Forest–Water–Atmosphere Theory: A Multiscale Framework for Management-Induced Coupling in Forested Landscapes

Dr. Eva Verena Müller

Research Institute of Forest Ecology and Forestry, Trippstadt, Germany

✉ eva-verena.mueller@wald-rlp.de

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How do management interventions alter coupled Forest–Water–Atmosphere processes across scales, and what are the implications for ecosystem resilience?

Abstract

Recent advances in ecohydrology, land–atmosphere coupling and Earth System Science increasingly recognize the importance of forests for coupled water, energy and climate dynamics. However, the explicit integration of forest management, multiscale hydrological pathways and atmospheric feedbacks remains limited, despite increasing recognition of forests as active biophysical regulators within Earth-system frameworks. This paper proposes the Forest–Water–Atmosphere Theory (FWAT) as a management-relevant conceptual framework that synthesizes these perspectives and provides a basis for developing testable hypotheses regarding the effects of forest management on coupled forest–water–atmosphere systems. FWAT does not propose new process physics, but a new way of integrating existing knowledge by explicitly conceptualizing forest management as an intervention in coupled forest–water–atmosphere systems operating across scales. Within this framework, evapotranspiration is hypothesized as a key candidate coupling variable linking hydrological, physiological and atmospheric processes across scales, while its relative importance and atmospheric relevance remain context-dependent empirical questions.

1. Introduction

Beyond their roles in biodiversity conservation, timber production and carbon sequestration, forests are increasingly considered key components of climate adaptation strategies through their influence on hydrological processes, drought buffering and regional climate regulation (FAO, 2021). At the same time, forest ecosystems worldwide are experiencing increasing pressures from rising temperatures, altered precipitation regimes, extreme drought and interacting disturbance processes, including insect outbreaks and wildfire (Allen et al., 2010; Anderegg et al., 2015; Bonan et al., 2024).

Across many regions, management interventions such as species conversion, stand restructuring, restoration of hydrological connectivity, retention measures or the modification of drainage systems are increasingly discussed not only in terms of productivity and ecosystem health, but also with regard to their potential contribution to climate resilience and water regulation.

The novelty of FWAT does not lie in proposing new hydrological, physiological, or atmospheric processes. Rather, it lies in explicitly conceptualizing how forest management propagates through coupled forest–water–atmosphere systems across organizational and spatial scales. Existing frameworks explain important components of these systems, but they rarely specify the mechanistic propagation pathways linking management interventions, hydrological and physiological responses, evapotranspiration, atmospheric coupling potential, and emergent system properties within a single testable conceptual architecture. FWAT addresses this gap by providing a multiscale framework that generates explicit, empirically testable hypotheses about when and how local management interventions may scale into broader forest–water–atmosphere responses.

A substantial body of research has demonstrated that forests strongly influence water and energy fluxes through processes such as transpiration, interception, infiltration and runoff generation (D'Odorico et al., 2010). Similarly, studies on land–atmosphere coupling have highlighted the importance of evapotranspiration (ET), soil moisture and vegetation feedbacks for boundary layer development, atmospheric moisture recycling and precipitation processes (Gentine et al., 2019; Findell et al., 2024). Forest resilience research has improved our understanding of vulnerability, resistance and recovery following environmental stress (Ibáñez et al., 2019), while Earth System Science increasingly recognizes the importance of terrestrial ecosystems as active participants in global biogeophysical cycles (Bonan et al., 2024).

Ecohydrological studies have substantially advanced understanding of vegetation–water interactions but frequently address atmospheric feedbacks only indirectly and rarely integrate forest management as a deliberate driver of system dynamics (D'Odorico et al., 2010). Research on land–atmosphere coupling has generated important insights into the role of ET, soil moisture and vegetation feedbacks for hydroclimatic processes (Gentine et al., 2019; Findell et al., 2024), yet forests are commonly represented as land-surface characteristics or vegetation types rather than as actively regulating components shaped by management decisions. Similarly, resilience frameworks have improved our understanding of ecosystem responses to disturbances (Ibáñez et al., 2019), but hydrological and atmospheric processes are often not integrated within a common systems perspective. Forests therefore occupy a dual position within coupled forest–water–atmosphere systems: their functioning and persistence depend on water availability and climatic conditions, while at the same time their structure and functioning influence hydrological and atmospheric processes and the ecosystem services associated with them. This reciprocal dependence is particularly relevant under climate change, because the capacity of forests to regulate water and energy fluxes is itself contingent on forest condition and resilience.

Earth system approaches increasingly acknowledge the relevance of forests for global energy and water cycles (Bonan et al., 2024), although the mechanistic pathways through which local forest management decisions may propagate across scales often remain unresolved.

Such a framework should not only synthesize existing knowledge but also provide a basis for developing testable hypotheses regarding the consequences of forest management for coupled environmental systems.

Within FWAT, evapotranspiration is hypothesized to represent a key candidate coupling variable linking soil-water processes, plant water status, forest structure and atmospheric dynamics, while management is conceptualized as a deliberate intervention capable of modifying these interactions.

By doing so, FWAT aims to establish a research agenda that facilitates the identification of critical control parameters, the development of testable hypotheses and the evaluation of how forest management may contribute to resilience and adaptation in a changing climate.

2. Existing conceptual perspectives

Ecohydrology provides a foundational view of coupled water-vegetation processes and has advanced understanding of soil moisture dynamics, vegetation feedbacks, thresholds, and streamflow responses. However, atmospheric feedbacks and the explicit integration of management are often not central in this literature, which makes it a necessary but incomplete precursor to FWAT (D'Odorico et al., 2010; Asbjornsen et al., 2011; Chandrathilake, 2023).

Land-atmosphere coupling focuses more directly on exchanges of water, energy, and matter between the land surface, the boundary layer, and the atmosphere. This literature is highly relevant for FWAT because it foregrounds evapotranspiration and feedback processes, but forest structure and management are often underrepresented as explicit system drivers (McPherson, 2007; Gentine et al., 2019; Findell et al., 2024).

Forest resilience and tipping point research contribute the language of stability, recovery, thresholds, and nonlinear regime shifts. These perspectives are important for FWAT because they help frame how coupled systems respond to stress and disturbance, but hydrological and atmospheric feedbacks are frequently treated only indirectly, and forest management is rarely positioned as a deliberate intervention in coupled forest-water-atmosphere dynamics (Ibáñez et al., 2019; Albrich et al., 2020; Forzieri et al., 2022; Brando et al., 2025).

Earth System Science broadens the scope by placing forests within global energy and matter cycles and by emphasizing climate feedbacks, forcings, and water-cycle regulation. This perspective is closest to FWAT in conceptual reach, but it often remains too coarse to resolve management-sensitive, site-specific, and multiscale coupling pathways that are central to the FWAT argument (Ellison et al., 2017; Creed et al., 2018; Lawrence & Vandecar, 2015; Bonan et al., 2024).

2.1 Ecohydrology and land–atmosphere coupling as complementary precursors

Ecohydrology provides one of the most important conceptual foundations for FWAT because it explicitly addresses interactions between vegetation, soil water and hydrological fluxes across scales. Seminal contributions such as those synthesized by Asbjornsen et al. (2011) frame ecohydrology as a field concerned with feedbacks between vegetation and water, including spatial heterogeneity, scaling from leaves to landscapes, thresholds and alternative stable states. Earlier conceptual work has similarly highlighted reciprocal interactions between vegetation dynamics and water availability across environmental gradients and hydrological regimes (Rodriguez-Iturbe, 2000; Newman et al., 2006). Together, these perspectives provide a strong basis for understanding how forest structure, plant functioning and hydrological processes are coupled.

However, ecohydrological frameworks do not usually place atmospheric feedbacks at the center of their conceptual architecture. Although evapotranspiration (ET) is recognized as an important process linking vegetation and water (Asbjornsen et al., 2011), boundary-layer dynamics, precipitation feedbacks and land-atmosphere interactions are often treated only indirectly. Similarly, management is frequently discussed as a practical or policy-relevant context, but less often conceptualized as a deliberate intervention capable of modifying coupling strength within a forest-water-atmosphere system.

Land-atmosphere coupling research offers the complementary perspective. Conceptual frameworks in this field explicitly address the role of soil moisture, evapotranspiration, surface-energy partitioning and boundary-layer dynamics in shaping hydroclimatic processes (Seneviratne et al., 2010; Gentine et al., 2019). More recent syntheses further emphasize the importance of land-atmosphere feedbacks for the development of hydroclimatic extremes and regional climate variability (Findell et al., 2024). This literature is therefore central for FWAT because it provides the atmospheric mechanics that remain only weakly developed in many ecohydrological frameworks.

At the same time, land-atmosphere coupling frameworks often treat forests primarily as land-surface characteristics, vegetation types or boundary conditions rather than as actively regulating systems shaped by forest structure and management decisions. Forest management usually enters these frameworks indirectly, for example through land-cover change or deforestation, but rarely as a conceptual core element. As a result, this literature provides a strong basis for understanding evapotranspiration-mediated atmospheric feedbacks, but a weaker basis for explaining how site-specific forest management may alter these feedbacks through soil water, plant water status and catchment-scale hydrological pathways.

Recent work at the interface of land-surface and atmosphere research further strengthens this perspective. Zemp et al. (2017), for example, demonstrate how vegetation–atmosphere feedbacks mediated through atmospheric moisture transport can propagate forest-loss effects across spatially connected regions.

FWAT emerges precisely at the intersection of these two perspectives. Ecohydrology provides the vegetation-water logic, while land-atmosphere coupling provides the atmospheric feedback logic. FWAT integrates both into a management-relevant multiscale framework by asking under which conditions forest management modifies soil water, plant water status and evapotranspiration strongly enough to generate scalable forest-water-atmosphere coupling signals.

2.2 Earth System Science and the role of forests as biophysical regulators

Recent developments in Earth System Science increasingly recognize forests as active regulators of water, energy and climate processes rather than merely as vegetation classes or carbon reservoirs. Reviews and syntheses have highlighted the role of forests in mediating evapotranspiration, surface cooling, atmospheric moisture transport and precipitation dynamics, thereby contributing to both climate mitigation and climate adaptation (Ellison et al., 2017; Lawrence & Vandecar, 2015; FAO, 2021). Emerging evidence further suggests that forest–atmosphere feedbacks may influence the hydrological consequences of forestation and land-cover change across climatic gradients (Kan et al., 2026).

At the same time, Earth-system perspectives often remain focused on broad land-cover transitions, climate benefits or biophysical feedbacks operating at regional to global scales. The mechanistic pathways through which local forest management decisions propagate through soil-water processes, plant water status, evapotranspiration and catchment hydrology to influence atmospheric dynamics are less consistently addressed. Forest management therefore tends to enter these frameworks indirectly, for example through forestation scenarios or land-use change, rather than as an explicit intervention shaping coupled forest-water-atmosphere interactions.

FWAT builds on this growing recognition of forests as active Earth-system components, but extends it through the explicit integration of management, multiscale hydrological pathways and process-based coupling mechanisms. In doing so, FWAT bridges Earth-system perspectives with management-oriented forest hydrology by asking under which conditions local interventions may generate scalable forest-water-atmosphere responses.

2.3 Forest resilience as an emergent property of coupled systems

Forest resilience is commonly conceptualized as the capacity of forests to resist, recover from and adapt to disturbances and environmental change. Influential resilience frameworks emphasize the maintenance of ecosystem functioning, adaptive capacity and the ability of systems to cope with uncertainty and change (Millar et al., 2007; Folke et al., 2010; Seidl et al., 2016). FWAT builds on this perspective by proposing that these capacities emerge, at least in part, from coupled forest-water-atmosphere processes operating across scales.

In this context, resilience is typically framed not as the preservation of historical ecosystem states but as the capacity to sustain essential functions despite changing environmental conditions (Millar et al., 2007; Seidl et al., 2016; Folke et al., 2010). Hydrological processes are increasingly acknowledged within resilience research, particularly in relation to drought stress, productivity and disturbance dynamics (Allen et al., 2010; Anderegg et al., 2015). Evapotranspiration, soil moisture and water limitation appear more frequently in contemporary studies, especially within ecohydrological contexts, but atmospheric feedbacks remain rarely explicit and tend to remain secondary components of resilience thinking (Ibáñez et al., 2019).

Forest management occupies a central position within resilience research, yet it is most often conceptualized as an adaptive response to climate change. Typical recommendations include modifying species composition, reducing disturbance risks, restoring degraded ecosystems and applying adaptive management strategies under uncertain future conditions (Millar et al., 2007; Seidl et al., 2016). Although some contributions increasingly recognize that management interventions may actively shape resilience pathways through changes in biodiversity, connectivity, landscape structure and governance (Folke et al., 2010), the mechanistic processes linking management decisions to resilience outcomes remain comparatively underdeveloped.

FWAT builds upon these resilience perspectives by explicitly conceptualizing resilience as an emergent property of coupled forest-water-atmosphere systems. In this view, management interventions influence resilience not only through structural or compositional changes but also through their effects on soil-water dynamics, plant water status, evapotranspiration and associated feedbacks operating across scales. FWAT therefore extends existing resilience frameworks by integrating hydrological and atmospheric processes as core mechanisms through which resilience may be stabilized, enhanced or potentially undermined.

2.4 Synthesis of remaining gaps across conceptual perspectives

Taken together, the perspectives reviewed above provide substantial insights into the interactions among forests, water and climate. Ecohydrology has advanced our understanding of vegetation–water interactions across scales and highlighted the importance of heterogeneity, thresholds and feedbacks. Land–atmosphere coupling research has clarified the role of evapotranspiration, soil moisture and surface-energy partitioning in shaping atmospheric dynamics and hydroclimatic variability. Earth System Science increasingly recognizes forests as active biophysical regulators influencing water, energy and climate processes, while resilience research has emphasized adaptive capacity, uncertainty and the importance of management under changing environmental conditions.

Despite these advances, important gaps remain. Management is increasingly recognized across these perspectives, but it is rarely conceptualized as an explicit intervention capable of modifying coupled forest–water–atmosphere processes; instead, it is often treated as an adaptive response, contextual factor or land-use category. Existing frameworks also operate at specific organizational or spatial scales, while the mechanisms linking processes across scales are less clearly articulated, so the propagation of management effects from soil-water processes and plant water status to catchment hydrology and atmospheric dynamics is often implied rather than explicitly conceptualized. Likewise, although evapotranspiration, soil moisture and related feedbacks are increasingly recognized as important components of hydrological and atmospheric systems, the pathways connecting forest structure, management interventions and broader system responses remain insufficiently integrated.

Resilience is similarly framed as an emergent property of ecological systems exposed to disturbance and environmental change, yet existing resilience frameworks rarely explain how management interventions modify resilience through coupled forest–water–atmosphere processes operating across scales. As a result, the mechanistic pathways linking management decisions, hydrological responses, physiological dynamics, atmospheric coupling and resilience outcomes remain insufficiently integrated (Millar et al., 2007; Seidl et al., 2016; Asbjornsen et al., 2011; Gentine et al., 2019).

FWAT addresses these gaps by framing forest management as an intervention within coupled forest–water–atmosphere systems. Rather than proposing new mechanisms, FWAT integrates existing knowledge into a management-relevant multiscale framework linking soil-water dynamics, plant water status, evapotranspiration, catchment hydrology and atmospheric feedbacks. In doing so, it provides a basis for testable hypotheses about when local management interventions may generate scalable forest–water–atmosphere responses and influence system resilience under environmental change.

3. Claims Matrix

The conceptual perspectives reviewed above do not compete in a strict sense. Rather, they illuminate different components of coupled forest-water-atmosphere systems and operate at different levels of explanation.

The purpose of the claims matrix is therefore not to rank competing theories, but to identify which processes, feedbacks and management dimensions are already well represented in the literature and where important conceptual gaps remain. In particular, the matrix highlights differences in the treatment of management, atmospheric feedbacks, multiscale coupling and resilience-related processes.

Table 1: Claims Matrix

Perspective	What is explained?	What remains open?	Hydrology / ET integrated?	Atmospheric feedbacks integrated?	Management treated as intervention?	Multiscale architecture?	FWAT relevance
Ecohydrology	Vegetation–water interactions, soil moisture dynamics, streamflow, thresholds and heterogeneity across scales.	Atmospheric feedbacks and management are not usually central, and the atmosphere is often implicit.	Yes	Partial	Partial	Yes	Foundational precursor; strong on vegetation–water coupling, weak on atmosphere and intervention logic.

Land–Atmosphere Coupling	Soil moisture, ET, surface energy partitioning, boundary-layer development and hydroclimatic feedbacks.	Forests are often treated as land-cover or vegetation classes rather than active, management-shaped regulators. Recent work further demonstrates how vegetation–atmosphere feedbacks can propagate land-surface changes across spatially connected regions.	Yes	Yes	No / Partial	Yes	Mechanistic bridge for ET-mediated feedbacks; weak on management and forest specificity.
Forest Resilience	Resistance, recovery, vulnerability and adaptive capacity under climate change and disturbance.	Hydrology and atmospheric feedbacks are often secondary, and resilience is frequently framed without explicit coupling pathways.	Partial	Partial	Yes / Partial	Partial	Useful for disturbance, thresholds and adaptive capacity; needs explicit coupled-process logic.
Earth System Science	Forests as active regulators of climate, water and energy fluxes within coupled Earth-system cycles.	Many studies still treat forests as vegetation classes, land-cover types or carbon stocks rather than managed system components.	Yes	Yes	Partial	Yes	Closest conceptual neighbour; provides the broadest systems framing but is often too coarse for management-sensitive mechanisms.
FWAT	Forest management as a deliberate intervention in coupled forest–water–atmosphere systems	Key open questions concern which coupling pathways dominate under which conditions and how management-induced effects propagate across scales	Yes	Yes	Yes	Yes	Integrative framework linking management, hydrology, physiology, atmospheric coupling and resilience-related outcomes

The claims matrix reveals a consistent pattern across the reviewed perspectives: hydrological processes, evapotranspiration and climate interactions are increasingly recognized across multiple research traditions, and management is frequently acknowledged as an important response to environmental change. However, explicit conceptualizations of how management interventions modify coupled forest-water-atmosphere processes across scales remain rare.

A second observation is that resilience, adaptive capacity and threshold behavior are often treated as system-level outcomes without an explicit representation of the hydrological, physiological and atmospheric mechanisms through which management influences system behavior.

FWAT is proposed as a response to these gaps. Rather than introducing new process physics, it provides a multiscale framework that explicitly links management interventions, hydrological and physiological responses, evapotranspiration, catchment dynamics and atmospheric coupling processes within a coherent systems architecture.

4. FWAT

4.1 Core statement

FWAT conceptualizes forest management as a deliberate intervention in coupled forest–water–atmosphere systems. It rests on established evidence that soil-water processes, plant functioning, evapotranspiration, catchment hydrology and atmospheric dynamics are interconnected across scales (Asbjornsen et al., 2011; Seneviratne et al., 2010; Gentine et al., 2019; Ellison et al., 2017), while treating management as an explicit intervention within this coupled system.

Building on advances in ecohydrology, land–atmosphere coupling, resilience research and Earth System Science, FWAT does not propose new process physics (Asbjornsen et al., 2011; Seneviratne et al., 2010; Gentine et al., 2019; Ellison et al., 2017; Ibáñez et al., 2019).

Rather, FWAT integrates these established process perspectives by explicitly linking management decisions to coupled system behavior across organizational and spatial scales. FWAT assumes that management effects can propagate through interacting and context-dependent process pathways. Interventions such as retention measures, drainage modification, stand restructuring or species conversion can modify soil-water availability, stand water use and plant water status (Asbjornsen et al., 2011; McNulty et al., 2021). These changes may influence evapotranspiration and catchment-scale water balances and, under suitable spatial and climatic conditions, contribute to atmospheric coupling processes (Seneviratne et al., 2010; Gentine et al., 2019; Ellison et al., 2017; Lawrence & Vandecar, 2015).

Within this framework, evapotranspiration is hypothesized to be a key candidate coupling variable because it links hydrological and atmospheric domains while remaining sensitive to forest structure, water availability and management interventions (Asbjornsen et al., 2011; Seneviratne et al., 2010; Gentine et al., 2019; Ellison et al., 2017).

However, FWAT does not assume that evapotranspiration is universally dominant; rather, it seeks to identify when different coupling pathways become important (Seneviratne et al., 2010; Gentine et al., 2019). Management interventions are therefore understood as potential drivers of coupled forest–water–atmosphere dynamics. The magnitude, propagation and scalability of these effects remain empirical questions rather than theoretical assumptions.

The central contribution of FWAT is not the identification of a new mechanism, but the explicit conceptualization of forest management as a driver of coupled forest–water–atmosphere dynamics and a testable framework for analyzing how such interventions propagate across scales and influence system resilience under environmental change (Millar et al., 2007; Seidl et al., 2016; Ibáñez et al., 2019; Ellison et al., 2017; Gentine et al., 2019).

4.2 Conceptual architecture

FWAT should be distinguished from related but broader operational and application-oriented frameworks. FWAT denotes the conceptual theory: the integrative framework that explains how forests may regulate coupled water and atmospheric processes across scales. The broader project context covers an operational research program for studying such coupling empirically and a downstream assessment layer in which findings are translated into evaluation, prioritization, and management-oriented decision contexts[1].

This distinction is important because it keeps the present manuscript conceptually focused. FWAT is the overarching theoretical frame, while the operational and assessment layers are treated as separate, ongoing work streams. In the preprint, only FWAT is developed in detail, while the other layers serve to clarify scope and future extension paths.

The conceptual architecture of FWAT is intentionally multiscale and process-oriented. It is not intended as a rigid causal hierarchy, but as a representation of interacting process domains and potential propagation pathways whose direction, strength and relevance may vary across environmental and management contexts. Management actions provide one entry point into this coupled system by altering stand structure, soil-water conditions and plant water status; these changes may propagate through evapotranspiration and catchment water balance and, under suitable spatial and climatic conditions, contribute to atmospheric feedbacks. The point is not that every intervention produces an atmospheric signal, but that management can create coupling pathways whose relevance depends on scale, context, and the magnitude of the underlying flux changes.

This architecture also helps separate processes, couplings, and outcomes. Soil water dynamics and plant water status are processes; evapotranspiration is hypothesized as a key coupling variable; atmospheric relevance is a conditional outcome; and resilience is a system property that emerges from the interaction of these elements.

In that sense, FWAT is not a single-process model but an organizing framework for linking levels of explanation that are often treated separately in ecohydrology, land-atmosphere coupling, resilience research, and Earth System Science.

4.3 Processes, coupling mechanisms and emergent system properties

FWAT distinguishes between three complementary levels of system organization: processes, coupling mechanisms and emergent system properties. This distinction provides the conceptual foundation for analyzing how management interventions propagate through coupled forest–water–atmosphere systems and influence system behavior across scales. At the process level, FWAT considers the hydrological and physiological mechanisms that determine the movement, storage and use of water within forest ecosystems, including soil-

[1] Within the broader FAWF research context, FWAT denotes the conceptual framework, FORWAS the international operational research framework, and HYWERT its regional German assessment counterpart. Together, FORWAS and HYWERT are being developed as the empirical and data-oriented basis for FWAT, with HYWERT focusing on German-based data configurations and modular threshold assessment, and FORWAS providing the wider system-level context and process logic.

water dynamics, infiltration, storage changes, runoff generation, groundwater recharge, plant water status and drought-stress responses; these processes constitute the mechanistic basis through which management interventions exert their immediate effects (Asbjornsen et al., 2011; Ellison et al., 2017).

At the coupling level, FWAT focuses on the interactions that connect hydrological, ecological and atmospheric processes across domains and spatial scales, with evapotranspiration hypothesized as a key coupling variable because it links water availability and vegetation dynamics to atmospheric conditions while remaining sensitive to forest structure, species composition and management interventions (Gentine et al., 2019; Seneviratne et al., 2010; Lawrence & Vandecar, 2015).

FWAT does not assume that evapotranspiration is universally dominant; rather, it seeks to identify the environmental conditions under which different coupling pathways become relevant.

Importantly, the integrative character of ET does not imply fixed, linear or necessarily causal relationships with other system variables. Observed covariation between ET and hydrological, physiological or atmospheric variables may arise from shared environmental controls, nonlinear feedbacks, scale-dependent interactions or indirect pathways. FWAT therefore treats ET as a candidate coupling variable whose causal role, explanatory power and relevance for cross-scale propagation must be tested explicitly rather than inferred from correlation alone.

At the level of emergent system properties, FWAT treats resilience, adaptive capacity, vulnerability, ecosystem services and threshold behavior as outcomes of coupled dynamics rather than primary processes, since they emerge from the interaction of hydrological, physiological and atmospheric processes operating across organizational and spatial scales. This separation of processes and outcomes is important because it allows management interventions to be understood as drivers of indirect, scale-dependent effects: they alter hydrological and physiological processes and their associated coupling mechanisms, while resilience and related properties respond indirectly rather than being directly modified by management actions.

Figure 1 shows the multiscale process–coupling architecture of the Forest–Water–Atmosphere Theory (FWAT).

FWAT therefore provides a framework for analyzing not only whether management interventions affect forest systems, but also how, through which mechanisms and under which conditions these effects propagate across scales. A central objective of FWAT is to understand the propagation of management effects from local interventions to broader system responses, treating their magnitude, direction and scalability as empirical questions rather than theoretical assumptions.

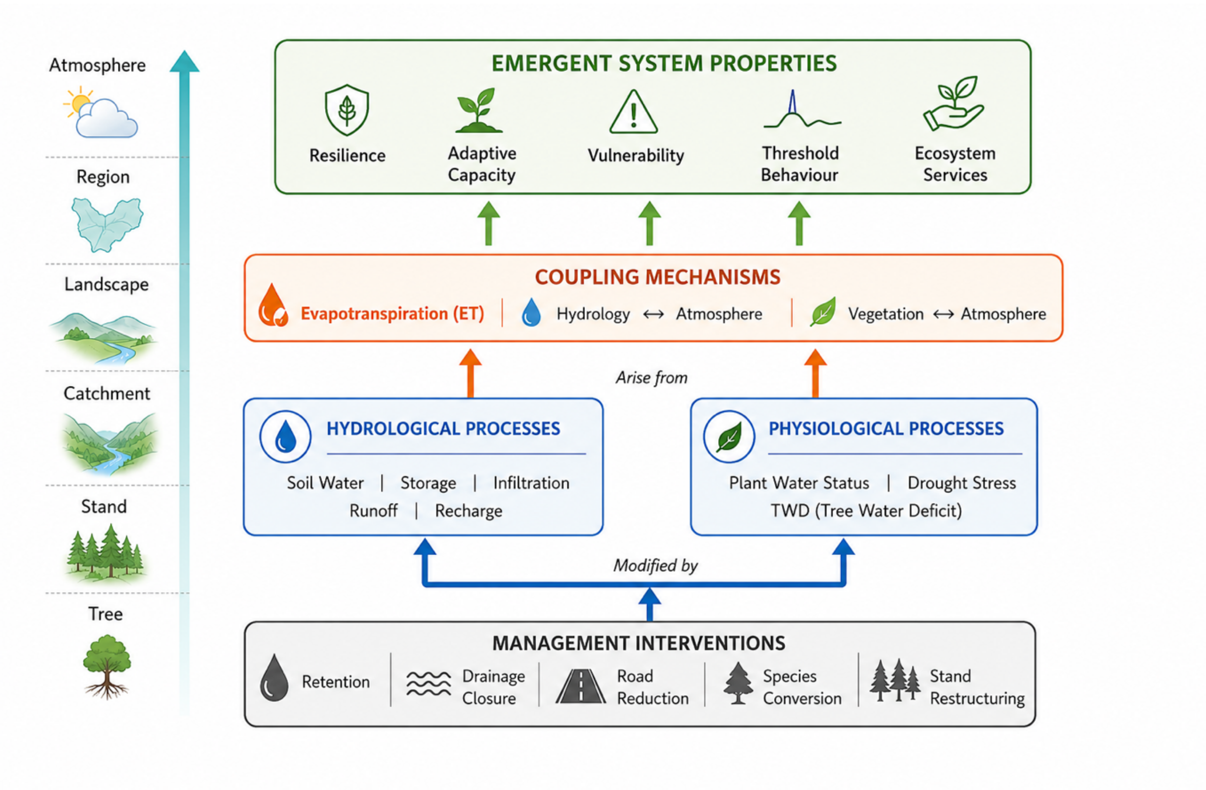

Figure 1. Multiscale process–coupling architecture of the Forest–Water–Atmosphere Theory (FWAT). Management interventions modify hydrological and physiological processes across organizational scales from trees to atmospheric systems. Coupling mechanisms, with evapotranspiration (ET) hypothesized as a key candidate coupling variable, connect these process domains and may contribute to the propagation of management effects across scales. Emergent system properties such as resilience, adaptive capacity, vulnerability, threshold behavior and ecosystem services arise from the functioning of these coupled forest–water–atmosphere dynamics. The magnitude and scalability of management-induced effects are treated as empirical questions rather than theoretical assumptions. This conceptual illustration was created by the authors with the assistance of generative AI and manually refined.

5. Conceptual model

FWAT assumes that management interventions can modify coupled forest–water–atmosphere processes. However, the magnitude, direction and scalability of these effects are treated as empirical questions that require explicit testing across sites, climatic conditions and management contexts.

FWAT is built around a simple but explicit systems logic: forest management can alter soil-water conditions, stand structure and plant water status, with potential consequences for evapotranspiration and catchment water balance and, under suitable spatial and climatic conditions, for the atmospheric coupling potential of managed forest landscapes. This logic is not intended as a fixed causal chain, but as a framework for testing interacting propagation pathways from site-level management to broader forest–water–atmosphere coupling.

The conceptual model therefore operates at two levels. First, it identifies *why FWAT is needed*: existing perspectives capture important parts of the system, but they remain fragmented with respect to management, atmospheric feedbacks, and scale integration (**figure 2**). Second, it explains how FWAT works: management can modify soil-water conditions and stand structure, these changes may influence plant water status and ET, and the resulting flux responses may affect catchment-scale water balances and, when scaled across landscapes under suitable coupling conditions, contribute to atmospheric coupling outcomes (**figure 3**).

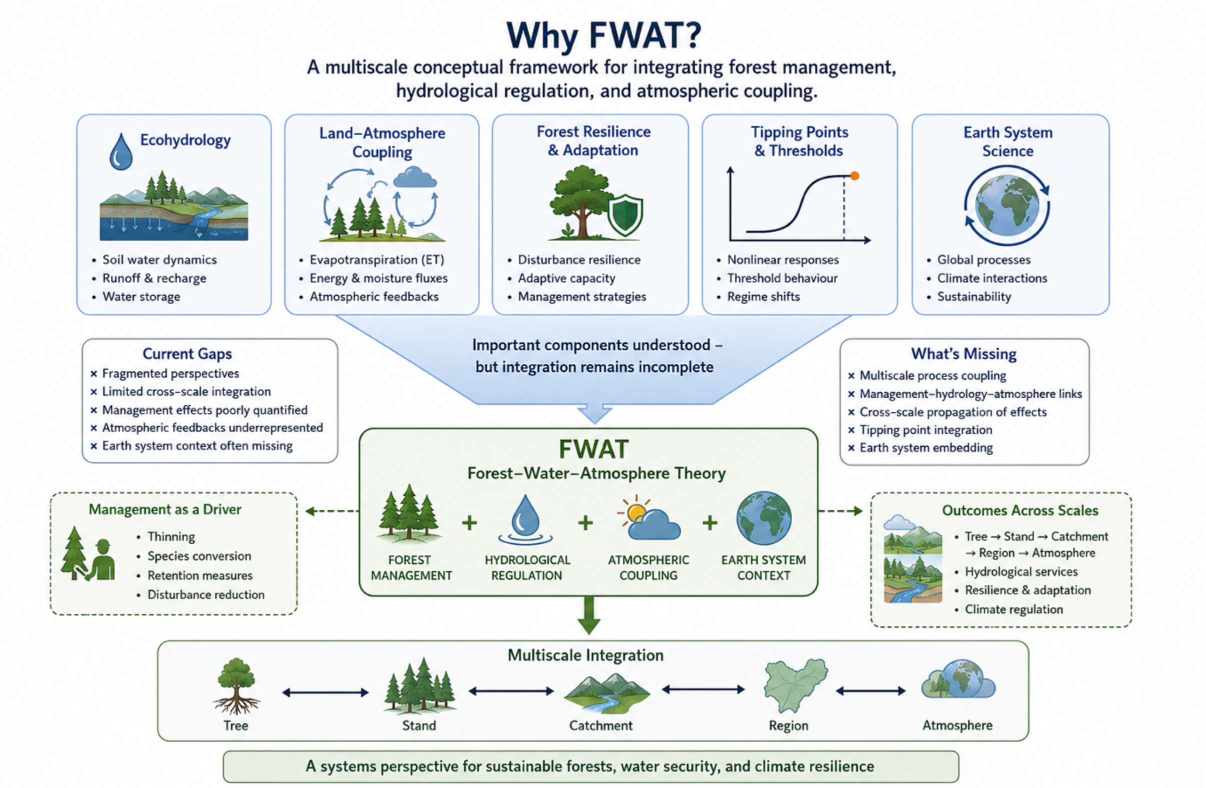

Figure 2. Why FWAT? A multiscale conceptual framework for integrating forest management, hydrological regulation, and atmospheric coupling.

The figure positions FWAT as a systems perspective that integrates ecohydrology, land–atmosphere coupling, forest resilience, tipping point research, and Earth system science into a single multiscale framework. It illustrates that existing perspectives explain important components of the forest–water–atmosphere system, but that their integration remains incomplete with respect to management, cross-scale dynamics, and atmospheric feedbacks. This conceptual illustration was created by the authors with the assistance of generative AI and manually refined.

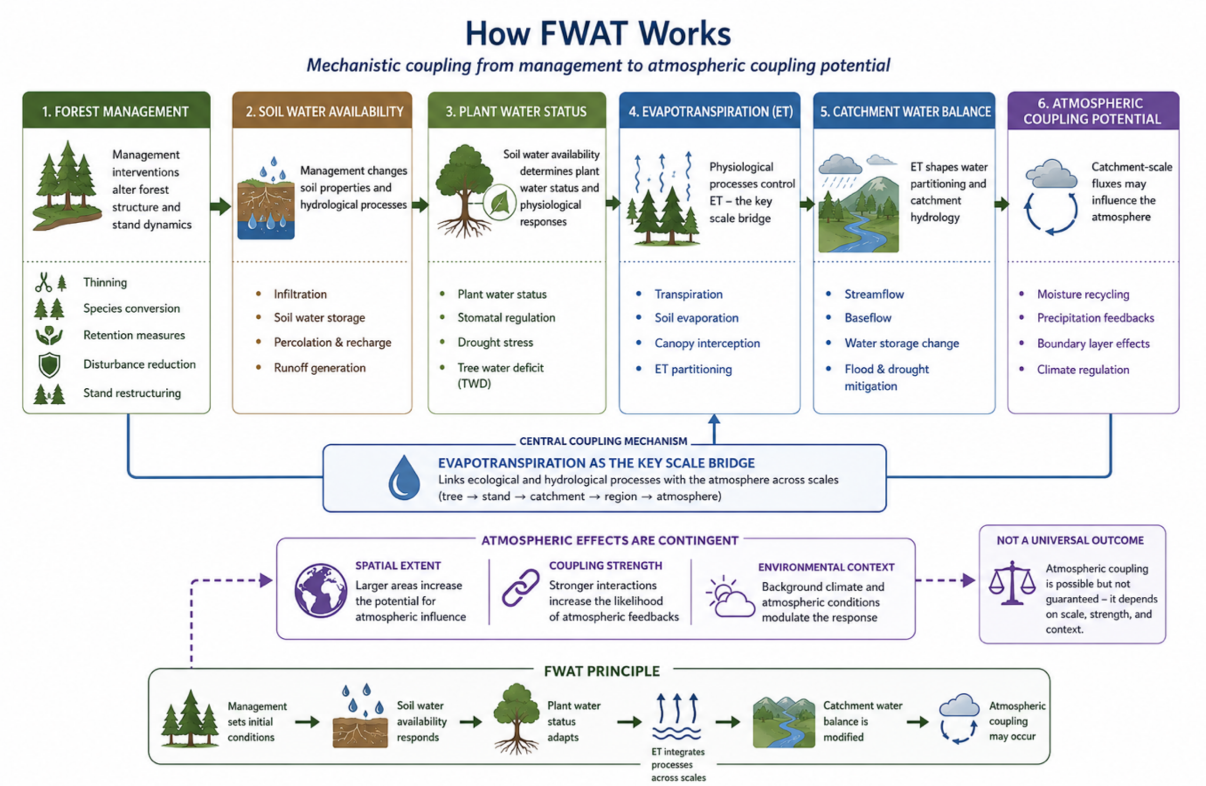

Figure 3. How FWAT works: mechanistic coupling from management to atmospheric coupling potential.

The figure shows the central FWAT pathway: forest management influences soil water availability and plant water status, which shape evapotranspiration and catchment water balance, thereby creating a potential pathway to atmospheric coupling. The model emphasizes evapotranspiration as a candidate key scale bridge and treats atmospheric effects as contingent on spatial extent, coupling strength, and environmental context rather than as a universal outcome. This conceptual illustration was created by the authors with the assistance of generative AI and manually refined.

6. Hypotheses and research agenda

FWAT is designed as a hypothesis-generating framework rather than a closed theory. Its purpose is to identify where, how, and under what conditions management-related changes in forest structure and soil water dynamics may propagate through plant water status and evapotranspiration to catchment-scale water balances and, potentially, atmospheric coupling outcomes.

The research agenda is therefore intentionally multiscale and comparative. It combines process-based reasoning, harmonized catchment modelling, and targeted measurements at sites where management interventions are expected to produce measurable hydrological and physiological responses. The six hypotheses below define the core of this agenda.

H1. Hydrological management interventions alter seasonal soil-water availability and redistribution

Hydrological management interventions, including retention measures, drainage modification, ditch closure and water-redistribution measures, can alter the residence time, spatial distribution and seasonal availability of water within the soil and near-surface storage system (McNulty et al., 2021; Ponce-Rodríguez et al., 2021). Depending on their design and site context, such interventions may increase local retention, redistribute water across the landscape or reduce rapid drainage.

For interventions designed to increase local retention or reduce artificial drainage, the expected signal is higher or longer-lasting soil moisture and slower drying during drought periods. The critical evidence would be soil-moisture gradients across hydrological interventions compared with reference plots.

H2. Changes in soil water availability affect plant water status and drought stress

If retention measures or reduced drainage increase plant-available soil water during critical dry periods, this should be reflected in altered dendrometer-derived indicators of tree water status, including tree water deficit and diurnal stem shrinkage dynamics (Szatniewska et al., 2022; Salomón et al., 2022; Peters et al., 2025). The expected signal is lower or more slowly developing tree water deficits, altered maximum daily stem shrinkage, delayed drought-stress responses, and faster recovery after rainfall events. The critical evidence would be dendrometer-based observations linked to the same soil-moisture gradients.

H3. Management influences evapotranspiration regimes and their response to dry periods

Management measures that alter soil-water availability, stand structure or canopy characteristics can affect transpiration, interception and total evapotranspiration, although the magnitude and direction of these responses depend on site conditions, stand characteristics and climatic context (Bosch & Hewlett, 1982; Aguilos et al., 2021; Isaacson et al., 2023). The key question is not only whether annual ET changes, but how management modifies the magnitude and temporal dynamics of ET during hot and dry periods. The expected signal is altered seasonal ET, altered ET/precipitation relationships, altered ET in drought years, and altered coupling between relative extractable water, vapor pressure deficit and ET. The critical evidence would come from BALANCE- and SWAT+-based ET analyses supported by soil moisture, dendrometer data, remote sensing and reanalysis products.

H4. Management effects are catchment-specific, but not random

The strength of the response should depend on controlling parameters such as soil depth, storage capacity, relief, drainage history, stand structure, tree species composition, disturbance extent and climatic water balance (McNulty et al., 2021; Zhang et al., 2022). The expected signal is that the same scenario produces different but explainable changes in ET, discharge and storage across different SWAT+ catchments. The critical evidence would be harmonized multi-catchment scenarios with identical scenario logic and a common output structure.

H5. ET can provide a key scale bridge between forest-water processes and Earth-system questions

ET integrates soil water, vegetation structure, plant hydraulics and meteorological demand, making it a plausible candidate for linking forest-water processes with atmospheric feedbacks across scales (Seneviratne et al., 2010; Gentine et al., 2019; Kan et al., 2026; Ma et al., 2026). This remains a testable assumption rather than a fixed conclusion, because the relative importance and causal role of ET and other coupling mechanisms may vary across system type, scale and climatic context. The expected signal is that management-induced changes in hydrological and physiological processes are associated with detectable changes in ET and latent heat fluxes and, under suitable coupling conditions, with VPD- and boundary-layer-relevant variables. The critical evidence would be comparisons of modelled ET with ERA5/ERA5-Land, remote-sensing ET, temperature and VPD anomalies and, where available, regional climate-model products.

H6. Atmospheric effects are not expected to be directly detectable at small catchment scale, but can be quantified as a potential space

At the scale of individual small catchments, a direct precipitation or atmospheric signal is unlikely to be robustly detectable. A more realistic first step is to quantify an ET potential that could become atmospherically relevant if implemented over larger areas (Kan et al., 2026; Ma et al., 2026; Zhang et al., 2022). The expected signal is area-weighted ΔET estimates for 10,000, 50,000, or 100,000 ha scenarios, together with corresponding latent energy flux estimates and, where suitable atmospheric modelling is available, estimates of potential moisture-recycling effects. The critical evidence would be robust ET effect sizes from multiple catchments and scaling across site types and management areas.

Research agenda

The research agenda follows directly from these hypotheses. First, harmonized multi-catchment modelling should be used to test whether comparable management scenarios produce reproducible ET and water-balance responses across different forested catchments. Second, targeted field measurements should focus on the critical process transitions that connect management to soil water and plant water status, rather than attempting full system coverage. Third, atmospheric relevance should initially be evaluated as a scaling problem, not as a direct precipitation-detection problem, with emphasis on ET magnitude, spatial extent, and coupling strength.

In practical terms, the first research phase should prioritize soil moisture measurements along hydrological interventions, dendrometer-based monitoring of stem water status, and model-based ET estimation from harmonized scenarios. This combination provides the minimum evidence base for testing whether management-induced coupling signals are mechanistically consistent, spatially scalable, and potentially relevant to atmospheric processes.

7. Discussion

7.1 Scope and boundaries

FWAT is intentionally not framed as a new process-based theory that would replace ecohydrology, land–atmosphere coupling research, resilience theory, or Earth system science. Instead, it is a conceptual synthesis that integrates these strands into a management-relevant multiscale framework centered on forest regulation, evapotranspiration, and atmospheric coupling potential.

This also means that FWAT does not assume a universal mechanism dominance. The framework explicitly allows the relative importance of different coupling pathways to vary with site conditions, spatial scale, management regime, and climatic context. In that sense, FWAT is deliberately open to empirical testing rather than closed by definition.

7.2 Management relevance

Forest management has traditionally emphasized stand-level objectives such as timber production, growth and sustained yield. Although multifunctionality, ecosystem services and climate adaptation have progressively broadened this perspective, forests are still rarely conceptualized in management frameworks as components of coupled hydrological and atmospheric systems operating across scales (Zhang et al., 2022; Bonan et al., 2024).

A central advantage of FWAT is that it treats management as a deliberate intervention in coupled forest–water–atmosphere dynamics rather than as a background condition. This makes the framework directly relevant for managed forests, where management interventions affecting drainage, retention, stand structure and species composition can modify soil-water availability, plant water status and evapotranspiration, with the magnitude and direction of these responses depending on site and climatic context (FAO, 2021; McNulty et al., 2021; Zhang et al., 2022).

From this perspective, management is not only an ecological or silvicultural issue, but also a coupling problem. FWAT therefore provides a language for asking when management changes remain local hydrological adjustments and when they begin to matter as broader forest–water–atmosphere coupling signals.

7.3 Implications for research design

FWAT implies that the most informative research strategy is not maximal system coverage, but targeted observation of the process transitions that connect management to atmospheric relevance. For empirical testing, a pragmatic observational sequence is management, soil water, plant water status, evapotranspiration, catchment water balance, and only then potential atmospheric coupling at larger spatial extent.

This has practical consequences for data collection. At the first stage, soil moisture, dendrometer-based plant water status, and harmonized catchment model outputs are more important than attempting to measure the full atmospheric system directly. In other words, FWAT prioritizes mechanistic continuity over observational completeness.

7.4 Limits and uncertainty

The main limitation of FWAT is also one of its strengths: it is a conceptual framework, not a directly observed mechanism. Its validity depends on whether the hypothesized coupling chain can be demonstrated across contrasting catchments and management contexts, and whether ET functions as a robust scale bridge under the relevant conditions.

A second limitation concerns atmospheric detectability. FWAT does not claim that atmospheric effects should be detectable at the scale of small catchments; rather, it proposes that management-induced changes may first be expressed as an ET potential whose atmospheric relevance depends on spatial scaling and coupling conditions.

Recent coupled-model evidence further indicates that forest–atmosphere feedbacks can substantially modify hydrological responses at larger spatial scales, while the direction and magnitude of these effects vary across climatic regions (Kan et al., 2026). Atmospheric relevance therefore remains a hypothesis to be tested rather than an outcome assumed *a priori*.

7.5 Connectivity to existing literature

FWAT remains strongly connected to established literature, especially ecohydrology and land–atmosphere coupling. Its novelty lies in reorganizing these strands around management and multiscale coupling, while also incorporating resilience and tipping point thinking as questions of stability, thresholds, and response variability rather than as separate explanatory silos.

In that sense, FWAT is best understood as a bridging framework. It helps translate between catchment-scale hydrology, forest management, and earth-system thinking, without overstating the maturity of any one linkage.

7.6 Concluding perspective

Taken together, FWAT provides a structured way to ask when forest management changes only local water fluxes and when it contributes to broader coupled forest–water–atmosphere behavior. Its immediate value lies in hypothesis generation, comparative modelling, and targeted measurement design, while its longer-term value depends on whether the proposed coupling pathways can be shown to scale across sites and management regimes.

This makes FWAT a management-relevant synthesis framework rather than a final explanatory endpoint. The framework is therefore best evaluated through iterative empirical testing, progressively stronger cross-catchment comparisons, and explicit attention to scaling and context dependence.

8. Conclusion

FWAT offers a concise way to organize a fragmented literature around a single multiscale question: when and how can forest management alter coupled forest–water–atmosphere dynamics through soil water, plant water status and evapotranspiration. Its main contribution is not new process physics, but the explicit integration of existing perspectives into a management-relevant synthesis framework.

The immediate value of FWAT lies in hypothesis generation, comparative modelling and targeted measurement design. In particular, it directs attention to the process chain from management to soil moisture, plant water status, ET and catchment water balance, while treating atmospheric relevance as a scaling question rather than a presupposed outcome.

At present, FWAT should be evaluated by whether its proposed coupling pathways can be demonstrated across sites, management contexts and spatial scales. If that proves to be the case, FWAT can serve as a bridging framework between ecohydrology, land–atmosphere coupling, resilience research, tipping point thinking and Earth system science.

FWAT therefore provides a testable conceptual basis for investigating when management-induced changes remain local hydrological responses and when they may propagate into broader, scale-dependent forest–water–atmosphere dynamics.

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