesis **Paper V** answers **RQ3** directly through the diversity of stories for each type of economic goods. Table 2 is created in the following pages to capture the important aspects that concern the ways moisture recycling is governed in the ten stories. In the 'Discussion', these aspects are assessed more deeply to reveal insights for imagining the governance of moisture recycling in the future.

Table 2 - Governance of moisture recycling observed in future stories in Paper V. Empty cell represents the absence of an explicit statement about the corresponding column.

Story *(Economic goods)*	**Moisture recycling-related knowledge inspiring governance**	**Events triggering governance**	**Means of moisture recycling governance** *(scale)*	**Ecological outcomes of governance**	**Social responses to governance**
We Are As Gods *(Public good)*	Inability to predict when and where precipitation falls at 100% accuracy	• El Niño-driven drought in 2031 across South America • Black Sea Drought in 2045 affecting wheat production in Ukraine	• Precipitation enhancement by cloud seeding in Argentina *(national)* and Ukraine *(regional)* • Suggested moratorium on cloud seeding while the technology is further studied *(international)*	Andean Hell Hail: precipitation enhancement resulted in hail instead, destroying wine production in Argentina	• Poor judgement of government and wrong assumption on aerosol led to Andean Hell Hail • Financiers used cloud seeding for wealth speculation
The Palash *(Public good)*		Droughts in Tibetan Plateau	• Cloud seeding in Trans-Himalaya in 2050 *(national)* • "Rights to Rain" treaty in 2082 prohibiting cloud seeding as it led to floods instead *(international)*	• 18 Brahmaputra floods inadvertently caused by cloud seeding in 2052-2075 • Great flood in Palashpari in 2074, leaving few survivors	The need to retrieve information from previous generations for improving the ecological understanding of ancestral lands
The Fertilizer Incident *(Public good)*	• Switchgrass as a bridge for clouds from the Indian Ocean to inland • Drought propagation across deserts	Sea level rise forcing communities to migrate from the Pacific Islands to the desert in the Outback	Planting of switchgrass throughout the Outback using robotic harvesters *(national)*	Maintained atmospheric water transport over switchgrass	Cross-scale knowledge sharing on the success of switchgrass farm in the Outback to delegations from the United Nations monitoring agency
Pride of Burma *(Common pool goodl)*	• Deforestation reduces downwind precipitation • Trees are "moisture leak" as transpiration moved water from land to the atmosphere	Regions downwind of cleared forests dried up and became unhabitable	• Global target to keep transboundary water underground by deforestation in 2020s *(international)* • TIRTHA tree monitoring system in 2037 to avoid deforestation upwind of drying regions *(international)* • Enhanced precipitation by pumping "binder" in 2056 countering deforestation *(national)*	Further drying of downwind regions due to misuse of global target to deforest	• Global target misused for national, instead of transboundary, water availability • Local community deceived to work at a "binder" factory for export
T-Trading *(Common pool good)*	Forest transpiration was important for precipitation		• Environmental Modification Convention for modifying weather for peaceful purposes only *(international)*	• Restriction on cloud seeding, mostly for agricultural production, released upwind transpiration	• Lack of coordination between T-sectors on microclimate management

Story *(Economic goods)*	**Moisture recycling-related knowledge inspiring governance**	**Events triggering governance**	**Means of moisture recycling governance *(scale)***	**Ecological outcomes of governance**	**Social responses to governance**
			• Law in 2039 granting local and Indigenous communities sovereignty in the Amazon *(national, international)* • Manaus Protocol in 2048 strictly restricting deforestation in the Amazon *(international)* • Stomatal monitoring of transpiration with aerial sensor *(local)* • Microclimate management with AI-optimizing drone fleet at T-sectors *(local)*	• Erratic microclimate resulting from lack of coordination between T-sectors	• Mismanagement after Manaus Protocol led to commodification of transpiration
Helping Heaven *(Club good)*	Drought could potentially be alleviated by weather manipulation	• Drought in 2030 led to invention of cloud seeding technology • Drought in 2045 kick-starting the cloud seeding deployment	• Precipitation enhancement by cloud seeding in Rao District, introduced in 2045 *(sub-national)* • Transferred cloud seeding technology to a province level between 2045 and 2060 *(sub-national)*	Alleviated droughts following the implementation of cloud seeding	Cross-scale knowledge sharing on the success of cloud seeding in Rao District to counties governed at the provincial level
Too Much Rain in Paradise *(Club good)*	Rainfall could be reduced by decreasing the size and distribution of condensation nuclei in the atmosphere	Above average rainy season in Lagos Bay in 2105 forcing politicans to intervene	• Precipitation suppression by deploying AI-operated aerosol management in Lagos Bay in 2105 *(local)* • A renewed 3-dimensional matrix of sensors, namely EkoCloud, monitoring and managing aerosol distribution in the atmosphere in 2121 *(local)*	Semi-coordinated rain suppressors went out of control in 2105, enhancing precipitation instead of suppressing it, causing catastrophic flood with over 10,000 people dead	Tension between scientists who were uncertain about the technology and politicians who were eager to do something
Igor's Diary *(Club good)*		Prediction that summer droughts would destroy wheat yields and increase fire hazard risk in forests and steppes	Precipitation enchancement by cloud seeding deliberately used for flooding in 2053 *(sub-national)*		• Failed attempt of Igor's War: unsuccessful fire attack on forests and steppes due to blocking of drones and sabotaged cloud seeding to flood a city by enemies • Technological advancement was misused for political campaign with elevated media control

Story *(Economic goods)*	**Moisture recycling-related knowledge inspiring governance**	**Events triggering governance**	**Means of moisture recycling governance** ***(scale)***	**Ecological outcomes of governance**	**Social responses to governance**
					• Government-backed private company stealing cloud seeding technology from foreign corporations • Betrayal by one of the leaders to take over power
Any-weather *(Private good)*		Global food crises due to changing precipitation patterns increased demand for irrigation,which cannot be implemented in agricultural fields on the hill due to little access to streams or groundwater. Heavy reliance on precipitation for agriculture called for an intervention.	AnyWeather app allowing users to order any kinds of weather anytime, with the help of particle-releasing drones that help promote or inhibit precipitation *(local)*	As elite users can supersede or outbid weather requests anytime, the 'delivery' of weather became unreliable. Soybean sprouting failure could not be avoided due to last-minute precipitation cancellation.	• Users with more premium subscription can supersede the requests from other lower tier users • Users can outbid each other, prioritizing those who can pay more • Negotiation on mutually beneficial weather between neighbours
Queen Bee *(Private good)*			Glaciogenic seeding with drones, called the Cloud Seeders, used for maintaining at least a foot of snow on ski tracks at a ski resort *(local)*	Lower efficiency of cloud seeding in a specific area within the ski park, as compared to the 100% efficiency in the rest of the park, resulting in insufficient depth of snow.	• Cloud seeding technicians being unappreciated and disrespected by management, interns, and customers at the ski resort • Dissatified customers on the depth of snow in some areas • Interns kept disobeying orders from technicians, leading to hazardous incidents • Shared discontent and frustration between the technicians about their work

Discussion

This section is divided into four sub-sections. The first three sub-sections refer to the three RQs in this thesis. Each of these three sub-sections is provided with an explanation on the contribution of this thesis to the broader scientific field. The last sub-section discusses the overall research limitations and future outlook.

Dependence of agriculture on moisture from upwind forests

***RQ1**: To what extent does agriculture depend on moisture from upwind forests?*

In **Papers I, II, and IV**, the dependence of agriculture on moisture from upwind forests is quantified. This thesis addresses the dependence through various aspects, including spatial scale, temporal dynamics, geographical coverage, and perspectives. The results from these papers show that forests are well connected to downwind agriculture at various scales through the moisture recycling process.

Spatial scale The dependence of agriculture on upwind forests is typically studied at the region scale, with a focus on the tropical regions and notably on the Amazon (Butt et al., 2011; Leite-Filho et al., 2024, 2021; Li et al., 2025; Nyasulu et al., 2024; O'Connor et al., 2021b; Oliveira et al., 2013). Three known studies establish the country-to-country moisture flows globally (De Petrillo et al., 2025; Dirmeyer et al., 2009; Keys et al., 2017) and a recent study also estimates the relevance of local moisture recycling at a 0.5˚x 0.5˚grid cell worldwide, equivalent to 50 km distance at the Equator (Theeuwen et al., 2023). The studies at the national and local scales did not focus on forests supplying moisture to agriculture.

> **Papers I, II, and IV** contributes to this variety of scales of analysis. **Paper I** estimates the dependence of agriculture on upwind forests by mapping out the spatial connection between forests and downwind agricultural areas at the national and regional scales, globally. Specifically, the paper investigates the moisture flows from forests to agriculture across countries (national scale) that are located within different regions of the world (regional scale). All regions of the world are covered globally (global scale), with forests being categorized as either extratropical or tropical forests. As compared to other studies looking at the moisture flows across countries that refer to the entire areas of each country, **Paper I** refers to only forested areas in the upwind countries and only agricultural areas in the downwind countries. This approach allows for more attribution of the forest-to-agriculture relationships across countries. **Paper II** analyzes the moisture recycling at the regional scale, based on the regional climate mechanism influencing the water transport due to atmospheric circulation characteristic of heatwaves. Meanwhile, **Paper IV** establishes the dependence of shifting cultivation practices on forests at the local scale. Although the case study regions in **Paper IV** span an area of 2˚x 2˚ grid cell, equivalent to 200 km distance at the Equator, which is bigger than that considered in the 'local moisture recycling' estimation (Theeuwen et al., 2023), it is still considerably local relative

to the expansive areas contributing to 80% of the precipitation falling within the regions, and as compared to the other scales in this thesis.

Temporal dynamics Increasing number of studies aim at capturing the role of moisture sources during extreme weather events beyond seasonal fluctuations, such as during floods, droughts, and heatwaves in Europe. Most studies on this topic focus on floods and how moisture sources have contributed to the excessive accumulation of water that precipitate downwind (Benedict et al., 2021; Cloux et al., 2021; Gimeno-Sotelo et al., 2024; Insua-Costa et al., 2022a, 2022b, 2019; Llasat et al., 2025; Skinner et al., 2023; Vicente-Serrano et al., 2024). Only one of these studies looks at moisture recycling during heatwaves and finds that the high pressure anticyclonic blocking over the Rhine Basin during heatwaves in 2003 and 2018 limited the contribution of moisture from the Atlantic Ocean to the precipitation in the basin (Benedict et al., 2021). Meanwhile, almost all studies on moisture recycling during extreme events address the terrestrial regions generally without distinguishing forested from non-forested sources. Only one study of those listed above investigated the direct role of forests as moisture source for the 2021 floods in Germany and Belgium (Insua-Costa et al., 2022a). The study finds that vegetated land cover contributed to the majority of moisture precipitated during the floods (Insua-Costa et al., 2022a). Furthermore, as moisture recycling process is fueled by upwind evaporation, a couple of studies compare the evaporation dynamics from forests with that from grasslands, following heatwaves (Lansu et al., 2020; Teuling et al., 2010). One of the studies suggest that forests decrease evaporation earlier than grasslands following the onset of heatwaves, which allow them to sustain evaporation over a longer period of time (Teuling et al., 2010).

In **Paper II**, similar response is also investigated, demonstrating that forests sustain moisture recycling in the three European regions during heatwaves, as compared to other natural vegetated landscapes and built-up areas. In this paper, we find differences in the spatial coverage of precipitationsheds between climatological summer and heatwaves, suggesting the temporal dynamics of moisture recycling during heatwaves. Particularly, the supply of moisture from the North Atlantic Ocean was replaced by terrestrial moisture in Northern and Western Europe, which is aligned with the study on the Rhine Basin (Benedict et al., 2021). In contrast to the role of forests in amplifying floods by supplying abundant moisture downwind, **Paper III** shows that forests act as a buffer for extremely dry conditions through sustained recycled evaporation during heatwaves. Limiting the reduction in precipitation during heatwaves might dampen the effects on agriculture, although these effects were not investigated explicitly in **Paper II**. In **Paper IV**, the temporal dynamics found in the three regions of the DRC are shown by the monthly fluctuations of moisture recycling ratio within the year. The central DRC differs slightly from the eastern and southern regions. In Central DRC, the differences in moisture recycling ratios between growing and non-growing seasons are least evident.

Geographical coverage This thesis highlights forested regions that are generally understudied in terms of moisture recycling. As mentioned previously, past studies on moisture recycling from forests to agriculture were mainly done on the tropical regions with a focus on the Amazon (Butt et al., 2011; Leite-Filho et al., 2024, 2021; Li et al., 2025; Nyasulu et al., 2024; O'Connor et al., 2021b; Oliveira et al., 2013). Other tropical forested regions, such as Southeast Asia and the Congo Basin, are less studied. Southeast Asia is least studied in terms of moisture recycling, possibly due to the fact that it is a region surrounded by the oceans, with limited contribution of moisture from land (Vicente-Serrano et al., 2024). In comparison, there are a few studies on moisture recycling over the Congo Basin and they mainly show relatively high annual moisture recycling ratio within the range of up to 68% of annual precipitation, with seasonal fluctuations (Bakels et al., 2025; Baker and Spracklen, 2022; Dyer et al., 2017; Nyasulu et al., 2024; Pokam et al., 2012; Sorí et al., 2017; te Wierik et al., 2022). Meanwhile, moisture recycling in the extratropical forests have been limitedly studied (Hoek van Dijke et al., 2022; Tuinenburg et al., 2022).

Paper I covers the understudied extratropical forests and their contribution to agriculture, which appears to be notable for a few major crops at the monthly scale. In **Paper I**, we find that moisture sourced from extratropical forests to downwind agricultural areas coincide with the growing seasons of wheat and maize, while this is not observed for tropical forests. However, tropical forests remain the biggest source of moisture for downwind agricultural areas globally in the absolute amount of precipitation. The essential role of mid-latitudinal extratropical forests in Europe is also emphasized during extreme events in **Paper II**. **Paper II** implies that mid-latitudinal forests are reliable moisture sources to help safeguard the much-needed precipitation during heatwaves in Europe. Meanwhile, **Paper I** also includes the forest-to-agriculture moisture flows in Southeast Asia. **Paper I** confirms the limited role of moisture recycling in Southeast Asia, as none of the countries in this region is identified as the top countries supplying moisture to downwind agricultural areas, despite having a vast area of forests. Furthermore, **Paper I** also focuses on the Congo Basin and finds that forests in the DRC are an important source of moisture for agricultural areas in the DRC and Cameroon, which are also important producers of agricultural crops for the region. This relationship is shown further at the local scale in **Paper IV**, where peaks of moisture recycling coincide with growing season mainly in the Eastern and Southern DRC.

Perspectives The significance of moisture from forests has been assessed through different perspectives, such as in its proportional use for agricultural water consumption (Nyasulu et al., 2024), maintaining agricultural yield (Oliveira et al., 2013), and generating agricultural revenue (Leite-Filho et al., 2021). Most of these studies detect the importance of forests for agriculture by estimating the effects of deforestation on the amount of recycled precipitation (Leite-Filho et al., 2024, 2021; Oliveira et al., 2013) and on rainfall onset (Butt et al., 2011; Leite-Filho et al., 2019; O'Connor et al., 2021b).

In **Paper I**, we introduced a new perspective through which moisture from forests can play a key role in agricultural trade across countries. We did this by directly accounting for agricultural production of various exported crops that were cultivated in countries located downwind of forests. To the best of my knowledge, it is the first ever study that conceptualizes this type of interconnection between forested countries, downwind crop-producing and -exporting countries, and cascading crop-importing countries. Moreover, **Paper IV** also provides a novel perspective of seeing the importance of moisture from forests not only for agricultural productivity, but also for agricultural livelihoods. By coupling moisture recycling from forests to agricultural livelihoods, it highlights how recycling moisture within forests is also crucial for sustaining the productivity and health of forest ecosystems, which uphold the livelihoods of smallholder farmers. **Paper I** and **IV** present these new perspectives for different types of actors; **Paper I** only represent farmers with medium to large agricultural plots, while **Paper IV** only considers farmers with small agricultural plots.

Interdependence between forests and agriculture

***RQ2**: Does moisture recycling process mediate an interdependence between forests and agriculture? If yes, what type of interdependence exists and how does it operate?*

In this thesis, I complement the results on moisture recycling from forests to agriculture in the previous sub-section with social dynamics in the opposite direction, in order to investigate the reciprocity of the dependence between forests and agriculture. This reciprocity would challenge the power imbalance between upwind and downwind regions. Across the national administrative boundary, moisture recycling process would give upwind countries power in affecting downwind countries through land use changes (Keys et al., 2017). This relationship is similar to upstream and downstream regions of a river basin or a catchment, where the controls to secure water in the catchment mostly rely on land use management or governance in the upstream regions (Hayat et al., 2022; Zeitoun and Warner, 2006). Meanwhile, the interdependence between forests and agriculture at the local scale is often seen as competing in terms of land, despite all the ecosystem services that forests provide to agriculture at the local scale, such as other local hydrological benefits (Bargués-Tobella et al., 2020; FAO et al., 2025). The reverse dependence of forests on downwind agriculture was quantified partially in **Paper I** through the relative crop import proportion and in **Papers III and IV** through the speed at which primary forests were cleared or fallow length was reduced. Using this approach, I find that different types of interdependence exist through moisture recycling and social dynamics between forests and agriculture in **Papers I, III, and IV**. The first type of interdependence is between upwind forested countries and downwind countries with agricultural areas found in **Paper I**. The second type of interdependence is between local forests and local agricultural areas observed in **Paper IV**.

In **Paper I**, the international moisture flows match with the international traded crop flows, giving rise to a circular dependence between countries. Such matches at what is considered a significant level, which is above the 5% threshold for both the annual precipitation and total imported crops, are applicable to Brazil, Paraguay, Uruguay, Argentina, and Bolivia in South America and Central African Republic and Cameroon in Africa, among all 254 countries investigated in the paper. The results imply that while countries that produce and export crops can be exposed to changes on forests in upwind countries, forested countries could in turn be exposed to disrupted agricultural import. This relationship challenges the power asymmetry between upwind and downwind regions by arguing that downwind agricultural areas can also hold power through the production and export of crops important for upwind forested countries. By promoting more symmetry in this power relation, the interdependence found in **Paper I** may contribute to a synergy between forests and agriculture. Mutual benefits could be achieved through forest conservation that supports downwind agricultural production in countries who export the crops back to the forested countries.

Papers III and IV are discussed together as the social dynamics between forests and agriculture was first studied in **Paper III**, but was then complemented with the moisture recycling analysis in **Paper IV**. In **Paper III,** the dependence of forests on agriculture was identified by relating the forest cover changes in the past decades to climate-induced changes on agriculture. The use of remote sensing analysis led to the findings that forest cover change was observed through the accelerated clearing of primary forests after the last studied decade (2011-2023) and the reduction of fallow length in shifting cultivation practices. The qualitative interviews that were intended to make sense of the findings from remote sensing analysis revealed that these changes on forests could only partially be linked to loss of agricultural production due to climatic changes. Other social-ecological pressures on land, such as globalized trade, commercialization, urbanization, and conflict, influenced the juggling of livelihood strategies of smallholder farmers, all of which depend on forest lands and resources. The findings in **Paper III** provide empirical evidence that there are social dynamics connecting agricultural production to the use of forests at the local scale in the three case study regions of the DRC, with cross-scale interactions with other processes at larger scales. The social dynamics found here and the moisture flow from forests to agriculture found in **Paper IV**, described in the previous sub-section, complete the evidence for forests and agriculture interdependence in the DRC, which represents a forest-agricultural system that is self-sustaining. Specifically, local forests sustain the agricultural practices and a functioning agricultural system ensures that forests are not disturbed further than unnecessary.

Insights for governing moisture recycling in social-ecological systems

***RQ3**: What do the key insights from this thesis suggest regarding the need to govern moisture recycling as part of social-ecological systems?*

Studies on the governance of moisture recycling limitedly address moisture recycling as a mediating process in SES (Keys et al., 2017; te Wierik et al., 2020; van Noordwijk et al., 2014; van Noordwijk and Ellison, 2019). However, do we have enough evidence to consider moisture recycling as a mediating process in SES? And if yes, what would governing moisture recycling in SES entail? Here, under 'Empirical Evidence', I inductively assess the results from **Papers I to IV** against some of the organizing principles and characteristics of SES (Folke et al., 2016; Preiser et al., 2018). I relate the principles and characteristics of SES, enabled by moisture recycling, with the opportunity to govern it. Under 'Imaginative Evidence', I reflect on the different future stories in **Paper V**, by identifying common patterns and surprising social-ecological elements that are relevant for moisture recycling governance.

Empirical evidence

Contextual All papers point towards the importance of contextualizing the moisture recycling process in SES. The implications of the forest and agriculture interdependence for moisture recycling governance differ based on the forest-agricultural contexts. Differences in at least one social-ecological process between two similar entanglements might lead to different needs for the means of governance.

> In **Paper I**, bilateral diplomatic relations between two countries determines the opportunity to govern them with regards to their moisture recycling relationship. The significant moisture flows to key global crop exporters, such as Brazil and Ukraine, do not equally incentivize the conservation of forests in the upwind countries. Brazil relies heavily on precipitation that is recycled nationally and thus the synergy between conserving forests and securing crop production within Brazil is thus in the interest of the country. Whereas, as Ukraine depends on moisture that is mainly supplied by Russia, motivating the conservation of forests in Russia to secure crop production in Ukraine is more complicated. The war between Russia and Ukraine that broke out in 2022 complicates the opportunity to cooperate to ensure sustained precipitation for agriculture in Ukraine. It might even act as a source of vulnerability for Ukraine as the dependent country.

In **Paper II**, the implication for governance lies in the regional climate that influences atmospheric circulation and the transport of atmospheric water to different regions. The increased importance of moisture recycling during heatwaves in Europe only holds for Northern and Western Europe, and not for Southern Europe. In Southern Europe, local surfaces processes and large atmospheric circulation interact differently than in Northern and Western Europe, which generates a different systems behavior. Specifically, the replacement of oceanic moisture by terrestrial moisture is not observed in Southern Europe, which limits the leveraging capacity of forests in buffering precipitation deficit during heatwaves. This finding suggests that regional forest governance that is tailored for coping with such extreme weather events in Europe might be relevant for the contexts of Northern and Western Europe, but not Southern Europe.

In **Papers III and IV**, other social-ecological processes beyond forestry and agricultural productivity determine the use of land, that need to be considered in governing moisture recycling in SES. Multiple social-ecological pressures on land in the DRC, such as crop commodity trade, urbanization, and conflict, interact and drive deforestation in the region. Similarly, the enabling and hindering factors of deforestation and forest degradation by smallholder farmers provide nuances that are uniquely applicable for shifting cultivation systems in the DRC. These factors suggest that in order to decrease the likelihood of deforestation in the DRC, forest governance needs to address other social-ecological processes, such as the development of road infrastructure, the availability of alternative energy sources, and the commercialization opportunities of crops.

Similarly, the contexts of agricultural systems also determines the types of actors who are influential in the SES and the speed of processes that are involved. In **Paper I**, forests and agricultural areas that are located remotely from each other, are linked through the moisture recycling process across countries. Upwind countries might be indirectly affected by changes in downwind countries who produce and export their agricultural crops, leading to adjustments in their national export policies or deforestation trajectories. The opposite effect is found where reducing deforestation rate or increasing forest cover is associated with increasing imports from other countries (Meyfroidt et al., 2010; Pendrill et al., 2019). In this case, national governments interact through bilateral and multilateral agreements on trade, that might take time to evolve. Meanwhile in **Papers III and IV**, deforestation in upwind regions is driven more directly by the need of smallholder farmers to survive amidst agricultural production losses, with limited influence of policy. In this case, smallholder farmers could make decision immediately at the household- or community-level on their proximate land or forests following agricultural losses (Leblois, 2021; Zaveri et al., 2020)

Dynamic with cross-scale interactions and non-linear dynamics Although the analysis done in the papers refers to different scales, the combination of the processes could be part of a nested system in which smaller scale systems are embedded in a bigger system. Cross-scale interactions between the social-ecological processes entangling forests, agriculture, and moisture recycling are important in a nested system. Studies on cross-scale processes on moisture recycling are scarce, although they are indirectly represented by the connectivity between the local decision-making on forests in the Amazon that could cascade into moisture recycling effect at the regional scale, and eventually could lead to a regional regime shift into the savanna ecosystem (see 'Introduction' for references). Meanwhile, non-linear dynamics of moisture recycling have been hypothesized and limitedly proven by empirics, specifically for forests' role in supplying precipitation to downwind agriculture (Lawrence and Vandecar, 2015). In the case of shifting cultivation systems, forests are cleared and are left with the mosaics of land cover and use types consisting of primary forests, secondary forests, fallow fields, active agricultural plots, newly cleared plots, roads, and settlements (Molinario et al., 2015). Deforestation into such a heterogenous landscape leads to different effects in downwind precipitation than for clear-cut expansive croplands, which demonstrates the non-linearity of the moisture recycling process based on the size of deforestation (Lawrence and Vandecar, 2015; Silveira et al., 2025; Smith et al., 2023).

When the results of **Papers I, III, and IV** are assessed together, forests and agriculture are nested in systems with social-ecological interactions across local, national, and regional scales through moisture recycling and social dynamics (Figure 10). **Paper I** has the largest coverage globally with one of the hotspot regions of forests and agriculture interdependence being the DRC. **Paper I** shows that DRC recycle 18% of precipitation from the forested to agricultural areas within their national boundary. DRC also recycles 5% of annual precipitation to agricultural areas in Cameroon. The combination of DRC and Cameroon contribute to regional crop distribution to Rwanda, Central African Republic, Equatorial Guinea, and Chad. Sustaining forest cover within the DRC is thus not only important domestically for DRC, but regionally for surrounding countries.

Meanwhile in **Papers III and IV**, local forests recycle 7-20% of precipitation during growing season on agricultural areas that are located within approximately 200 km distance. Forests thus help sustain local agricultural productivity. However, multiple social-ecological pressures on forests that lead to accelerated loss of primary forests in the past decade threatens the function of local precipitation recycling. Loss of primary forests in the three regions ranges between 5 to 9% of the region proportion between 2001 and 2023, which corresponds to 0.2 to 0.4% annually. The precipitation recycling capability and the deforestation patterns are observed in all three case study regions of the DRC in **Papers III and IV**.

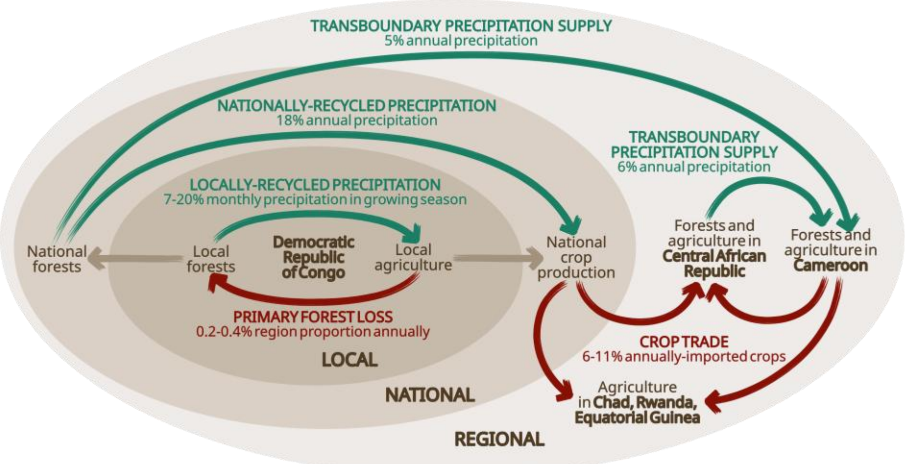

Figure 10 - Processes considered in Papers I, III, and IV that commonly refer to Central Africa. Moisture recycling (green) and social dynamics (red) processes connect forests and agriculture across scales within SES. Within one sector, for instance forests or agriculture, cross-scale (brown) processes might apply.

A predicted 40% forest cover loss by 2100 in the Congo Basin may lead to 8-10% reduction in precipitation (Smith et al., 2023). Based on this nested system, the observed deforestation at the local scale in **Papers III and IV** together with the deforestation trajectory within the DRC might put other surrounding countries at risk of disruption through their agricultural production and import. Additionally, the different social-ecological pressures on forests in the DRC originate from a scale larger than the DRC, such as the crop commodity pressure and climate change that operate at a global scale, and commercialization, conservation policy intervention, and conflict that occur at a regional scale. In **Paper III**, a causal loop diagram was mapped out to illustrate the feedback loops within the system, giving rise to non-linear dynamics between the elements of the system. Meanwhile in **Paper IV**, non-linear dynamics were observed as effects of forest loss on evaporation and precipitation differs as forest loss increases. However, only Eastern DRC shows forest loss effects that were mostly statistically significant.

Radically open The choice for applying the forest-agricultural contexts on the SES studied in this thesis determines the boundary of the system that define which processes are included or excluded in the system. However, the system's boundary remains radically open as deforestation and agricultural production in the SES are still influenced by social-ecological processes at either smaller or larger scales than those considered in the scope. The best example for this is climate change, which is a process that takes place at the global scale, but appears to have profound effects on social-ecological processes at the smaller scales, observed in the papers in this thesis.

In **Paper I**, climate change motivates the need to think about forests as buffer for sources of precipitation on agriculture, given that agricultural areas might be more exposed to extreme weather events that are destructive for crops (Chen et al., 2024; Han et al., 2024; Kim et al., 2019). Apart from climate change, although not specifically mentioned in the paper, aspects such as regional trade agreement and diplomacy take place at a scale larger than the national scale, but are detrimental for the configuration of agricultural trade.

In **Paper II**, the increased frequency and intensity of heatwaves in recent years have been associated with climate change and are predicted to worsen in the coming decades (Della-Marta et al., 2007; Fischer and Schär, 2010; Meehl and Tebaldi, 2004; Rasmijn et al., 2018). However, as a response to globally-driven climate change, the persistent recycled evaporation from forests throughout the three case study regions in **Paper II** demonstrates the role of local scale processes in safeguarding the recycling of precipitation, such as vapor pressure deficit controlling the water fluxes at the species level (Lansu et al., 2020). Safeguarded precipitation not only avoids the impact of water scarcity during these events, but also the intensification of extremely high temperature at the regional level, as precipitation and temperature are highly coupled (Miralles et al., 2019; Schumacher et al., 2019; Seneviratne et al., 2010; Teuling, 2018). Understanding forests as a reliable source of moisture is relevant for future mitigation strategies towards heatwaves.

In **Paper III**, the combination of climate change and other social-ecological pressures on land generate a systems outcome of accelerated encroachment into forests and modified shifting cultivation practices. Changing climate has been found to be one of the prominent pressures encountered by smallholder farmers in their shifting cultivation practices (Pavageau et al., 2018; Somorin, 2010; Somorin et al., 2012). Nevertheless, the systems dynamics mapping of the social-ecological processes entangling forests and agriculture in the DRC displays the intricacies of livelihoods that are influenced by processes at diverse scales. For instance, as compared to larger scale processes described in the previous section, labor capital and the gender dimension within households also affect decision making processes whether or not to deforest upon crisis (Samndong et al., 2018).

Constituted relationally What happens if we replace moisture recycling and social dynamics in the SES with other processes? I hypothesize that the same main components of deforestation and agricultural production might form another version of SES, but with very different behaviors. In Figure 11, I use a simplification of the SES empirically studied in **Papers III and IV** (Figure 11a), and compare it with another SES involving deep percolation and surface runoff as other hydrological processes replacing moisture recycling (Figure 11b). Both SES represent a local system where forests and agriculture can be found in close proximity from each other. In the first SES, agriculture depends on precipitation that is supplied by upwind forests through the moisture recycling process (Figure 11a). Deforestation leads to less recycled precipitation downwind that can lower agricultural production (negative effects in Figure 11a) (Lawrence and Vandecar, 2015; Smith et al., 2023). In the second SES, deforestation increases local water availability for agricultural production by directing more water for run off and percolating deeply into streamflow of a local river, instead of for evaporation (positive effects in Figure 11b) (Hoek van Dijke et al., 2022; Ilstedt et al., 2016). Meanwhile, agriculture is assumed to affect forests in the same way in both systems, which is through the conversion of forests into agricultural land upon loss of agricultural productivity (negative effects in both Figure 11a, b) (Leblois, 2021; Ordóñez et al., 2025; Zaveri et al., 2020). This is only one of the theories suggesting the relationship between agricultural productivity and deforestation. There is also another theory, namely the rebound effect or the Jevons paradox, that suggests the opposite effect, where increased agricultural productivity increases deforestation through various factors, such as increased demand and higher profitability (García et al., 2020).

The combination between the social-ecological processes with positive and negative effects result in different feedback mechanisms. The first SES has a reinforcing feedback loop (Figure 11a), while the second has a balancing feedback loop (Figure 11b). In the first SES, a vicious cycle is pertinent, as more deforestation leads to less precipita-

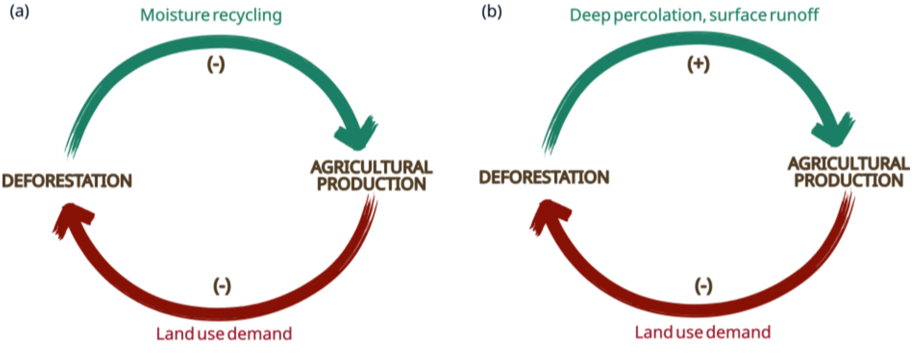

Figure 11 – Comparison of two SES constituted by different hydrological processes, resulting in different systems behaviors. Hydrological processes (green) and social dynamics (red) connect deforestation with agricultural production. Dominant hydrological processes are either through moisture recycling (a) or deep percolation and surface runoff (b). Social dynamics in both SES consider the agricultural land use demand that leads to deforestation.

tion and reduced agricultural productivity, which in turn drives more deforestation. In contrast, in the second SES, the balancing feedback loop stabilizes the system into a thriving agricultural system. Governance interventions in afforestation, reforestation, and forest conservation might thus lead to different outcomes in these two systems. However, these two SES examples are certainly unrealistic because in the real world, all the different hydrological processes, along with other biophysical processes, and the social dynamics interact and create synergies or trade-offs that determine the net effects on the system. The ’optimum tree cover’ theory is based on the consideration of these synergies and trade-offs, by proposing that an optimum intermediate level of tree cover delivers maximum groundwater recharge over seasonally dry tropical landscapes (Ilstedt et al., 2016). Beyond the optimum tree cover, evaporation and surface runoff would outcompete infiltration and deep percolation, limiting the benefit on groundwater recharge (Ellison et al., 2017; Ilstedt et al., 2016). The simplification of these two SES examples is only useful to illustrate how SES involving forests and agriculture are constituted relationally.

Intertwined The quantified dependence and observed interdependence between forests and agriculture found in **Papers I, III, and IV** in this thesis suggest the intertwinedness of processes to a certain extent. By acknowledging the moisture recycling circular and cascading flows between countries in **Paper I**, it is hard to address forest changes in one country without thinking about the impact on agricultural production and trade in another country, and vice versa. The relationship established in **Paper I** adds to the entanglement between forests and agricultural areas globally. In **Papers III and IV**, the ecological services that forests provide locally and regionally through moisture recycling cannot be separated from the different factors influencing the livelihood strategies. The causal loop diagram in **Papers III and IV** shows the complexity of the shifting cultivation livelihoods in forested landscape and how entangled the different elements of the system is, as each endogenous process connects with different processes and thus affects each other upon change.

Imaginative evidence

In **Paper V**, different forms of moisture recycling governance in the future were imagined in ten short stories. In these stories, the different contexts in which moisture recycling is acknowledged and plays an important role for our society are dealt with appropriate management and governance measures. These stories involve diverse actors, from individuals, private companies, national governments, to international organizations operating at the global scale. Here, I analyzed the commonalities between the ten stories that were created by six different authors, based on the relevant aspects in Table 2 (See ‘Paper V’ under ‘Summary of papers’). The main objective of doing this analysis is to reveal any insights on any important aspects to consider for, or to be cautious about, moisture recycling governance, based on the perceptions of different authors. Story-based scenarios disclose assumptions and hidden biases of the storyteller on the topic, as well as help the storyteller to explore an alternative world to the current trajectory (Riedy, 2020). Story-based scenarios also help the storyteller and the readers to make sense and create meaning of the current phenomenon of interest (Bentz et al., 2022; Riedy, 2020). As I went through the stories, five aspects emerged as important in revealing the moisture recycling governance opportunities. These are listed as the columns in Table 2 and comprises (1) the ecological knowledge related to moisture recycling that inspires moisture recycling governance, (2) the events triggering the governance, (3) the means of governance, (4) the ecological outcome of governance, and (5) the social response to governance. The following paragraphs discuss the content of Table 2.

Moisture recycling governance in half of the stories stemmed from an ecological understanding related to moisture recycling, such as the importance of forests and switchgrass for precipitation, the effects of deforestation on precipitation, and the physical possibility to manipulate weather by adding condensation nuclei to the atmosphere. One story describes how the absence of knowledge on predicting precipitation at 100% accuracy motivated the main character to develop technology that allowed precipitation to occur at a desired time and place. However, an ecological understanding alone seems insufficient to initiate a modification of the atmospheric water. Events triggering the initiation of moisture recycling governance are observed in most of the stories. Changing precipitation patterns, especially droughts but also floods, are present in almost all of the stories as a turning point at which the characters in the story felt the need to intervene with moisture recycling. The majority of the stories implemented a direct governance of moisture recycling through weather manipulation by cloud seeding or aerosol management. Only three stories included a form of indirect governance of moisture recycling through planting of switchgrass, tree or stomatal monitoring, and control of deforestation.

Interestingly, means of moisture recycling governance evolve in a few stories due to surprising ecological or social responses. A common ecological surprise as a consequence of the modification of atmospheric water resulted in governance adjustment in a couple of stories. In these stories, precipitation-enhancing cloud seeding led to destructive hails or floods instead. In another story, cloud seeding that was meant for precipitation suppression went out of control and caused catastrophic flood. In these cases, the cloud seeding intervention was then reversed by other governance means, including a moratorium, a treaty, and a better and renewed monitoring system. There are also ecological successes of the governance such as in two stories, where drought was alleviated with cloud seeding, and planting of switchgrass resulted in sustained transport of atmospheric water across the continent. Only one story had a turning point that did not involve climate. In this story, the discontinuation of cloud seeding, as a management practice to secure precipitation for agriculture, released transpiration from being manipulated into precipitation and hence made it accessible for commodification.

Furthermore, social responses to governance of moisture recycling are mostly surprising and lead to unintended consequences. In a couple of stories, governance mechanism on promoting deforestation and on precipitation enhancement by cloud seeding were misused to exploit water from local streams and to create flood for trapping citizens in a city during a military operation, respectively. In the first case, a tree monitoring system was introduced to avoid further misuse. In one story, the idea of ordering a weather on an app ended up benefiting only elite users who pay the highest, as they have the privilege to supersede other users' requests for weather, even down to the very last minute. There are also cases of tension, disrespect, betrayal, and deception between characters in the stories, while trying to meet their own agenda in achieving a certain ecological outcome from moisture recycling governance. More positive social responses are also observed following either a success of governance or a conflict, where knowledge of success was shared between institution across scales or negotiation took place between disadvantaged customers for mutually-beneficial solutions.

Reflection

Combining the empirical and imaginative evidence above, this thesis shows that forest-agricultural systems that are enabled by moisture recycling are contextually defined, dynamic, radically open, constituted relationally, and intertwined. The future stories also reveal that the element of surprise, through events triggering the moisture recycling governance, as well as ecological outcomes and social responses to governance, are evident and should prepare our anticipation for constant changes in the system. Given these two findings, governing moisture recycling seems to require an approach that is less conventional than governance applied on river basins, watersheds, or groundwater aquifers. One study recognized how the ways we govern river basins and watersheds are currently not aligned with the growing knowledge of water processes in the Anthropocene, through which spatial and temporal connectivity of water systems across scales is increasingly understood (Moore et al., 2024). One of the processes creating the spatial connectivity across scales is moisture recycling, while the temporal connectivity across scales can be due to regime shifts and delays of consequences following an intervention in the water systems (Moore et al., 2024). Together, they challenge the static governance of river basins and watersheds that is fixed within a geographical boundaries and across times (Moore et al., 2024). As discussed before in the 'Theoretical Underpinning' section, the nature of moisture recycling already differs from that of river basins and watersheds, in terms of geographical connectivity between upwind and downwind versus upstream and downstream. The findings in this thesis further emphasize the need to think about governing moisture recycling in the future that caters for the principles of contextuality, dynamics, openness, relationality, intertwinedness, with constant surprises ecologically and socially. This implies that extending the current governmental institutions on river basins, watersheds, and groundwater aquifers to moisture recycling seems inadequate to address the characteristics of SES. An exception to this, would be when the spatial coverage of watershed with upstream and downstream regions overlap with the spatial coverage of precipitationsheds with upwind and downwind regions. In this case, although moisture recycling governance could build on the current governmental institutions in terms of the geographical regions being governed, the complexity, dynamics, and adaptiveness of the system within the geographical boundary could be more recognized. Adding the moisture recycling process to an existing water governance could thus offer a revamp and improvement to accommodate the organizing principles of SES.

Research limitations and future outlook

This thesis has several limitations that inform the future outlook. Firstly, as discussed earlier, SES that entangles forests and agriculture would encompass other hydrological processes than moisture recycling, which were not considered in this thesis. This thesis also only presents few of the possible versions of SES in which moisture recycling entangles forests and agriculture. In the Amazon and Southeast Asia, different processes may dominate and thus different feedbacks may take precedence in the SES. For instance, in the Amazon, deforestation is more driven by large-scale croplands producing global crop and livestock commodities, while in Southeast Asia, palm-oil, rubber, and pulp plantations dominate (Curtis et al., 2018; Fisher, 2010; Turubanova et al., 2018). Accordingly, different types of actors operating at different scales are involved in the decision making in the Amazon and Southeast Asian forests. Therefore, for having the generalizability and robustness of the conceptual model of moisture recycling in SES proposed in this thesis (Figure 2b), it should be tested on different types of forests-agricultural systems in other regions than the DRC.

Secondly, the knowledge gained in this thesis for understanding the agriculture dependence on moisture from upwind forests is limited by the uncertainty of the moisture recycling ratio estimation. In this thesis, two numerical models were used, which are the UTrack and WAM2layers (Kalverla et al., 2025; Tuinenburg and Staal, 2020; van der Ent et al., 2010). As found in **Paper IV**, the two models have discrepancies, although they agree more with each other as compared to the mass balance model, which is another method to quantify moisture recycling (Cropper et al., 2021). The state of the art numerical models here are also not validated directly by any observations. Isotope data and modelling have the potential to validate numerical models, however the availability of in situ measurements, data standardization, and data availability currently limit their use (Galewsky et al., 2016). Meanwhile, an intercomparison project aims at comparing different moisture tracking methods to quantify the uncertainties of moisture recycling ratio estimation was established in 2022. In their first undertaking, they compared 14 different moisture tracking methods to track moisture during three extreme precipitation events in Pakistan, Australia, and Scotland (Benedict et al., 2025). Similar studies in the future that aim at improving the confidence in moisture recycling ratio estimation by comparing the different modelling approaches, among other means, should be encouraged.

Thirdly, the interdependence found here pertains to the potential pertinence of a reinforcing feedback within SES that create a vicious cycle between deforestation and agricultural production. However, this feedback was not explicitly quantified here, other than conceptually, especially with regards to proving the causal relationships between the different elements in the system (particularly referring to the causal loop diagram in **Paper III**). Another study has quantified SES feedback involving moisture recycling, between deforestation, drought, and fire risk in the Amazon (Staal et al., 2020b). In this study, the feedback mechanism was compartmentalized into two causal processes, which are the effect of deforestation on drought and the effect of drought on deforestation (Staal et al., 2020b). Both processes were investigated empirically by hydrological modelling, moisture tracking modelling, and linear regression, and their combination results in the quantification of the feedback strength, namely the 'drought-deforestation feedback factor' (Staal et al., 2020b). The factor compared observed deforestation with estimated deforestation in the absence of the feedback (Staal et al., 2020b). Similar approaches to the ones applied in this study can be used in future studies for quantifying the feedback mechanism stemming from the interdependence between forests and agriculture through moisture recycling. However, in that attempt, the conceptualization of the SES needs to be made much simpler without disregarding any dominant processes.

Moreover, the interdisciplinary approach applied in this thesis suggests that investigating the applicability of a feedback mechanism within SES also requires data beyond the biophysical aspects of the system. An interdisciplinary, or even a transdisciplinary approach, requires higher involvement of stakeholders in the system and more data collection on the social dynamics of the system, most probably through fieldwork. Fieldwork further requires establishing of good relationships with local researchers and partners based on trust building, which demands investment in time and efforts from all stakeholders and the researcher. The Congo Basin and the DRC in particular, as a case study in this thesis, are considerably remote with limited infrastructure that allows physical access and have scarce ground observations, as compared to other tropical regions. Although, this should not limit the willingness to study them and to collect new data in the future. Having these data would enrich the understanding of the SES. Furthermore, in the 'Empirical Evidence' two organizing principles of SES, namely the adaptive and complex behaviors of the system, were not assessed in this thesis because the analysis done here is not sufficient to make any conclusion on these two aspects. However, this also reflects the gaps in knowledge for future research on moisture recycling in SES.

Fourthly, the insights for governing moisture recycling in SES reflected on in this thesis focuses on the theoretical aspect of moisture recycling within SES, by assessing the findings against the characteristics of SES. This reflection would more benefit from scrutinizing the findings against governance mechanisms that have been applied in the real world in different case studies. Examples of governance mechanisms that already link forests with agriculture are the EUDR and the REDD+ programs. This type of scrutiny needs to be grounded in the understanding of the motivation, premise, implementation plans, and intended outcome of the governance mechanisms, which is beyond the scope of this research and beyond my background qualification. Regardless, starting with an existing governance mechanism would offer a good entry point for considering moisture recycling governance in forest-agricultural systems, and for assessing the synergies between forests, agriculture, and moisture recycling.

Conclusion

Moisture recycling creates a synergy between forests and agriculture. This thesis shows that moisture recycling is a relevant process that entangles forests and agriculture, and that using the forest-agricultural systems as a lens to understand moisture recycling in social-ecological systems is appropriate. Three questions were posed and answered by the five papers in this thesis.

First, the thesis quantified the dependence of agriculture on moisture from upwind forests from local to global scale. Second, the thesis revealed the interdependence between forests and agriculture through moisture recycling in different types. Interdependence was observed between upwind forested countries and downwind countries with agricultural areas connected by agricultural trade, as well as between local forests and local shifting cultivation practices connected by livelihood strategies. Third, using the insights from this thesis to reflect on the moisture recycling governance in the future emphasizes the need to address moisture recycling as embedded within SES that are contextual, dynamic, radically open, relational, intertwined, and are prone to unpredictable ecological outcomes and social responses.

Given the role of moisture recycling, getting the objective on food security by conserving forests for safeguarding crop production and alleviating extreme events is highly relevant for tackling the climatic risks threatening the food system. The importance of forests is also recognized universally since global, regional, and local agendas to conserve forests, afforest, and reforest, have long been advocated for. Conserving forests for sustaining precipitation is also aligned with other goals to sequester carbon for climate mitigation, slow down biodiversity loss, and protect the livelihoods of Indigenous People and Local Community (IPLC). Using the all-encompassing sectors, such as forests and agriculture, also means that cross-scale, cross-sectoral, and cross-disciplinary processes should be considered in governing moisture recycling in social-ecological systems. Nevertheless, knowledge of moisture recycling still needs to develop further beyond the biophysical aspects, with multi-, inter-, and transdisciplinary approaches, for it to be used wisely for safeguarding the biosphere that support our society.

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