Report on transformation pathways towards innovative NBS

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Executive Summary

The trans4num project seeks to redefine nutrient management in agriculture by shifting from linear, intensive practices to circular, sustainable approaches rooted in nature-based solutions (NBS). This transformative vision addresses the environmental consequences of synthetic fertilizer overuse, particularly nitrogen (N) and phosphorus (P), which contribute to water pollution, biodiversity loss, and soil degradation. The goal is to establish closed nutrient cycles that recycle resources within agricultural systems, reducing reliance on synthetic inputs and enhancing long-term sustainability.

A defining characteristic of nutrient management transformation in **trans4num** is its **incremental yet transformative approach**. While the broader goal is to contribute to a radical, systemic shift in nutrient management, the pathway to transformation involves **deliberate, incremental steps**. This pragmatic strategy recognizes that agricultural systems are complex and require gradual transitions to achieve large-scale change. Each transition, such as adopting NBS at trial sites, contributes to the larger transformation. By leveraging small-scale innovations and scaling them through adaptive and iterative processes, trans4num ensures that these incremental changes align with the overarching vision of a radical transformation.

The deliverable's **literature review highlights drivers and barriers** influencing nutrient management transformation. It underscores the importance of distinguishing between (1) **Short-term barriers**, such as resource constraints or knowledge gaps, which can be addressed through education, subsidies, and outreach and (2) **Systemic lock-ins**, including entrenched reliance on intensive agricultural practices and weak governance, which require long-term structural reforms in policies, supply chains, and market incentives. Importantly, many factors identified in the literature can act as either drivers or barriers depending on how they are implemented and influenced by contextual factors. This dual potential necessitates continuous monitoring within trans4num to steer these factors toward fostering transformation.

Stakeholder engagement is central to trans4num's success. Farmers, local communities, researchers, policymakers, and institutions actively co-design pathways through participatory methods such as workshops and hackathons. This inclusive approach ensures **solutions are practical, widely accepted, and tailored to local contexts**. By integrating the knowledge and experiences of diverse groups, trans4num builds trust and commitment, which are critical for sustained change. Tailored transition pathways are developed to reflect the unique characteristics of each site, considering factors like environmental conditions, governance structures, and cultural norms. We suggest approaches such as scenario planning and backcasting, to help stakeholders envision desirable futures and map out the steps to achieve them. Participatory assessments ensure that strategies remain aligned with community needs, while monitoring and evaluation track progress on both environmental and social indicators, such as improved soil biodiversity and stakeholder collaboration.

The project's **incremental and adaptive framework** ensures that every step contributes meaningfully to the overarching transformation: (1) Initial actions focus on implementing and refining NBS at trial sites, leveraging local knowledge to develop effective solutions. (2) Incremental steps build momentum toward systemic change, ensuring that small-scale transitions contribute to the larger transformation. (3) Monitoring and feedback loops ensure pathways remain responsive, continuously refining strategies based on stakeholder input and research findings.

By focusing on deliberate transitioning and incremental progress, trans4num demonstrates how targeted interventions at the local level can cumulatively contribute to a radical transformation in nutrient management. This approach bridges the gap between immediate, practical actions and the long-term goal of systemic change, positioning trans4num as a catalyst for a sustainable, resilient future in agriculture.

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Abbreviations

AKIS	Agricultural Knowledge and Innovation System
NBS	Nature-based Solution
SDGs	Sustainable Development Goals
SE	Stakeholder Engagement
SER	Social-Ecological Resilience
SET	Socio-Ecological Transformation

1. Introduction

The need for sustainability transformation in nutrient management is pressing, driven by ecological imperatives and social demands, aligning with the Sustainable Development Goals (SDGs) and the Common Agricultural Policy. The trans4num project seeks to address these needs by promoting a shift towards circular nutrient supply and management through nature-based solutions (NBS). This deliverable investigates possible transformation pathways and their influencing factors from a socio-ecological perspective, providing a foundation for how trans4num can foster this transformation.

Despite the growing recognition of the need for sustainable nutrient management, there are significant barriers to achieving this transformation. These barriers include technical challenges, economic constraints, policy limitations, and social resistance. Additionally, the pathways to achieve such a transformation are often unclear, as they are complex and unpredictable, with various factors influencing the success of different approaches. Understanding these pathways and the factors that foster or hinder them is crucial for guiding effective interventions and achieving the desired sustainability outcomes.

This deliverable aims to enhance our understanding of how trans4num can contribute to nutrient management transformation. The specific outputs of this task include:

1. **Theoretical Grounding**: Establishing a solid foundation in transformation literature to thoroughly understand nutrient management transformation and trans4num's role within this context.
2. **Analysis of Fostering and Hindering Factors**: Identifying and analysing the factors that can either facilitate or impede the transformation of intensive farming towards sustainable practices, mainly focusing on nutrient management through NBS.
3. **Analysis of Transformation Pathways**: Defining a trans4num way forward to contribute with NBS sites' experimentation as basis to a nutrient management transformation.

The methodological approach for this deliverable is informed by a comprehensive review of transformation and transformation pathway literature, encompassing both grey and scientific sources. This foundation enables a robust understanding of the processes and mechanisms of achieving nutrient management transformation. Additionally, a systematic review was conducted to identify fostering and hindering factors specific to sustainable agricultural transformation, ensuring a thorough and nuanced analysis. Finally, we integrated the principles for navigating complex transformations. This approach is incremental, adaptive, and iterative, ensuring the transformation process remains flexible and responsive to new knowledge and stakeholder input throughout the trans4num project. The trans4num consortium cross-checked the content of this deliverable during project events to ensure a common understanding.

This deliverable is a critical component of the trans4num project, providing essential insights and frameworks that will guide the consortium's efforts towards fostering a sustainable and circular nutrient management transformation through NBS.

2. Nutrient supply and management transformation

Nutrient supply and management in agricultural production encompass a broad field of nutrient flows. In this deliverable, we narrow our focus to two critical nutrients: Nitrogen (N) and Phosphorus (P). These are among the primary nutrients upon which intensive agriculture heavily relies. However, this reliance has significant environmental drawbacks and challenges future food security by exceeding earth system boundaries (Lott et al., 2011; Richardson et al., 2023).

The easy and cheap production of N through the Haber-Bosch process has led to its overuse, resulting in environmental pollution, such as biodiversity loss and groundwater contamination (Penuelas et al., 2023; Staude et al., 2020). In contrast, P is a finite resource, with most global deposits in Morocco, raising concerns about future dependency (Lott et al., 2011; USGS, 2024). Despite the different initial reasons for changing N and P management, they share a common solution: recycling rather than generating new resources, aiming for a circular nutrient management system.

In the trans4num project, we specifically focus on nutrient flows within agricultural crop production and the wider environment, such as watersheds. Manure from animal production is also included as a fertiliser input, while human consumption and waste management are not considered at the trial sites. The scale of our analysis will vary from case to case, ranging from field-level to regional and supra-regional level studies. Additionally, the scope may expand even further when considering organisational or cultural aspects. Therefore, clearly defining the context being examined in each instance is crucial. Further, it is essential to include social factors to understand how to transform complex ecological systems. These socio-ecological factors can vary depending on thematic, political, or cultural contexts and the involvement of different actors. Therefore, trans4num adopts a transdisciplinary approach, integrating a multi-site and multi-level framework. This approach allows for specific responses to the unique situations of the NBS sites while maintaining a focus on the overarching nutrient management transformation.

In this deliverable, we examine various aspects relevant to nutrient management transformation within the trans4num context:

1. Characteristics of a social-ecological transformation;
2. Specific innovation situations of the NBS sites in trans4num and
3. Connections between nutrient management transformation and the trans4num NBS sites.

By addressing these aspects, we aim to provide a comprehensive understanding of achieving a sustainable and circular nutrient management approach in agriculture.

2.1 Nature-based Solution and Innovation

The literature on NBS is fragmented and contested, with various interpretations and applications across different contexts. An overview of different notions regarding agricultural NBS was presented by Vér et al. (2023). For the trans4num project, the consortium agreed to adopt the following three statements during the online general assembly on 18th September 2023 to encapsulate the project's understanding of nutrient management-related NBS in agriculture:

1. **Environmental and Socioeconomic Benefits**: NBS are characterised by the application of diverse agronomic practices that yield positive environmental outcomes (e.g., reduction of nitrogen and phosphorus surpluses, decreased greenhouse gas emissions) and socioeconomic benefits (e.g., stabilisation or increase of crop yields, improved labour productivity).
2. **Local Circularity**: NBS are based on the principle of local circularity, which involves implementing adaptive agronomic practices that close local nutrient cycles while maintaining or enhancing crop yields and nutritional quality.
3. **Farmer-Centric and Societal Services**: NBS must meet farmers' needs and have a neutral or positive impact on the agroecosystem. When scaled beyond the field level, they should additionally provide societal services.

Nutrient management NBS in trans4num is a nested concept that incorporates the three statements above. This concept is expressed at multiple levels: the field/farm level, within the encompassing ecosystem, and the broader societal, socioeconomic, and cultural environment and contexts (e.g., represented through value chain models, rural-urban relationships, and the Agricultural Knowledge and Innovation Systems (AKIS) concept).

In trans4num Europe, four specific NBS were selected for implementation at sites in Denmark, Hungary, the Netherlands, and the UK, and three sites for trans4num China, each addressing local or regional challenges in nutrient management. These NBS are viewed as innovations. According to the Food and Agriculture Organization (FAO), "Innovation is the process whereby individuals or organizations bring new or existing products, processes or ways of organisation into use for the first time in a specific context in order to increase effectiveness, competitiveness, resilience to shocks or environmental sustainability and thereby contribute to food security and nutrition, economic development or sustainable natural resource management" (Ruane, 2019: VI). The NBS's tested in trans4num relate to different aspects of this definition. Some NBS can be defined as new products. In contrast, others build on existing products and relate to the process (e.g., new crop rotation and management practices) or context (local or regional adoption).

The innovations introduced through NBS in trans4num are directly linked to the broader goal of nutrient management transformation. Each NBS represents an incremental step towards more sustainable nutrient management practices. By gradually introducing these innovations, the project aims to reduce dependency on synthetic fertilisers and promote the recycling of nutrients within local systems, which is crucial for a long-term transformation. The socio-ecological perspective of NBS ensures that social and environmental factors are considered. This holistic approach helps to align agricultural practices with societal needs and environmental limits, promoting a balanced and sustainable nutrient management system.

2.2 The specific challenges of awareness raising for nutrient management transformation

There are specific challenges related to a transformational approach for more sustainable agricultural nutrient management. Individual and social changes of practice often come more slowly for issues with low observability, e.g. sustainable nutrient management, because they are less present in personal and public awareness compared to topics like biodiversity losses or climate change-related risks and damages. Visibility tends to increase awareness and concern, motivating individual and collective action. For instance, biodiversity loss is directly observable through declining species populations and habitat loss, and it's often showcased through charismatic species that evoke strong emotional responses, making the issue more tangible to the public (Chan et al., 2012). In contrast, nutrient management issues such as nitrogen and phosphorus cycling are complex, abstract, and largely invisible processes that operate "behind the scenes" in agricultural systems, meaning they don't naturally capture attention in the same way.

This invisibility affects the trans4num research project in several ways. Generally, there is an overall need for the project to communicate the relevance and importance of nutrient management to a broader audience. Public engagement and stakeholder buy-in may be easier with visible, relatable impacts. This requires trans4num to develop effective outreach and information strategies to illustrate the link between nutrient management, environmental health, and long-term agricultural sustainability (Schneider et al., 2009). The project must also work hard to foster a sense of urgency and connection to nutrient management issues by linking them to more tangible problems, such as water quality degradation or greenhouse gas emissions.

Moreover, the subtle nature of nutrient management challenges calls the trans4num project partners to directly engage decision-makers, farmers, and other practitioners and use targeted communication strategies that convey improved practices' immediate and long-term benefits. This effort is essential to overcome the psychological barrier of delayed gratification that often accompanies nutrient management interventions, where benefits may not be apparent for years, compared to the more immediate rewards of visible biodiversity initiatives (Markard et al., 2012). By emphasizing both the environmental and socio-economic advantages, the project can better align individual and community actions with broader sustainability goals.

3. Social-ecological Transformation

Transformations are "fundamental changes in structural, functional, relational, and cognitive aspects of socio-technical-ecological systems that lead to new patterns of interactions and outcomes" (Patterson et al., 2017). This involves profound, substantial, and irreversible changes, altering fundamental status quo attributes (Brand et al., 2013; Feola, 2015) and leading to new ones with different characteristics. These changes encompass environmental, structural (e.g., institutions, culture), and agency aspects (Brown et al., 2013), making the transformation complex and multi-faceted, encompassing broader systemic shifts. These characteristics distinguish transformation from transition, which are deliberate, goal-oriented changes within specific subsystems (Brand, 2012).

3.1 The four dimensions of transformation

The understanding of transformation is diverse and often contested (Fazey et al., 2017; Feola, 2015). The transformation's end state is shaped by the starting point and transformation vector, with non-linear processes providing insights into direction and meaning (O'Brien et al., 2012). The term "transformation" can mean different things to different people while arguing that a single agreed-upon concept across all disciplines might not be possible or desirable (O'Brien et al., 2012). Instead, specifying the transformation's initial and desired states (Fazey et al., 2017) is crucial

In the literature, four characteristics are described for the conceptualisation of transformation. Depending on the interpretation of these characteristics, the understanding of transformation may vary:

(a) the depth: The quality of change occurring at which level (individual, organisation, governance, system) (Jahn et al., 2020);

(b) the breadth: Considering the type of system (social-ecological system, socio-technical system) or subsystem (energy sector, agricultural sector);

(c) the process over time: Is there incremental and/or rapid change (Fazey et al., 2017), and

(d) the character of change: Is the change intended or unintended (Kliem & Tschersich, 2017)

The depth of change

Transformations in nutrient management necessitate profound structural changes across multiple scales and levels, acknowledging the complexity and dynamism of agricultural systems. These systems operate at various spatial scales, such as individual, local, regional, and national levels, and encompass functional levels, including markets, states, and civil society. Understanding these layers is crucial for implementing NBS to foster circular nutrient management.

Several theories emphasise the importance of structural changes within socio-technical and socio-ecological systems:

- **Deliberate Transformation** (O'Brien et al., 2012): This theory focuses on intentional, managed changes, often initiated at the individual and community levels.
- **Progressive Transformation** (Pelling, 2011): This concept highlights gradual changes that accumulate over time to produce significant system shifts.
- **Transformational Adaptation** (Kates et al., 2012): This framework addresses how adaptive responses to environmental pressures can catalyse transformational changes.
- **Social Practice** (Shove et al., 2012): This theory examines shifts in social behaviours and practices at the individual level.

Other theories, such as Societal Transitions (Grin et al., 2010), Regime Shift (Folke et al., 2010; Walker et al., 2004), and Socioecological Transition (Fischer-Kowalski & Haberl, 2007), focus on meso and macro levels, addressing broader systemic changes and the interactions between societal and ecological components.

The depth of change required for transformation is intricately linked to leverage points within systems, as these represent the areas where targeted interventions can have the greatest impact. Meadows (1999) outlined a hierarchical list of leverage points within systems, ranging from surface-level parameters, such as taxes and subsidies, to deeper, more profound elements like societal mindsets and paradigms. According to Göpel, (2016), feedback and adaptation to environmental pressures alone are insufficient for achieving profound systemic change. Instead, altering mindsets and paradigms is crucial for instigating profound structural changes (Abson et al., 2017; Göpel, 2016). These leverage points are pivotal for implementing effective NBS in nutrient management transformation, as they address the root causes of unsustainable practices and foster a systemic rethinking of agricultural and environmental interactions. For instance:

- **Mindsets and paradigms**: Changing the fundamental agricultural paradigms from linear to circular nutrient management is essential. This involves promoting a holistic understanding of nutrient cycles and the environmental impacts of farming practices.
- **Rules and incentives**: Establishing and enforcing policies that promote sustainable nutrient management practices and discourage the overuse of nutrients is critical for structural change.

This insight underscores the need for deliberate strategies to address the root causes of nutrient management issues comprehensively. For nutrient management, these findings mean fostering a circular agricultural mindset among farmers and stakeholders, encouraging practices that aim to close nutrient loops and enhance sustainability.

In trans4num, the depth of change is addressed by integrating these theoretical insights into practical interventions at multiple levels:

- **Individual and farm level**: Empowering farmers with knowledge and tools to adopt NBS.
- **Local and regional levels**: Facilitating collaborations among stakeholders to implement region-specific solutions and fostering a circular agricultural mindset.
- **National level**: Influencing policy frameworks to support sustainable nutrient management practices.

By recognising the interconnectedness of different levels and leveraging critical drivers of change, trans4num aims to achieve a comprehensive transformation in nutrient management. By integrating these theoretical insights, the transformation of nutrient management within projects like trans4num can be approached in a manner that ensures sustainability and effectiveness, addressing the multi-faceted nature of socio-ecological systems.

The breadth of change

Transformation concepts vary considerably in their scope and focus. Some approaches, such as Socioecological Transition (Fischer-Kowalski & Haberl, 2007) and Social Practice(Shove et al., 2012), examine transformations across different societal levels, ranging from local communities to global networks. Conversely, frameworks like Regime Shift (Folke et al., 2010; Walker et al., 2004), Societal Transitions (Grin et al., 2010), and Transformational Adaptation (Kates et al., 2012) extend their application to broader systems, including specific subsystems like ecosystems or economic sectors. Within the discourse on social-ecological transformation, there's a growing recognition of the necessity for profound shifts in production and consumption behaviours. While technical innovations are crucial, they are deemed insufficient on their own to drive comprehensive SET. Instead, emphasis is placed on the pivotal role of social innovations in instigating and sustaining these transformative changes (Brand et al., 2013).

Transformation concepts exhibit significant variation in scope and focus, reflecting the complexity and diversity of systems undergoing change. This breadth is crucial for understanding and implementing NBS in nutrient management, highlighting the need for interventions within various subsystems. Approaches such as Socioecological Transition and Social Practices explore transformations across various societal levels, from local communities to global networks. These frameworks emphasise the interconnectedness of social and ecological systems and the need for integrated strategies that address local and global challenges.

- **Socioecological transition**: This concept examines long-term changes in the relationship between society and the environment, focusing on how societal shifts impact ecological systems and vice versa (Fischer-Kowalski & Haberl, 2007).
- **Social practices**: This approach studies the routines and behaviours of individuals and communities, highlighting how everyday practices contribute to larger systemic changes (Shove et al., 2012).

Other frameworks, such as Regime Shift, Societal Transitions, and Transformational Adaptation, focus on broader systems, including specific subsystems like ecosystems or economic sectors. These theories underscore the importance of systemic changes that affect entire sectors or regions, rather than isolated interventions.

- **Regime Shift**: This concept focuses on abrupt, large-scale changes in the structure and function of ecosystems or socio-ecological systems, often triggered by external shocks or internal feedback loops (Folke et al., 2010; Walker et al., 2004).
- **Societal Transitions**: This framework explores the processes through which societies transition from one dominant socio-technical regime to another, emphasising the role of innovation and policy in driving these shifts (Grin et al., 2010).
- **Transformational Adaptation**: This approach addresses how adaptive responses to environmental changes can lead to profound, systemic transformations in both social and ecological systems (Kates et al., 2012).

Within the discourse on social-ecological transformation, there is a growing recognition of the necessity for fundamental changes in the relationships between social systems and ecological processes. Technical innovations, while essential, cannot drive comprehensive transformations on their own. Instead, social innovations, which involve changes in social norms, behaviors, and institutional arrangements, are critical for sustaining long-term, systemic changes (Brand et al., 2013).

- **Social Innovations**: Changes in governance, policy, and community engagement practices that promote sustainable nutrient management (Brand et al., 2013).
- **Ecological Resilience**: Enhancing the capacity of ecosystems to absorb and recover from disturbances, thereby supporting sustainable agricultural practices (Holling, 1973).

For the trans4num project, understanding the breadth of change is vital for designing and implementing effective NBS. The project's focus on circular nutrient management requires interventions integrating social and ecological dimensions at multiple levels. By prioritizing SET, trans4num can ensure that its strategies address the social dynamics and ecological impacts of nutrient management practices. By integrating these social-ecological perspectives, trans4num can develop comprehensive strategies addressing local challenges and broader systemic issues. This approach ensures that technical and social innovations work synergistically to achieve sustainable nutrient management, fostering a deep and broad transformation in its impact.

The process over time

The transformation process can vary significantly in duration and complexity, encompassing long-term and short-term changes. Understanding these temporal dynamics is crucial for implementing effective NBS in nutrient management, as it provides insights into how incremental changes can lead to substantial systemic shifts.

Transformation theories often distinguish between long-term processes, such as those observed during the Industrial Revolution, and shorter-term processes spanning a few decades, like societal transitions. The socio-ecological transition primarily focuses on these long-term, gradual processes of change, which involve profound shifts in the relationship between society and the environment. Conversely, societal transitions often pertain to more immediate changes within 40 to 50 years, reflecting quicker adaptations in socio-technical systems. These transitions highlight how societies can undergo significant shifts in relatively shorter periods, driven by innovations, policy changes, and evolving social norms.

Theories rooted in resilience, such as Deliberate Transformation and Progressive Transformation, suggest that the distinction between short and long-term changes is not always clear-cut. Incremental changes can accumulate, leading to transformative shifts when certain thresholds are crossed (Folke et al., 2010). This concept underscores the importance of recognising and fostering small-scale innovations and adaptations that can result in significant systemic changes.

- **Deliberate Transformation**: Focuses on intentional changes driven by strategic planning and proactive interventions.
- **Progressive Transformation**: Emphasizes gradual, continuous improvements that cumulatively lead to substantial transformations.

Göpel, (2016) argues that altering mindsets can bridge the gap between radical and incremental change strategies. By envisioning radically different futures, new goals for the system can be set and gradually implemented. This approach highlights the role of visionary thinking and long-term planning in driving transformations, even if the initial steps appear incremental. Transformational Adaptation distinguishes between transformative and incremental change by the level at which change is observed. Adaptive changes that scale, for instance, from the local to the regional level are considered transformative (Kates et al., 2012). This perspective emphasises the importance of scaling successful local innovations to achieve broader systemic impacts.

Transformative changes are often described as non-linear, dynamic processes in complex systems with potential tipping points (Fazey et al., 2017). These changes involve ruptures, discontinuities, and thresholds that can lead to sudden and profound shifts in system behavior. To conceptualise these processes, cycles and phases are often used, characterising the general flow of transformations rather than providing specific details (Feola, 2015). Linnér and Wibeck (2019) e.g., describing transformation through five major narratives: a journey, a building process, a war, co-creation, and recuperation. Each narrative implies different mechanisms and pathways for transformation, influencing how problems are framed, policies are developed, and power balances are adjusted.

Understanding the process over time is essential for the trans4num project to foster sustainable nutrient management transformations. By recognizing the potential for incremental and transformative changes, trans4num can develop strategies that leverage small-scale innovations while navigating towards long-term systemic shifts.

1. **Incremental Innovations**: Supporting and scaling up local NBS that demonstrate potential for broader application.
2. **Visionary Planning**: Encouraging long-term thinking and setting ambitious goals for nutrient management transformation.
3. **Adaptive Scaling**: Ensuring that successful local practices are adapted and implemented at regional and national levels to maximize their impact.
4. **Dynamic Monitoring**: Continuously assessing the progress of transformations, identifying tipping points, and adjusting strategies as needed.

By integrating these approaches, trans4num can navigate the complexities of nutrient management transformation, ensuring that both short-term gains and long-term goals are achieved. This comprehensive understanding of the process enables the project to adapt to changing conditions and seize opportunities for profound, lasting change in agricultural nutrient management.

The character of change

The character of change in transformation processes involves the nature of shifts within systems and the role of human agency in these processes (Boudon, 1986; Polanyi, 1944; Turner et al., 1990). Two primary types of transformation processes are recognised: unintended (emergent) and intended (deliberate).

Unintended transformations, or emergent transformations, occur naturally without explicit human direction. These processes include the historical development of advanced civilisations or the evolution of life and species, often catalysed by crises or extinctions that lead to new life forms. Such transformations are typically linked to natural evolutionary processes and large-scale environmental changes (Boudon, 1986; Polanyi, 1944).

Intended transformations, also known as deliberate (O'Brien, 2012), directional (Chapin et al., 2009) or purposive transformations (Berkhout, 2002), are intentionally managed and directed by human actions. This type of transformation involves strategic interventions and proactive efforts to steer systems towards desired outcomes. Examples of intended transformation include:

- Establishing nature conservation areas to foster habitat development (O'Brien, 2012).
- Implementing the Haber-Bosch process and genetic modification techniques to advance industrialised agricultural systems (Chapin et al., 2009).

Agency is central to intended transformations, where humans actively shape and influence the direction of change (Nelson et al., 2007; O'Brien et al., 2012; Pelling, 2011). Small groups and shadow networks often initiate these processes, highlighting the importance of grassroots efforts and community involvement (Olsson et al., 2006; Pelling et al., 2008). Human agency plays a crucial role in achieving intended transformations. However, societal systems' barriers, such as power dynamics, political interests, and institutional resistance, can hinder transformative efforts. These barriers raise critical questions about who should influence the direction of change and how decisions should be made (Pelling & Manuel-Navarrete, 2011).

Achieving a precise target state for social-ecological transformation is challenging due to the complex and dynamic nature of these processes. Addressing environmental challenges necessitates leveraging existing economic and political methods, even though their adequacy may be uncertain (Jahn et al., 2020). Immediate actions are essential, but only when envisioning and working towards fundamentally different, sustainable lifestyles can we prevent future crises. Democratic and justice considerations demand that social-ecological transformations result from inclusive, participatory processes considering diverse perspectives and interests (Leach et al., 2010).

Understanding the character of change is vital for driving effective nutrient management transformations in the trans4num project. This involves recognising the role of both unintended and intended transformations and leveraging human agency to steer the process towards sustainable outcomes.

(1) **Unintended Transformations**: Acknowledge and harness naturally occurring shifts within agricultural systems, such as spontaneous changes in market demand that may prompt farmers to change practices.

(2) **Intended Transformations**: Focus on deliberate actions, such as implementing innovative agronomic practices, promoting NBS, and engaging stakeholders in strategic planning to achieve targeted nutrient management objectives.

(3) **Human Agency**: Empower local communities, farmers, and other stakeholders to actively shape the direction of nutrient management transformations. Facilitate the formation of small groups and networks to initiate and sustain transformative efforts.

(4) **Addressing Barriers**: Identify and mitigate barriers within societal systems that may hinder transformation. This includes addressing power imbalances, political resistance, and institutional inertia through inclusive and participatory approaches.

(5) **Democratic Processes**: Ensure that nutrient management transformations are guided by democratic and justice considerations, involving diverse stakeholders in decision-making processes to achieve fair and equitable outcomes.

By integrating these approaches, trans4num can effectively navigate the complexities of nutrient management transformation, ensuring that both emergent and deliberate processes contribute to sustainable agricultural systems. This comprehensive understanding of the character of change enables the project to leverage human agency, address barriers, and foster inclusive, democratic processes that drive lasting and meaningful transformation in nutrient management.

3.2 Social-ecological transformation in the context of trans4num

A socio-ecological transformation involves profound, systemic changes that affect both social and ecological systems. It implies changing practices within a given system (like agriculture) and fundamentally transforming the relationship between society and the environment. In the case of circular nutrient management, if the change also involves a rethinking of societal values, such as moving from extractive, growth-oriented models of agriculture to more regenerative, ecological ones, then it can be seen as part of a broader socio-ecological transformation. This would include changes in social norms, governance structures, and human-environment relationships that emphasise regeneration, circularity, and ecological balance. A transformation would change how nutrients are managed and redefine the goals and ethics of the agricultural system, potentially leading to shifts in food sovereignty, social equity, and environmental justice.

Trans4num aims to transform nutrient supply and management intentionally, categorising this as a deliberate transformation (Chapin et al., 2009; O'Brien, 2012). It contributes to a radical transformation towards a circular and sustainable nutrient management system. This transformation aims for long-term, systemic change in agricultural practices, ecosystems, and socio-economic systems. It goes beyond simple, incremental improvements and aims to create fundamental shifts in how nutrients are managed. While the overall goal is radical change, the process will unfold gradually, and various transitions will simultaneously occur (Figure 1). These transitions often appear more gradual at first and are part of a broader process. As with most transitions in agriculture and nutrient management systems, changes will require time to establish new technologies, behaviours, and norms (Kirchhoff et al., 2013; Vecchio et al., 2020). This incremental process, while slower, allows for continuous adjustments, which are crucial for addressing the complexities of agricultural systems and their socio-ecological contexts. Therefore, **trans4num's incremental transition will contribute to the broader, radical transformation of circular nutrient management**.

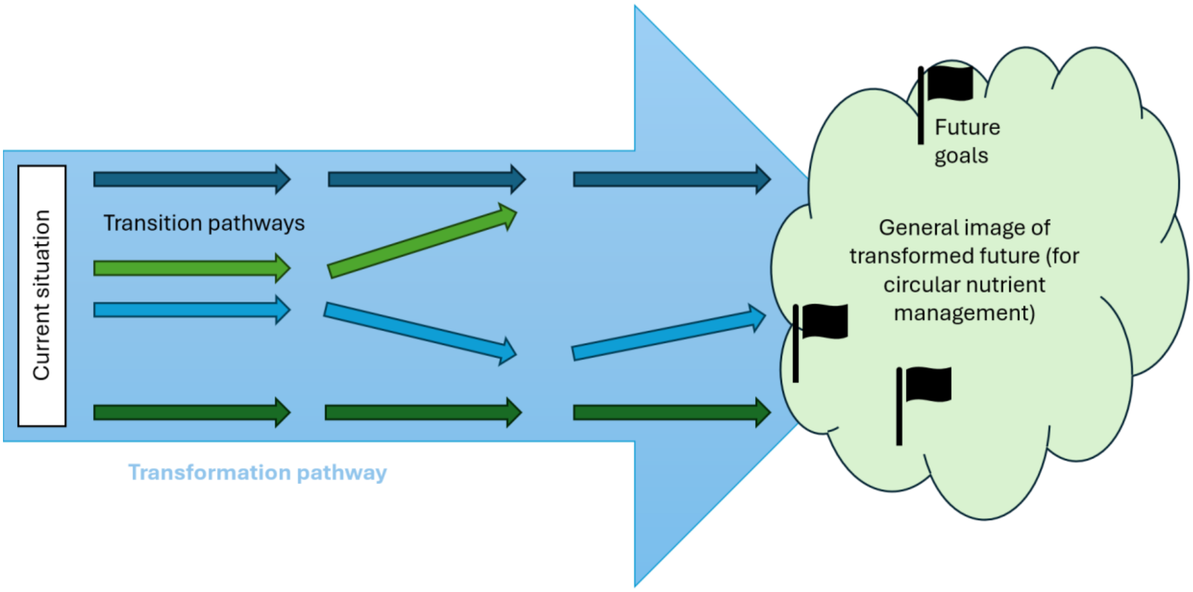

Figure 1. Connection of transition and transformation pathways.

It is crucial to comprehensively analyse the transformation process, identify barriers, and develop pathways to overcome them. Therefore, the project engages with farmers, advisors, and other stakeholders through direct collaboration and hackathons and utilises the AKIS framework. These approaches provide an in-depth understanding of how NBS innovations can be practically implemented and identify relevant actors and groups at each site. By closely working with these actors, trans4num can identify NBS case-specific barriers and foster factors from diverse perspectives, effectively influencing the transformation process with NBS innovations.

The current agricultural system faces significant challenges that require fundamental structural changes to ensure long-term environmental health and food security (Folke et al., 2010; Leach et al., 2010). Trans4num evaluates how NBS can contribute to a social-ecological transformation of nutrient management, taking a normative stance while relying on descriptive and analytical methods to understand current and past dynamics. This broad perspective ensures that the project addresses the multifaceted nature of agricultural contexts. Transformations in nutrient management involve changes across multiple levels—fields, regions, watersheds and beyond—and their interactions. This multi-level approach ensures that the project addresses the full scope of ecological and societal changes necessary for sustainability and addresses the complex challenges (Brand et al., 2013).

Social-ecological transformations, in particular, are characterised by significant uncertainty and a high degree of interdependence among various actors and factors (Leach et al., 2010). Envisioning a precise target state for such transformations is challenging, and democratic and justice considerations demand that they result from deliberative processes involving diverse stakeholders and/or societal groups rather than being predefined (Leach et al., 2010). Transformational change involves shifts in power relations, institutions and the development of new, robust solutions that provide stability in times of crisis (Folke et al., 2010; Kliem & Tschersich, 2017; Schoon et al., 2011; Westley et al., 2011). In the context of trans4num, acknowledging the complexity and long-term nature of social-ecological transformations is essential. This involves preparing for intended changes in light of transformation, recognising the interdependencies among various actors and factors, and ensuring a democratic and just process. By engaging stakeholders in a deliberative process, trans4num can define goals and pathways collaboratively rather than imposing predefined outcomes.

By integrating these principles into its approach, trans4num ensures that the transformation of nutrient management systems is effective but also equitable and sustainable. This holistic, inclusive approach is crucial for addressing the multifaceted challenges of agricultural practices. Taking these considerations into account, the project trans4num proposes a process-oriented understanding of a social-ecological transformation based on alternative seed breeding approaches from Kliem & Tschersich (2017) and modified for circular nutrient management:

> Social-Ecological Transformation of nutrient management within the agricultural regime is understood as an incremental process that is open-ended, inclusive and empowering to transformative actors (farmers, researchers, communities etc.) on and between different intervention levels (local, regional, national etc.), acknowledges different forms of knowledge (including local and culturally-specific knowledge) and ideas, and that strives towards circular agriculture, with the objective of creating more socially just and resilient

4. Evaluating barriers and drivers

Understanding the factors that foster or hinder agricultural transformation is crucial for research projects like trans4num, as it provides conceptually relevant information for designing and implementing effective interventions. Agricultural transformation, particularly nutrient management, involves complex interplays between technological innovation, policy frameworks, and social dynamics (Markard et al., 2012). Reviewing these factors enables researchers to identify leverage points for change, allowing projects to anticipate and mitigate challenges commonly arising in systemic shifts (Smith & Stirling, 2010). It also offers insights into successful strategies from other initiatives, creating a knowledge base to inform adaptive approaches and enhance the project's responsiveness to unforeseen challenges (Köhler et al., 2019). Furthermore, identifying and understanding hindering factors can help avoid repeating past mistakes, thus making the pathway to transformation more efficient and cost-effective (Geels, 2011). This targeted approach is particularly relevant in trans4num, where multi-stakeholder collaboration and context-specific solutions are critical in achieving sustainable nutrient management. Overall, such a review supports evidence-based decision-making and optimises the potential for achieving lasting change in the agricultural sector.

Linnér & Wibeck (2021) describe three major categories of deliberate transformational drivers: directional, top-down traction, and bottom-up traction (**Error! Reference source not found.**). Directional drivers include vision, value, political leadership, public engagement, and communication. These actions represent external stimuli for SET. For example, policymakers, researchers, and NGOs can influence targeting, funding, and promotion of sustainability transformations, thus providing goals and shaping paradigms.

Policymakers can also enable transformation using top-down drivers by removing barriers and reinforcing changes. These top-down traction drivers include institutional modification, economic rules, technological innovations, and political decisions. Modifying rules and regulations can influence social-ecological decision-making. The third driver of deliberate transformation creates bottom-up traction. Transformative learning, perspective shifts, and lifestyle changes help to remove friction within a social-ecological context, thus facilitating fundamental changes. Bottom-up traction drivers also influence the social-ecological context characteristics like values, knowledge, and motives. Each driver can be interlinked. Creating bottom-up engagement via education can lead to increased public engagement, which helps shape the direction of transformation.

Table 1: Transformation drivers, based on Linnér and Wibeck (2021).

	Direction	Top-down Enablement	Bottom-up Enablement
Goal	Provide guidance and vision for transformation	Enable transformation by removing institutional barriers	Enable transformation by empowering individuals
Examples	Political leadership, public engagement, communication	Political decisions, economic rules, technological deployment	Education, shifts in perspective, lifestyle changes
Leverage Point	External Stimuli: - environmental degradation - climate change - economic pressures - policy shifts	Decision-making process: - include multiple perspectives and choices	Social-Ecological Characteristics: - values - cultural norms - governance structures - ecological factors

			…unique to a particular community or ecosystem

Transformational pathways describe actors and general playbooks for creating action, while drivers or barriers are more specific. Since transformation is systemic and non-linear, its pathway is impossible to predict. Providing more specific leverage points may create more effective transformation goals (**Error! Reference source not found.**). Targeting smaller, nested transformations may catalyse rapid systemwide evolutions.

4.1 Methods

This review identifies key factors that foster or hinder the adoption of sustainable agriculture practices, with implications for deliberate transformation efforts. These insights can guide the identification of factors in specific contexts, helping to anticipate future obstacles or opportunities. The review focuses on literature covering agricultural change processes that aim to implement sustainable practices. This is defined as achieving improvement across at least two described dimensions—social, ecological, or economic—while having long-term positive impact potential.

We framed the review around two core questions:

1. What factors foster and hinder agricultural practices sustainability transformation?
2. How do they matter for trans4num's transformation pathways?

To address these questions, a systematic literature review was conducted on Scopus in April 2023 using keywords related to "transformation," "transition," and "socio-ecological systems" in agriculture and sustainability. Studies were screened for relevance, focusing on nature-based or sustainability-oriented agricultural practices. The final data set of 108 relevant studies provided insights into fostering and hindering factors (Figure 2).

An extraction table was used to record each study's field, methods, location, connection to nature-based solutions (NBS), and degree of transformation (categorised as none, partial, or complete). "Partial transformation" referred to limited adoption, often within pilot projects, while "complete transformation" signified substantial, systemic changes (e.g., urbanisation as a land-use transformation). Exclusion criteria were refined during the review to focus on studies directly relevant to agriculture, excluding unrelated fields.

This study followed the PRISMA protocol, which helps reduce bias and ensures replicability. However, some limitations should be noted: only one researcher reviewed each abstract, which may introduce bias. The diverse interpretations of "transformation" and "transition" across fields also made strict categorisation challenging. Instead, studies were classified based on transformation extent, from none to complete, with "complete" signifying documented radical changes across multiple dimensions (social, ecological, or economic).

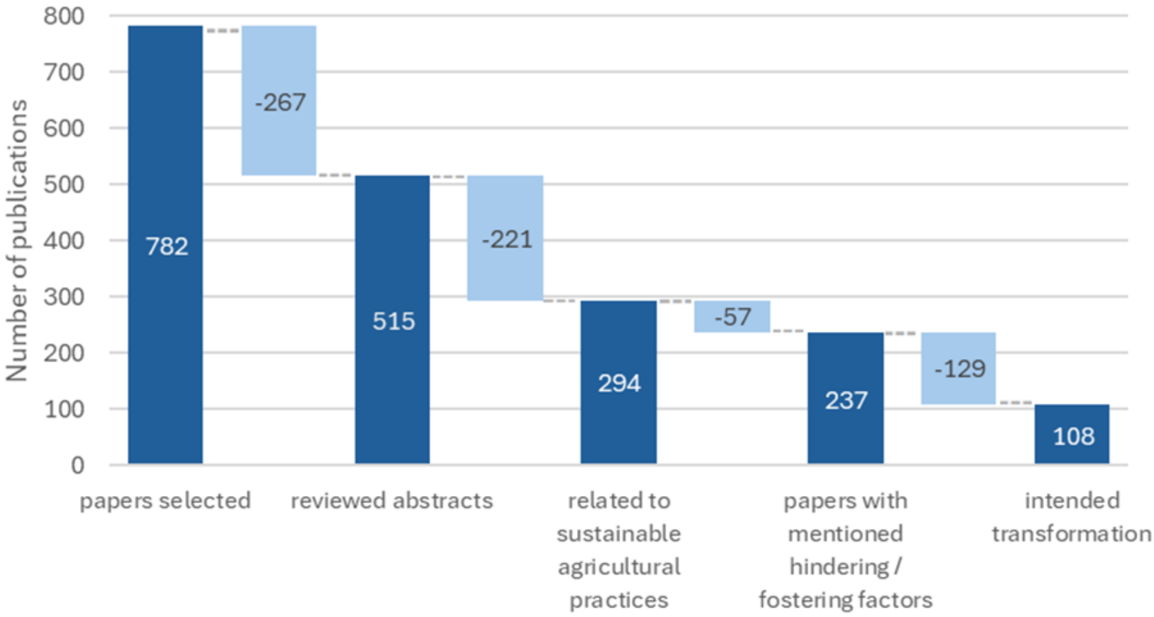

Figure 2. Summary of the literature review.

Results

More than 50% of the reviewed publications looked at examples in Europe or from a global perspective. Five percent of papers focused on Africa, and only 2% of reviewed papers were from Oceania. This geographic concentration may skew results towards a European perspective.

Fostering and hindering factors were summarised, grouped, and sorted by frequency. The most frequently mentioned factors fostering innovative NBS were the social valuation of ecosystem services, participatory stakeholder cooperation, local/traditional knowledge, and the involvement of local actors (*Figure 3*). Status quo, local livelihood strategies, lack of farmers' resources, and governance were the most frequently mentioned factors hindering transformation processes (**Error! Reference source not found.**). Table 2 and Table 3 in the appendix describe each major factor with an exemplary quote. The most frequently mentioned factors are elaborated in more detail below.

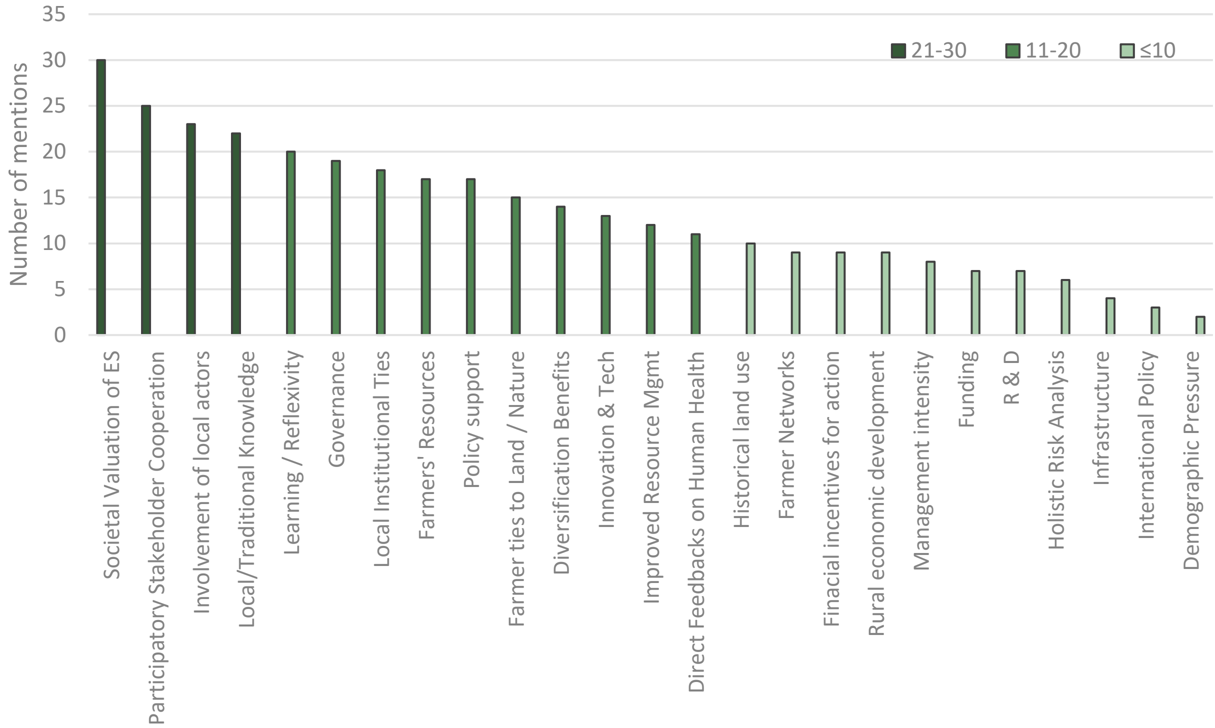

Figure 3. Key factors fostering sustainable agricultural practices are mentioned in the review literature.

There needs to be more consensus in the literature about creating deliberate transformation (IPCC, 2023). Transformation is a complex, non-linear system process. Research and analysis can help one understand transformation, though it can rarely be predicted (IPCC, 2023). However, several critical characteristics of deliberate transformation are well-established in the literature. This research found the most frequently mentioned factors fostering transformation:

(1) **Valuation of agricultural ecosystem services** shapes transformation outcomes. When a farmer or a collective entity sees agriculture as providing more results or services than only food or feed products, the value of sustainable practices increases. For example, traditional agricultural practices are part of cultural identities worldwide. Preserving the resulting unique or typical landscapes is more than just an ecologic goal, as it comes with socio-cultural gains, and therefore is valuable to the local, regional, and national society (Espluga-Trenc et al., 2021; Zinsstag et al., 2016). If a social-ecological context values agriculture, it may mobilise more communal support or financial remuneration to farmers. Valuation of the regulating, cultural, and supporting services agriculture provides helps farmers pursue more sustainable practices. Yield remains essential, but it is one of many factors for farmers to consider when weighing the pros and cons of more sustainable agriculture.

(2) **Participatory research and effective stakeholder management** foster transformation. Including diverse actors in planning, implementation, and assessment facilitates sustainable transformations by stimulating communication, building trust, and proactively identifying concerns (IPCC, 2023; Teschner & Orenstein, 2022). Transformation requires more than just presenting good ideas; it needs cooperation, alignment, and iteration to succeed (Mutoko et al., 2014). Aligning stakeholders with

a common goal, shared vision, mutual respect, and trade-off acknowledgement creates more effective transformation.

(3) **The involvement of local actors** is foundational for initiating and supporting transformation, even in less formalized ways than full participatory stakeholder cooperation. Engaging local actors in a more informal, integrative capacity—such as incorporating insights from local farmers, community leaders, and small local institutions—can build momentum for sustainable practices without requiring extensive formalized stakeholder processes. This level of involvement strengthens transformation by embedding local knowledge, fostering preliminary buy-in, and setting the groundwork for larger-scale changes. Mutoko et al. (2014) point out that connecting with local actors context-sensitively can help facilitate early steps in adopting sustainable technologies and practices tailored to local needs. For example, local actors may informally influence which crop varieties or soil management practices are suitable based on lived experience and traditional knowledge. This type of involvement, while less structured than participatory stakeholder cooperation, plays a critical role in easing transitions toward sustainable productivity by supporting locally relevant, adaptable solutions to build trust and set the stage for broader engagement.

(4) **Respecting local knowledge** advances transformation, which requires locally adapted solutions. Traditional knowledge is a vast repository of place-specific agricultural practices and solutions, so weaving scientific and local knowledge together can lead to more creative and sustainable outcomes (Guerrero Lara et al., 2019; Mantyka-Pringle et al., 2017; Salisu Barau et al., 2016; Seijo et al., 2018).

(5) **Local institutional ties** strengthen transformation efforts by providing a foundation for sustainable practices. Solid local institutions, such as cooperatives, farmer associations, or community-based organisations, can enhance the social and economic resilience of agricultural systems. These institutions provide critical resources, support networks, and a platform for sharing knowledge, which aids farmers in adapting to sustainable practices and reinforces social cohesion. For instance, research shows that local institutions can play a pivotal role in establishing trust and facilitating access to resources necessary for sustainable transformation (Bennett et al., 2018). Such institutional support structures help ensure that transformation efforts are contextually relevant and responsive to the specific needs of a community, reducing resistance and fostering greater adoption of sustainable practices.

(6) **Learning and reflexivity** underpin sustainable transformation through adaptive and iterative processes. In the context of sustainability, learning is a dynamic process that supports the continuous evolution of NBS to fit changing ecological, social, and economic conditions. Reflexive learning, or the ability to evaluate and adjust practices based on outcomes, enables stakeholders to adapt solutions iteratively, fostering more resilient and imaginative approaches to sustainable agriculture. Yen & Chen (2014) highlighted the role of social learning in traditional ecological knowledge, demonstrating how agricultural communities incorporate inherited wisdom and innovative practices in their production techniques. For instance, social learning allows communities to integrate feedback from past seasons or environmental

changes, enhancing adaptability and ecological knowledge over time. Through iterative cycles of implementation, reflection, and adjustment, learning and reflexivity build a foundation for sustainable transformation that is both resilient and locally relevant.

(7) **Policy support** significantly influences the pace and scope of agricultural transformation. Effective policies can serve as either enablers or barriers, depending on their alignment with local sustainability goals. Supportive policies—subsidies for sustainable practices, land-use regulations, and biodiversity conservation incentives—encourage adopting sustainable practices by reducing financial barriers and offering guidance for implementation (IPCC, 2023). However, policy misalignment or inconsistent enforcement can hinder transformation. For example, poorly designed policies that prioritize short-term economic gains over ecological resilience may inadvertently support unsustainable practices (Folke et al., 2016). Thoughtful policy frameworks responsive to local conditions and challenges can help overcome structural barriers, enabling more effective and lasting transformations.

The most frequently found factors hindering sustainable transformation in agriculture are diverse and encompass social, economic, political, and ecological dimensions (Figure 4). These barriers range from entrenched historical practices and insufficient governance support to the limited resources and capacities of individual farmers. While some obstacles stem from economic or policy-related structures, others are deeply rooted in social and cultural frameworks, reflecting the complexity of shifting toward sustainable systems. Together, they illustrate how diverse and interconnected the challenges are in achieving a resilient, sustainable agricultural transformation.

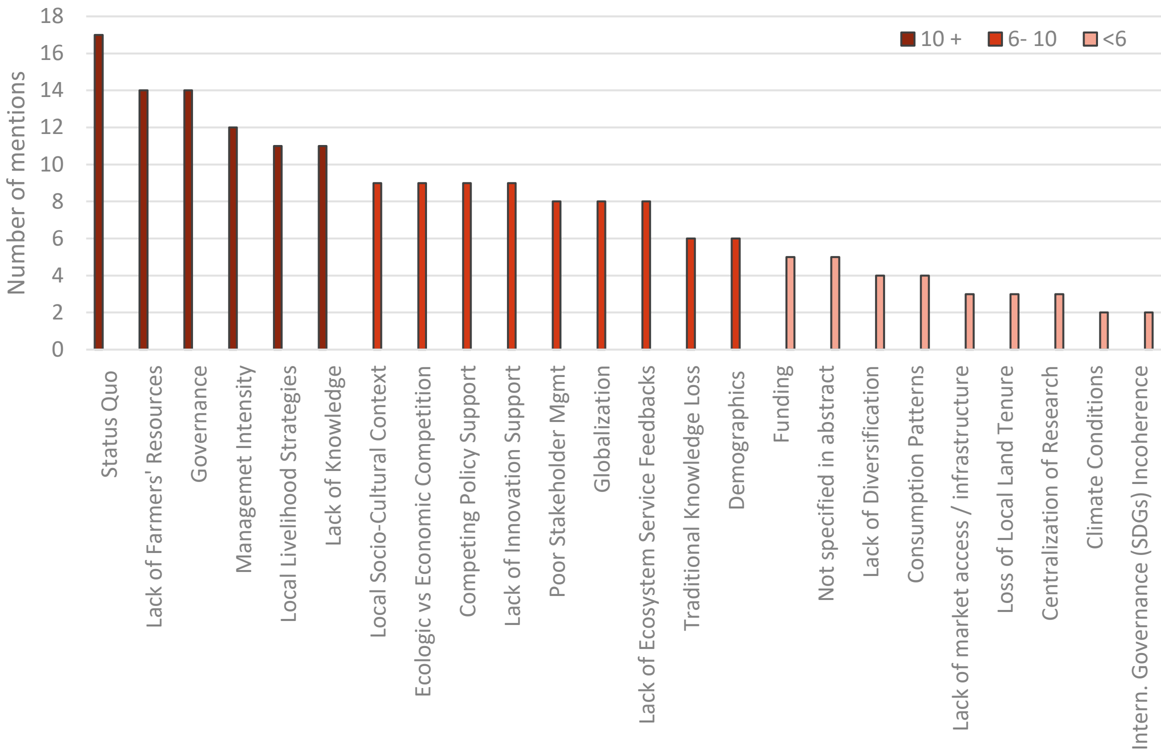

Figure 4. Key factors hindering sustainable agricultural practices mentioned in the review literature.

(1) **Status quo persistence** and the entrenchment of historical intensification practices hinder sustainable transformation. The deep-rooted shift toward industrialized agriculture limits the adoption of sustainable practices, as existing technologies and infrastructures were developed for high-intensity, yield-focused production. Sgroi (2022) describes how Italy's agricultural evolution has embedded these intensive methods, making it challenging to revert to more sustainable models.

(2) **Lack of farmer resources** obstructs sustainable adoption. Farmers often need more capital, technical skills, or experience to shift to sustainable practices. High initial investments and technical requirements can dissuade farmers from adopting diversified, sustainable models due to financial constraints or knowledge gaps (Dumont et al., 2020).

(3) **Weak governance** issues impede effective transformation. Inconsistent or poorly enforced governance, regulation, and policy can undermine efforts for sustainability by failing to support local needs or curb unsustainable practices. Horstink et al. (2023) highlight the lack of institutional mechanisms for local actors to pursue sustainable and democratic food systems, especially in regions where policy supports industrialisation.

(4) **Management intensity** favours high-yield, less sustainable practices. Sustainable methods can yield lower short-term profits than intensive systems, leading many farmers to prioritize economic returns. For instance, while environmentally beneficial, grazing-based systems are often replaced by high-profit, intensive agriculture due to financial pressures, which damages social and ecological systems (Tittonell, 2021).

(5) **Local livelihood strategies** describe the agricultural struggle of many regions to remain competitive or valued as a primary livelihood. Economic shifts and socio-political factors frequently drive populations to prioritise sectors like urban employment, industry, or tourism, which often promise greater financial stability or upward mobility. Biasi et al. (2017) highlight the fragmentation of agro-forest landscapes caused by urbanisation and population growth, undermining the socio-economic structures supporting agriculture. In regions with insufficient agricultural returns, land abandonment or conversion to urban or industrial use becomes a rational choice for local actors.

(6) **Lack of knowledge** and scientific consensus restricts transformation. Limited scientific consensus and farmer knowledge on sustainable practices and NBS constrain sustainable transformation. Farmers face uncertainty in implementing NBS without well-established bodies of knowledge, and fragmented knowledge weakens institutional support (Raymond et al., 2017). This lack of systematic, accessible information leads to inconsistent adoption of sustainable practices across regions, slowing overall progress (Eakin et al., 2017; Lu et al., 2022).

4.2 Discussion

Interestingly, many of these factors could hinder or foster transformation, depending on the unique situation and socio-ecological context (**Error! Reference source not found.**). Effective governance, for instance, can support sustainable outcomes by establishing clear regulations and incentives. A well-known example is Costa Rica's Payment for Environmental Services program, which encouraged forest conservation among landowners through financial incentives; this policy effectively linked government resources with local conservation goals and led to positive environmental impacts on a national scale (Sánchez-Azofeifa et al., 2007). Conversely, ineffective governance, such as lax enforcement or policy prioritizing other outcomes—such as permitting mining or industrial activities within conservation areas—can undermine sustainable transformation, turning policy support into a hindering factor.

Another significant factor is land tenure. Studies suggest that secure property rights encourage farmers to invest in sustainable practices because they can be assured of long-term benefits. For example, research by Meinzen-Dick and Di Gregorio (2004) highlights that farmers with stable property rights are more likely to adopt sustainable resource management practices, improving land quality over time (Meinzen-Dick & Di Gregorio, 2004). By contrast, insecure tenure often discourages long-term planning, making sustainability less likely.

Local culture and values also influence transformation processes. In many regions, cultural and social ties shape farmers' decisions, which can either support or restrict sustainable adaptations. For instance, religious beliefs in Australia have been shown to impact conservation efforts positively, with some farmers viewing land stewardship as a moral obligation to future generations. However, this can also become a limiting factor where beliefs discourage participation in scientifically-based conservation practices (Morrison et al., 2015).

These examples illustrate the importance of understanding and balancing these factors for effective policy and governance in transformation initiatives. A nuanced approach that considers local context, stakeholder engagement, and place-specific knowledge is essential for supporting sustainable agriculture and adopting nature-based solutions.

In the context of transformation processes, particularly those aiming for sustainability transitions, it is crucial to distinguish between barriers and lock-ins. Both concepts represent challenges that hinder progress but differ significantly in their nature and implications for strategic interventions.

Barriers are obstacles that impede the initiation or continuation of transformation processes. They can be temporary and context-specific, making them susceptible to targeted interventions (Burch et al., 2014; Kirchhoff et al., 2013). While restrictive, these barriers are responsive to policy interventions, outreach, and financial incentives, which can help farmers overcome short-term hurdles and transition to sustainable practices more smoothly.

- **Resource constraints**: As noted by Dumont et al. (2020), farmers frequently face financial limitations, which hinder their adoption of sustainable practices. Addressing these financial challenges through subsidies, education programs, or short-term support can often mitigate these barriers, allowing farmers to experiment with sustainable practices without immediately compromising their livelihoods.
- **Knowledge gaps**: Another key barrier is the lack of technical expertise and accessible information on sustainable practices (Biasi et al., 2017). For example, limited awareness about sustainable nutrient management methods can be addressed through training and extension services, which provide practical guidance on low-impact farming methods.

Lock-ins are entrenched conditions that create self-reinforcing cycles, making deviation from the current state exceedingly difficult. They are often structural and systemic, involving complex interdependencies and feedback loops (Arthur, 1989; Unruh, 2000).

- **Economic and market dependencies**: The agricultural sector's reliance on chemical fertilizers and high-yield practices is an example of a lock-in (Unruh, 2000; Sgroi, 2022). Established supply chains, economic incentives, and market demand for low-cost, high-yield products create a cycle that discourages deviation from conventional practices. Systemic reforms are needed to address these entrenched dependencies, including market restructuring and support for alternative practices.
- **Policy and institutional constraints**: Unclear or inconsistent policies around sustainable practices act as lock-ins (Horstink et al., 2023). Regulatory frameworks that prioritize industrial agriculture over sustainable practices reinforce existing patterns. Systemic changes must dismantle these cycles, including policy reform and institutional restructuring.

Understanding the distinction between barriers and lock-ins is essential for developing effective interventions within trans4num's transformation objectives. Barriers like resource constraints or lack of knowledge can often be addressed through targeted, short-term actions, such as providing subsidies or education. Lock-ins, however, require a longer-term, multi-dimensional approach, tackling the underlying economic, institutional, and regulatory structures that perpetuate unsustainable practices. By recognizing whether a challenge is a barrier or a lock-in, trans4num can better design interventions that directly address immediate needs or work toward dismantling more structural obstacles in sustainable transformation processes.

4.3 Implications for trans4num

Contributing to transformative change in the context of trans4num requires carefully considering the fostering and hindering factors identified in the literature review. A core insight from the review is the importance of **considering the local social-ecological context** when implementing NBS. It encompasses the interconnected ecological and social dimensions of agricultural landscapes, including the values, perceptions, and behaviors of local stakeholders (Kenter et al., 2015). Farmers' decisions are influenced by how ecosystem services—such as water regulation, soil health, and cultural heritage—are valued. When stakeholders prioritize these ecological and social benefits, there is a greater likelihood of adopting sustainable practices that go beyond merely optimizing yields. Therefore, within the trans4num project, particular attention should be paid to understanding and addressing the specific context characteristics of each trial site, ensuring that interventions align with local stakeholder values and concerns. By fostering a shared understanding of the ecosystem services that sustainable agriculture provides, trans4num can help stakeholders appreciate the long-term benefits of NBS, even when these benefits may not immediately translate into short-term profits.

The deeply embedded nature of **intensive agriculture** represents a significant barrier to sustainability transformation. This "status quo" is upheld by economic, cultural, and policy structures that often create resistance to alternative practices. Despite being frequently cited in the literature, descriptions of these barriers are often vague, making it difficult to pinpoint the particular factors that maintain the intensive agricultural model. For trans4num, it will be essential to explicitly identify and address these hindering factors rather than treat them as general or intangible obstacles. By precisely understanding local barriers at each site, the project can devise more tailored strategies to address and potentially overcome these challenges. This approach is crucial for scaling successful practices beyond the trial sites and into its regions or other regions, where similar obstacles may exist but manifest differently due to contextual variations.

The transition from conventional intensive to sustainable agricultural practices involves short-term trade-offs that can create disincentives for adoption. These include potential reductions in yield as farmers adjust land, labour, and inputs to accommodate sustainable practices. Additionally, demographic changes such as urbanization and rural depopulation create further pressures. With fewer available workers in rural areas, maintaining food production levels efficiently is a growing challenge. For trans4num, this highlights the importance of supporting farmers and stakeholders through transition phases, potentially by advocating for policies or financial incentives that buffer the short-term economic impacts of sustainable transitions to enable further transformation.

In analyzing the factors influencing nutrient management transformations within trans4num, it is notable that certain factors may act as either enablers or barriers, depending on context and implementation. Additionally, some seemingly opposing factors can reinforce one another, as discussed in Chapter 4.3. These insights emphasize the need for a nuanced approach within trans4num to tailor interventions to local contexts, leveraging supportive factors while mitigating potential hindrances.

The literature review provides valuable factors that foster and hinder sustainable agricultural transformation. However, as noted, the existing research still needs to clarify the distinction between incremental and transformative adaptations. Consequently, trans4num should consider these findings as a foundation for identifying potential pathways toward transformation rather than as a definitive roadmap. To maximize the utility of these findings, the project should prioritize further contextual investigation at each trial site. This will provide a nuanced understanding of factors in different socio-ecological contexts.

5. Transformation Pathways

The concept of transformation pathways has emerged as a key framework in the discourse on sustainability, emphasizing the need for systemic, long-term changes that address the interconnections between societal, economic, and environmental domains. These pathways provide approaches to envisioning, planning, and executing transformations that can tackle complex global challenges, such as climate change, biodiversity loss, and unsustainable resource management. This chapter explores the concept of transformation pathways, focusing on how they can inform and advance nutrient management in agriculture through NBS and how they intersect with transition pathways. The latter is essential to understanding how trans4nums work as a transition can contribute to the broader transformation of circular nutrient management. This chapter synthesizes the preliminary discussions on defining transformation and identifying fostering and hindering factors, presenting a trans4num way that integrates the unique circumstances of each NBS innovation. Since pathways are very individual depending on several factors such as context and actors, comparing single pathways or cases in this chapter, is not meaningful for trans4num. Instead, we gather learnings from the described pathways relevant to NBS in nutrient management.

5.1 Transformation and transition pathway concepts

While transformation pathways focus on radical, systemic changes, transition pathways operate at a more focused, sectoral level (Brand, 2012). Transition pathways refer to the processes by which specific sectors or systems evolve from one state to another through gradual yet significant changes. These pathways often involve sector-specific innovations and improvements—such as those in renewable energy, transportation, or, in the case of nutrient management, the adoption of NBS. However, transition pathways are not isolated processes but can be components of broader transformation pathways (Figure 1). As incremental changes in one sector accumulate, they can trigger more profound, systemic shifts across multiple sectors. For example, renewable energy transitions transform energy systems, supporting the broader shift toward a low-carbon economy. Similarly, circular nutrient management in specific contexts, such as the trans4num sites facilitated by NBS, can be seen as part of a transformation pathway within the agricultural nutrient management sector, contributing to its more extensive transformation.

A growing body of literature contributes to a deeper understanding of transformation pathways, especially across environmental, agricultural, and socio-ecological fields (Folke et al., 2016; IPCC, 2023; Meadowcroft, 2011; Scoones et al., 2020). From this stock of knowledge, we identify four critical conceptual features and frameworks that are prominently used in the literature describing aspects of transformation pathways:

- **Strategic Niche Management**: This framework emphasizes how experimental initiatives in niche settings can inform broader transformations by creating space for learning and adaptation (Smith & Raven, 2012). This concept helps understand the development of transition pathways, particularly in cases where early-stage, localized innovations contribute to systemic transformation.
- **Multi-Level Perspective (MLP)**: Geels et al. (2017) refine the Multi-Level Perspective (MLP) framework, which is widely applied in transition studies. The MLP explains that transitions occur through interactions between niches (where innovations develop), regimes (dominant systems and practices), and landscapes (broad external pressures). This framework is useful for understanding how localized transition pathways in one sector (e.g., agricultural nutrient management) can build up and influence broader transformation pathways.
- **Transformative adaptation**: O'Brien and Sygna (2013) discuss transformative adaptation to address climate and environmental challenges through profound, systemic change. They distinguish between incremental adaptation (minor adjustments) and transformative adaptation (systemic shifts) and highlight how pathways for transformation often require addressing underlying social, economic, and political structures.
- **Pathways to sustainability**: Scoones et al. (2020) offer a framework focused on pathways to sustainability, emphasizing the need to consider multiple pathways that are equitable, inclusive, and tailored to diverse local contexts. Their approach highlights the political, social, and environmental dimensions of transformation, stressing the importance of engaging marginalized groups to ensure fair and just outcomes.

Developing transition pathways is a practical approach to preparing for transformation. The six-step process model proposed by Dijkshoorn-Dekker et al. (o. J.) offers a structured method for exploring and implementing transformation pathways, in the following we briefly give an overview of the steps.

1. **Setting the scene**: Preparation is the foundation of transformation. This step focuses on defining the process before addressing content, ensuring that stakeholder involvement, decision-making processes, and potential added value are clarified. Nutrient management involves thinking critically about the possible positive and negative consequences of circular nutrient management (Macnaghten, 2017) and engaging relevant stakeholders from the outset.

2. **Analyse the context**: Before defining pathways, it is essential to conduct a thorough analysis of the current food and nutrient management system. This analysis can be done internally or with a small group before involving a more comprehensive range of stakeholders. It serves as the basis for identifying future paths and opportunities for transformation.

3. **Envision the future**: With a solid understanding of the current system, stakeholders can come together to envision a desired future. This step involves discussing shared goals and aligning them with broader societal objectives, ensuring agreement on the vision for circular nutrient management and its role within the larger agricultural system.

4. **Develop pathways**: Transition pathways are the roadmap connecting the current system to the envisioned future. By breaking down the path into smaller, actionable steps, stakeholders can create a structured plan that considers the timing and comprehensiveness of necessary changes. Nutrient management could involve setting milestones for adopting specific NBS technologies or practices.
5. **Propose actions**: This step is about translating the pathways into concrete actions, identifying who is responsible for what, and ensuring that all stakeholders understand their roles, which is critical. Actions should be assessed against SMART criteria (Specific, Measurable, Achievable, Relevant, Time-bound), increasing the likelihood that they will be successfully implemented and lead to the desired outcomes.
6. **Assess the impacts**: Finally, reflecting on the proposed actions and pathways is essential for ensuring their long-term success. If resources permit, external researchers can assess the expected consequences of the actions; if not, stakeholders can collectively reflect on potential outcomes, particularly about marginalized groups that may not have been directly involved in the process. This step ensures that the actions taken are effective but also just and equitable.

The process model outlined here provides a practical guide for structuring and preparing for transformation, ensuring that interventions are well-planned, inclusive, and capable of creating lasting change. Key themes include frameworks for structuring transformation pathways, tools for managing complexity, and approaches for evaluating the progress and outcomes of transformations. In practice, distinguishing the individual transformation steps and identifying the most appropriate approaches is often challenging. Some strategies may address multiple steps simultaneously. Therefore, in the following sections, we will simplify the distinction by focusing on three main stages: preparing, navigating, and assessing transformation.

5.1.1 Preparing for Transformation

Preparing for transformation in socio-ecological systems, such as nutrient management in agriculture, requires establishing conditions, structures, and strategies supporting sustainability shifts. Key approaches from empirical studies on sustainability transitions demonstrate concrete examples and methods to enable these shifts.

Local knowledge and community engagement play pivotal roles in shaping sustainable agricultural practices. Although grassroots innovations, as discussed by Smith et al., (2005), are not the primary focus of trans4num, the project does emphasize the importance of incorporating local knowledge and practices. By prioritizing locally adapted nutrient management strategies and involving community members, nutrient management transitions can benefit from more relevant, accepted, and feasible solutions within specific contexts. For example, understanding traditional nutrient practices can reveal sustainable methods aligning with environmental goals and community preferences.

Critical factors for effective transformation include stakeholder engagement, policy support, and technological innovation (Markard et al., 2012). These components are crucial to ensure that nutrient management initiatives are effective and scalable, addressing challenges arising within agricultural systems. In nutrient management, stakeholder engagement may involve collaborating with farmers, local businesses, and policymakers to assess needs and identify sustainable nutrient solutions. Policies supporting nutrient recycling or limits on fertiliser use can drive innovation and make sustainable practices more accessible and economically viable. Building on these factors, Köhler et al. (2019) emphasize the role of actors, power dynamics, and interdisciplinary approaches in sustainability transitions. In nutrient management, engaging diverse actors—from farmers and scientists to policymakers—helps create inclusive processes that can lead to more effective and equitable transitions. Power dynamics are also relevant, as decision-making and resource access can differ significantly across regions, particularly between smallholders and large-scale producers. An interdisciplinary approach to nutrient management can integrate ecological, economic, and social insights to create comprehensive, context-sensitive strategies.

This phase of a socio-ecological transformation involves creating conditions, structures, and strategies that enable future shifts toward sustainability. The focus is on building adaptive capacity, supporting innovations, and engaging stakeholders to ensure readiness for transformation.

- **Scenario planning and foresight**: Scenario planning is a valuable tool for preparing governance systems to address future uncertainties and envision various possible futures (Wiek & Iwaniec, 2014). Foresight methods like this are essential for organizing systems to manage challenges, such as those arising from climate change within the context of the 1.5°C target (Vervoort & Gupta, 2018). Scenario planning enables stakeholders to imagine various potential futures and explore how different choices may lead to different outcomes. In nutrient management, this approach can help stakeholders anticipate impacts of changes in soil health, water availability, or market demands and explore adaptive responses. By enhancing adaptive capacity, scenario planning helps create flexible pathways for governance and agricultural practices to withstand uncertainties and change.
- **Backcasting**: Backcasting, as presented by (Quist & Vergragt, 2006), is another valuable method for outlining potential pathways of transformation. It involves envisioning a desirable future state and working backward to identify the steps necessary to reach that vision (Wiek & Iwaniec, 2014). This approach is particularly relevant for long-term planning and stakeholder engagement, especially in complex domains like nutrient management, where the path to sustainability is uncertain and requires coordinated, incremental steps. For example, stakeholders might envision a future where nutrient cycles are circular, and resources are fully recycled within agricultural systems. Working backward, they could identify intermediate targets to achieve that vision, such as increased use of organic fertilizer waste.
- **Stakeholder engagement and co-design**: Engaging diverse stakeholders is crucial in preparing for transformation, as it ensures that pathways are adaptable to local contexts and gain legitimacy. It highlights the value of co-production of knowledge, involving scientists, policymakers, farmers, and community members in the design of transformation strategies (Wyborn et al., 2016). Co-design processes allow for integrating local needs and perspectives, increasing the likelihood that proposed changes are practical and effective. For example, co-designing nutrient management pathways with farmers can lead to solutions that contextually better balance productivity needs with environmental sustainability, making it more likely for these solutions to be adopted.

These preparatory steps ensure that transformation pathways are context-sensitive, resilient, and inclusive, thus laying a solid foundation for future systemic changes. Through careful preparation, projects like trans4num can contribute to sustainable nutrient management that aligns with environmental goals and community needs, supporting broader socio-ecological resilience.

5.1.2 Navigating transformation

Navigating transformation requires structured and adaptive approaches to guide systemic changes. In this very long phase, the goal is to create transformation pathways that remain contextually relevant, resilient, and responsive to evolving challenges.

Transition management provides a framework for managing complex, long-term change through strategic planning and stakeholder engagement (Rotmans et al., 2001). This approach emphasizes co-creating pathways that align with local needs and aspirations, fostering collaboration among those most affected by the changes. Some approaches, such as backcasting and scenario development, have already been introduced. De Haas and Dijkshoorn-Dekker (2021) provide a summary of methods for further pathway development with stakeholders, noting that the suitability of these methods varies depending on the specific context, project goals, and participants involved. By selecting the most appropriate methods, projects can foster engagement that results in actionable and locally adapted pathways.

In navigating transformation, inclusivity is essential for capturing diverse perspectives, particularly those from marginalized or traditionally excluded groups. Including diverse voices helps to design pathways that are fair, more resilient, and adaptable to the needs of all stakeholders, making the transformation process more robust (Macnaghten, 2017). In agricultural nutrient management, this could involve a diversity of farmers or women's groups in decision-making to ensure that policies and practices account for varied needs and knowledge bases. This diversity in participation enhances the relevance of transformation strategies and builds trust and commitment among stakeholders.

Pathways are unique to each context, reflecting different available resources, governance structures, and stakeholder goals (Bulten et al., 2022). There is no one-size-fits-all approach; instead, multiple pathways can be created to explore diverse future scenarios. By developing alternative visions, stakeholders can respond flexibly to new information or changing circumstances. A pathway focused on nutrient recycling might involve different strategies in regions with biomass production or ample organic waste resources compared to areas with limited resources. This tailored approach also highlights the role of researchers in adopting a reflexive, adaptive practice, continuously assessing and aligning their work to the changing needs and perspectives of stakeholders (Darnhofer et al., 2015).

Adaptive governance is a crucial component in navigating transformation. Effective adaptive governance structures are flexible, responsive to new information, and capable of facilitating collaboration among diverse stakeholders. This form of governance is crucial in nutrient management, where complex environmental and social factors often necessitate adjustments to planned actions (Darnhofer et al., 2015; Scoones, 2017). Continuous reflection on the social and ethical implications of transformation pathways ensures they remain relevant, equitable, and effective. For example, suppose research reveals that a particular nutrient recycling technology disproportionately benefits large-scale farms. In that case, governance structures must adapt to ensure that benefits are accessible to smaller-scale producers as well.

One of the main challenges in adaptive governance is distinguishing between incremental changes that lead to gradual improvements and more radical changes that can trigger significant system shifts (Darnhofer et al., 2015). In nutrient management, this might mean differentiating between the benefits of small-scale interventions, like adjusting fertilizer use, and transformative changes, such as adopting circular nutrient models that fundamentally alter nutrient cycles across agricultural systems.

This phase of transformation pathways involves managing the complexities of change processes, responding to unexpected challenges, and maintaining momentum. This stage requires flexibility, adaptive governance, and ongoing stakeholder engagement to ensure the transformation remains on track and can adapt to dynamic socio-ecological contexts.

- **Transition management and adaptive governance**: The concept of transition management is a governance approach that focuses on enabling long-term, participatory change processes. Loorbach and Rotmans (2010) highlight the value of involving a broad range of stakeholders and using visioning, experimentation, and learning to guide complex transitions. Transition management approaches can provide practical insights for structuring transformation pathways, particularly in sectoral transitions that require sustained engagement and adaptive governance. The latter is critical to navigating transitions, allowing policies and management practices to adjust as transformations unfold. Successful adaptive governance requires flexibility, stakeholder collaboration, and multi-level institutional arrangements to respond effectively to environmental change (Chaffin et al., 2014). In nutrient management, adaptive governance could mean adjusting policies around nutrient recycling based on the results of pilot projects or emerging environmental data.
- **Managing barriers and adaptation**: Moser & Ekstrom (2010) emphasise the need to recognize and address barriers that hinder adaptive actions, such as procedural or structural obstacles. Diagnosing these barriers is essential for designing effective strategies that enable adaptation, especially in diverse agricultural systems with varying local and institutional challenges. Recognizing this, stakeholders might develop advocacy efforts to modify regulations favoring sustainable practices.
- **Sustainability transitions and the role of narratives**: Rosenbloom et al. (2016) highlight the power of narratives in sustainability transitions, noting that stories, visions, and metaphors can help stakeholders align on shared goals and build collective motivation. Narratives provide coherence to complex pathways, fostering common understanding and purpose among diverse stakeholders. In nutrient management, a shared narrative around “closing nutrient loops” might help unify stakeholders with differing priorities around a common goal of resource efficiency and environmental sustainability.
- **Transformative innovation policy**: Schot and Steinmueller (2018) introduce Transformative Innovation Policy, a framework that directs innovation towards societal challenges rather than economic growth alone. This policy-oriented approach aligns with transformation pathways in sectors like agriculture, where policy

incentives can promote practices that benefit society and the environment. For nutrient management, transformative policies include support for technologies that reduce nutrient loss or promote circular nutrient systems.

5.1.3 Assessing Socio-Ecological Transformation Pathways

Assessment frameworks can be valuable in capturing both the progress and the complex, multi-dimensional impacts of transformation pathways. Scholars emphasise the need for evaluation methods beyond traditional metrics, advocating for tools that incorporate adaptive, resilience-based, and equity-focused approaches. For instance, Turnheim et al. (2015) argue that assessments should account for systemic interactions across ecological, social, and economic dimensions, making it possible to evaluate transformations to reflect real-world complexities. Furthermore, Pereira et al. (2020) call for participatory evaluation frameworks that involve local stakeholders, ensuring that assessments capture diverse perspectives and align with community priorities. Ongoing debates also address the need for longitudinal evaluations to monitor the sustainability of transformations over time and to understand cumulative impacts on ecosystems and social systems. These discussions underscore the value of adaptive, inclusive, and long-term evaluation strategies as essential tools for understanding and refining transformation pathways.

Assessment is essential to evaluating the effectiveness of transformation pathways, identifying lessons learned, and refining strategies based on outcomes. It often measures progress toward sustainability goals, resilience, and the impacts on communities and ecosystems.

- **Monitoring and evaluating transformation success**: Fazey et al. (2018) highlight the importance of adaptive evaluation frameworks, which allow for ongoing assessment and adjustment as transformations unfold. For instance, an adaptive evaluation framework could monitor shifts in community engagement and collaboration among farmers and local institutions, tracking how these relationships evolve and support resilience as sustainable practices are introduced. Indicators like increased trust among farmers, mutual aid networks, or shared resources for sustainable practices can reveal how well the transformation process fosters the social bonds that often underpin successful long-term change. Adaptive evaluation makes it possible to steer the process toward key sustainability outcomes, such as improved soil biodiversity or higher nutrient-use efficiency in farming.
- **Evaluating resilience and adaptability**: Folke et al. (2016) advocate for resilience-based assessments that look at ecological and social indicators to gauge a system's adaptability in the face of change. A resilience assessment could track indicators such as soil nutrient retention, crop diversity, and farmer livelihoods in agriculture. By evaluating how well these aspects perform under variable conditions (e.g., extreme weather or pest outbreaks), resilience assessments can inform nutrient management practices that help maintain ecological and social stability, ensuring farms are better equipped to withstand shocks.
- **Assessing equity and social impacts**: According to Scoones et al. (2015), socio-ecological transformations should strive to be just and inclusive. This means evaluating how nutrient management changes affect different groups, particularly vulnerable populations like smallholder farmers or low-income rural communities. For

example, the cost and labour involved in transitioning to other fertilizing practices could be a barrier for small farmers. Assessments focusing on equity would identify such challenges and support policies offering subsidies or technical assistance, ensuring that nutrient management transformations do not disproportionately burden those least able to absorb costs.

- **Backcasting and participatory approaches**: Backcasting can be a powerful method for planning and tracking progress toward long-term sustainability goals (Vergragt & Quist, 2011). This iterative assessment process helps ensure that socio-ecological systems remain sustainable, highlighting gaps between envisioned and actual progress. A combined participatory approach enables communities to align on strategies, creating a shared pathway for sustainable socio-ecological transformation (Nikolakis, 2020).

Assessment plays a crucial role in evaluating the progress of socio-ecological transformation pathways, drawing lessons from experiences, and refining strategies to meet sustainability goals better. Practical evaluation in agriculture and nutrient management can help ensure that interventions foster resilience, equitable outcomes, and environmental sustainability.

5.2 Transformation pathways in trans4num

Given the diverse characteristics of transformation processes, the pathways are highly variable. As discussed in Chapter 2, trans4num focuses on an incremental transformation approach. Each NBS innovation proceeds through small, iterative steps, testing, revising, and retrying practices to refine and improve their effectiveness. This approach ensures that innovations are continuously adapted and optimized based on real-world feedback and changing conditions. Moreover, trans4num is designed to be iterative and cumulative. Building upon the findings of each phase and progressively increasing the level of intervention, this methodical progression creates robust pathways that can be refined and adapted to transform nutrient management practices effectively.

By integrating the fostering and hindering factors identified in our literature review and analysis, we can tailor these pathways to address specific challenges and leverage opportunities. This chapter will detail how these elements combine to form a strategic, adaptable approach to nutrient management transformation through NBS. The goal is to provide a clear, actionable framework guiding the individual NBS innovations and the overarching project towards sustainable and impactful outcomes.

The suggested transformation approach for implementing nutrient management improvements in the trans4num project will be (**Error! Reference source not found.**):

- **Incremental:** We have a preliminary vision of a transformed nutrient management system and its essential characteristics. This allows us to use backcasting to outline the steps needed to move from our current state to the desired future states, progressing step by step.
- **Adaptive:** Our approach will be flexible and responsive to feedback from various sources. This includes internal project reviews, sharing research results at conferences, engaging with external stakeholders, and incorporating their input. This feedback will help us refine our pathways and make necessary adjustments.

- **Iterative:** We will continuously reassess our findings, involve relevant stakeholders, and reflect on the progress and changes. This ongoing process of reflection and adaptation ensures that we stay on course and improve as new information and insights become available.

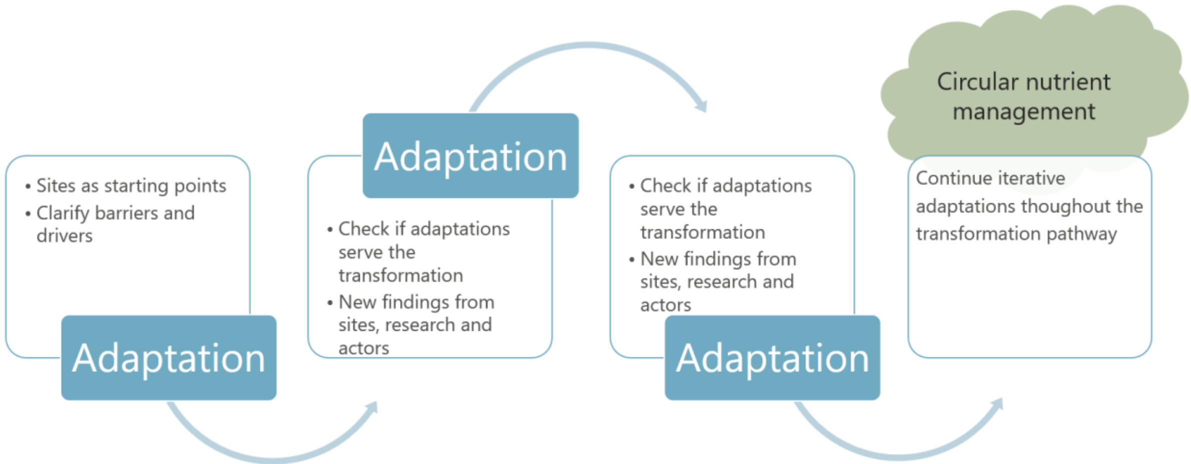

Figure 5. Iterative adaptations for an incremental transformation pathway.

This method leverages incremental progress, adaptability to feedback, and iterative reflection to ensure the transformation pathways of trans4num and transition pathways of NBS cases remain relevant, effective, and aligned with the overall goals of improved nutrient management.

The chapter on fostering and hindering factors already indicated the various topics that could lead to barriers but also drivers of the pursued transformation. Combining incremental, adaptive, and iterative elements creates a comprehensive framework for achieving sustainable nutrient management. Each component supports the others: incremental steps make the process manageable, adaptive flexibility ensures responsiveness to changing conditions (Berkhout et al., 2004; Pelling, 2011), and iterative refinement guarantees continuous improvement. Together, they provide a structured yet flexible pathway that can navigate the complexities of transformation processes, address barriers, and dismantle lock-ins (Unruh, 2002).

The diagram in **Error! Reference source not found.** illustrates such an open-ended, adaptive, iterative, and incremental transformation pathway. On the left, it traces the progression from past pathways to the present. Dark blue arrows represent various potential paths, while circular arrows signify decision and adaptation points. Lighter arrows indicate maladaptive lock-ins and dashed arrows represent segments of potentially transformative pathways. The background reflects the context in which these pathways evolve, with the unshaded area denoting socially and environmentally sustainable adaptation responses. The boundary of this space may shift due to factors such as climate change or economic conditions.

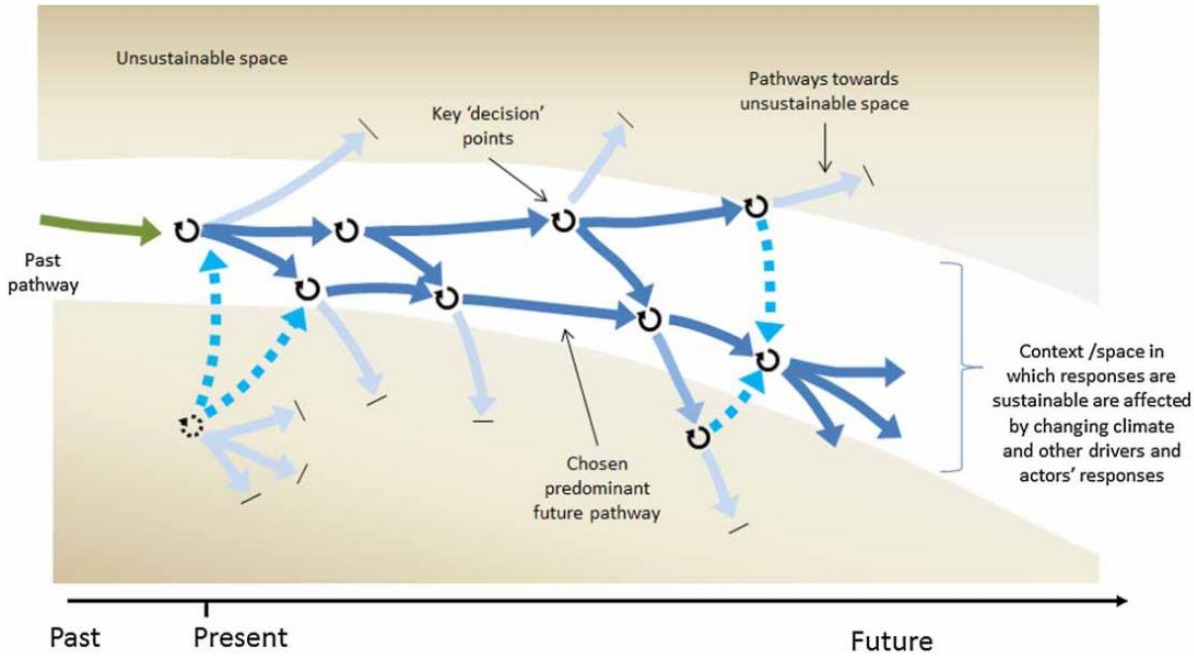

Figure 6. Adaptation pathways illustrate potential pathways towards an open-ended transformation goal (Fazey et al., 2015).

In nutrient management, this unified approach facilitates the gradual implementation of sustainable practices. For example, incremental steps involve testing new nutrient management techniques on a small scale to pave the way for broader implementation through small, manageable steps (Patterson et al., 2017; Rotmans et al., 2001). Adaptive feedback mechanisms would continually refine these techniques based on stakeholder input and environmental data (Sørensen & Torfing, 2011). Iterative testing cycles and refinement would help perfect these techniques before they are widely adopted (Rogers, 1983). This holistic approach ensures that nutrient management practices evolve in a sustainable, resilient, and context-specific manner.

5.3 Concrete steps for a trans4num approach

Ensuring that every task in trans4num serves the transformation of nutrient management is complex, but we have the tools to achieve this. Three main components need to be considered for the short-term transition that sets the scene for the long-term transformation:

1. **Transformation goal**: The core of the trans4num approach is to contribute to a clearly understood and shared goal by every project member. The project aims to facilitate a broader change in nutrient management towards circularity. This goal was established during the General Assembly in March 2024. To support this shift, we ensure that our direction remains clear and that the mechanisms, specifically NBS discussed in previous trans4num work, are well-defined. Achieving transformation also involves incorporating diverse perspectives on the challenge, which is realized through trans4num's interdisciplinary approach. By doing so, trans4num lays the groundwork for a social-ecological transformation towards circularity. However, within the boundaries of the project, it will contribute to a transition staying in the field of agriculture rather than levelling circularity up to a cross-sectoral transformation.

2. **Hindering and fostering factors**: To address specific topics needing attention, we examine drivers and barriers identified in similar and previous work. Understanding these factors helps pinpoint crucial areas for intervention. These insights guide the initial stages of our backcasting process and can be adapted as new information emerges. By identifying these factors early on, we can strategically navigate the transformation pathway, addressing obstacles and leveraging enablers effectively.
3. **Iterative adaptation**: New knowledge is continuously generated throughout the project via research and stakeholder engagement at the NBS innovations. Consequently, our pathways need to be periodically reviewed and adjusted as needed. General assemblies, work package meetings, and deliverable preparations provide opportunities for interdisciplinary reflection. This iterative process ensures the project remains aligned with its goal of contributing a circular nutrient management transformation, adapting to new findings and feedback to maintain directionality and coherence.

By integrating these three components—clear transformation goals, understanding hindering and fostering factors, and practising iterative adaptation—, trans4num can systematically advance towards its objective of sustainably and effectively transforming nutrient management.

6. Conclusion

The trans4num project operates within the theoretical framework of transformation pathways, aiming to integrate diverse disciplinary perspectives and practical domains to address systemic challenges in nutrient management and sustainability. By examining key concepts and terms, trans4num has clarified the interconnections within transformation theory, shedding light on nuanced distinctions, such as those between incremental and transformational change, as highlighted by adaptation literature (Moser and Ekstrom, 2010; Nelson et al., 2007; Pelling, 2011). The project's approach acknowledges that while incremental changes may be more immediately feasible and encounter less resistance, achieving true sustainability in agriculture and nutrient management will require transformative change that disrupts established social norms, economic structures, and institutional frameworks. This transformational ambition brings complex barriers that call for innovative strategies, such as transformative learning and leadership development (Heifetz et al., 2009; Tschakert and Dietrich, 2010), to equip stakeholders with the skills and perspectives needed to envision and enact deep-rooted changes.

Despite the challenges inherent in transformative approaches, trans4num recognizes the practicality and appeal of incremental transitions at the local level. Localized, incremental steps taken by individual sites and project tasks can serve as foundational actions, contributing to gradual progress and building momentum. However, trans4num's ultimate objective is to bridge these individual efforts and assess their cumulative impact on the potential for radical transformation. By reflecting on how each incremental step might scale up to influence system-wide shifts, the project aligns site-specific actions with its broader ambition for a socio-ecological transformation.

The project's focus on multiple, context-specific pathways further acknowledges that there is no one-size-fits-all solution. Individual pathways emerge in response to local conditions, informed by the unique challenges and opportunities each site or region faces. At the same time, the project distils insights from these diverse pathways to develop broader transformation strategies. These strategies are pluralistic and adaptable, emphasizing alternative approaches to sustainability that respect contextual diversity and promote resilience.

To advance this agenda, trans4num uses a multi-level, multi-actor approach that leverages fostering and hindering factors identified in the transition and transformation literature. The role of context and locality emerges as paramount, as local conditions often define which factors support or inhibit transformation. The project underscores that stakeholder engagement is essential, enabling a nuanced understanding of these contextual constraints while integrating local expertise and perspectives. Such engagement also provides a foundation for envisioning governance and policy pathways rooted in community realities. Through active research into fostering and hindering factors, trans4num strives to create pathways that are theoretically sound and practically viable within the context of nutrient management.

Ultimately, trans4num's transformative vision transcends technical optimizations in nutrient management; it seeks to fundamentally reconfigure the relationship between human and ecological systems to address pressing global challenges, from climate change to biodiversity loss and social inequities. This work aligns with a transformative vision beyond incremental changes, aiming for profound, systemic reorientation across social, ecological, political, and economic dimensions. By combining actionable insights from local initiatives with systemic perspectives, trans4num fosters pathways that can adapt to the complexities of socio-ecological transformation, advancing a more resilient and sustainable future in agriculture and beyond.

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8. Appendix

Table 2: Most frequently mentioned factors fostering innovative NBS.

Factor	Mentions *(Count)*	Dimension	Description	Example Quote *(Emphasis added)*
Societal Valuation of ES	30	Social	*Society values many ecosystem services provided by NbS/sustainable agriculture.*	"Agroecological approaches, which involve effective interactions between researchers, policy makers, farmers, and consumers, can **improve social cohesion and socioeconomic synergies while reducing the use of various agricultural inputs**" (Cheng et al., 2022)
Participatory Stakeholder Cooperation	25	Social	*Stakeholders cooperate in participatory processes (e.g. shared vision, trust, and shared benefits)*	"the territory as a place for articulating **public, market, and civil society actors** around a **shared vision** of sustainable agri-food systems" (Triboulet et al., 2019)
Local/Traditional Knowledge	22	Social	*Local/traditional knowledge is used & valued. Solutions are local and site-specific.*	"Building on the increasing recognition of the relevance of **traditional agroecological knowledge (TAeK)** in sustainable food systems…" (Lara et al., 2019a)
Involvement of Local Actors	23	Social	*Local actors are involved.*	"reasonable prospects such as some technology adoption activities and **organization of local actors** that are necessary for triggering the transformation process to sustainable state of productivity" (Mutoko et al., 2014)
Local Institutional Ties	18	Social	*Local institutions (religious, cultural, civic) provide legitimacy.*	"Sacred groves, while dependent on respect for **religion**, **local cultural structures** and individual peer pressure, offer a role that may support and also be supported by official conservation efforts." (O'Neal Campbell, 2004)
Governance	19	Political	*Governance/Rules/Regulations are clear and enforced.*	"the combined role of public policy and private action in supporting the implementation of **coherent management mechanisms** and **effective governance** settings" ((O'Neal Campbell, 2004)

Farmers' Resources	17	Social	*Farmers have resources for sustainability, including capital, knowledge, and/or experience.*	"Resilience is thus more likely to emerge when farmers hone the **capacity to transform** the farm" (Darnhofer et al., 2010)
Policy Support	17	Political	*Policy supports for sustainable agriculture.*	"**interventionist policies** and independent **market support** are vital for individual and community capacity building and **public infrastructure development** to stimulate agricultural adaptation and rural transformation towards sustainability." (Li et al., 2022)
Farmer Ties to Land / Nature	15	Social	*Farmers have personal ties to land and nature.*	"farmer's interaction with nature is functional, but through agroecological practices, a **deeper understanding** of the ecosystems in which greenhouse landscapes are embedded may be gained. **As they become more connected to nature and benefit from ecosystem services, they can transition to more sustainable agricultural systems**." (Giagnocavo et al., 2022)
Diversification Benefits	14	Economic	*Diversification from NbS & sustainable management provides lower risks*	*"We observed several farmer innovations of utilizing **agro-biodiversity to stabilize productivity** and **enhance** farm **income**." (Limnirankul & Gypmantasiri, 2012)*
Learning / Reflexivity	20	Social	*Learning supports sustainable NbS solutions; solutions are iterative/reflexive and imaginative.*	*"**Social learning** plays an important role in traditional ecological knowledge (TEK) and innovation for the technique of agricultural production" (Yen & Chen, 2014)*
Innovation	13	Other (Tech)	*Innovation and technology adoption activities are applied to sustainable agriculture; innovation culture exists.*	"a broad and lasting transition towards sustainable multifunctional landscapes based on agroecological principles requires (**co-)innovation at both technical and institutional levels**." (Tittonell, 2021)

Improved Resource Management	12	Ecologic	*NbS improves resource management by lowering inputs or helping combat climate risks. Status quo has failed.*	"Agroecology has [allowed]…Cuban peasants…to **boost food production without scarce and expensive imported agricultural chemicals**" (Rosset et al., 2011)
Direct Feedback on Human Health	11	Ecologic	*Sustainable agriculture creates direct feedback between the environment and human health/well-being.*	"Stable management paradigms (one dominated by conventional, homogeneous practices and the other by diversified practices) can emerge purely from **temporal feedback between human decisions and ecological responses**." (Chapman et al., 2022)
Historical land use	10	Other (Historical)	*Historical land use is linked to sustainable agriculture.*	"Key steps to harness agroforestry for sustainable landscape management comprise: …(ii) **understanding local land-use trajectories, histories, and traditions**;…" (Plieninger et al., 2020)
Farmer Networks	9	Social	*Farmers have social networks (e.g. farmers associations).*	*"Farmers cultivated farm-level biodiversity and enterprise diversity, developed new cognitive and psychological competencies, and overcame barriers to innovation by developing external **network linkages with peers**, knowledge organizations, and federal policies." (Blesh & Wolf, 2014)*

Table 3: Most frequently mentioned factors hindering innovative NBS.

Factor	**Mentions** *(Count)*	**Dimension**	**Description**	**Example Quote** *(Emphasis added)*
Status Quo	17	Other (Historical)	*Historical extent & entrenchment of intensification limits sustainable agriculture.*	"The **evolution** of **historical facts** and the **changes** induced by the economic development models **adopted** in Italy have led to a transformation from a neighborhood agriculture to an industrialized agriculture. " (Sgroi, 2022)
Local Livelihood Strategies	11	Social	*Social trends accelerate transitions away from sustainable agriculture (e.g. land abandonment, economic development).*	"The worldwide increase of human pressure in rural areas has resulted in a progressive fragmentation of agro-forest landscapes... caused by **recent urbanization** stimulated by **economic development**, **population growth** and **improved accessibility** of rural areas" (Biasi et al., 2017)
Management Intensity	12	Economic	*Yields and profits are lower in sustainable production.*	"Traditional graze-based systems are **less economically attractive** than intensive livestock or grain production and they are being replaced by such activities, with negative social and environmental consequences." (Tittonell, 2021)
Lack of Farmers' Resources	14	Economic	*Farmers do **not** have resources for sustainability, including capital, knowledge, and/or experience.*	"The need for **new technical skills** and sometimes **high initial investments** can act as strong inhibitors of farm diversification" (Dumont et al., 2020)

Local Socio-Cultural Context	9	Social	*Local socio-cultural practices and context are lost or do not support sustainability.*	"Changes need to be aligned with the **specificities** of the **local bio-physical** environment and the **logic of the political economic environment**... while they are place-specific they are **far from locally**/regionally-bounded" (Swagemakers et al., 2019)
Governance	14	Political	*Governance/Rules/Regulations are **not** clear and enforced.*	"To jointly realise food democracy and food system sustainability, the tensions resulting from the current political support for hyper-industrialisation and the **lack of democratic**, **institutional**, **and legal mechanisms available to local actors** will need to be addressed head-on" (Horstink et al., 2023)
Competing Policy Support	9	Political	*Policy does **not** support sustainable agriculture.*	"**Policy** and **development initiatives** were implemented in order to **overcome** the **perceived** causes of these **negative** scenarios, such as overstocking, open access tenure and low output subsistence production. They typically **ignored** the **multi-purpose goals** of **traditional** pastoral systems and **emphasized commercialisation** of livestock farming and **privatisation** of communal land, which resulted in the weakening or destruction of local, traditional land management institutions." (Rohde et al., 2006)
Lack of Innovation Support	9	Other	*Innovation and technology adoption activities are **not** applied to sustainable agriculture; innovation culture does **not** exist.*	"There continues to be undue **focus on technology solutions** per se and **not enough attention on the coupling of technologies and socio-economics** and how they become **embedded** in ecological systems underpinning smallholder agriculture" (Hellin et al., 2021)
Poor Stakeholder	8	Social	*Stakeholders are **not** involved in participatory processes (e.g. of*	"There are still old problems and variances under the new national park management, namely the scientific evaluation and realisation of ecological values of products and services, **the**

Management			*cooperation like shared vision, trust, and shared benefits*	**identification and inheritance of cultural values, and the communication and consensus of multi-stakeholders**." (B. J. Wang et al., 2022)
Lack of Knowledge	11	Other	*Knowledge or scientific consensus is missing.*	"Their potential as nature-based solutions is **yet to be fully recognised**, and the systematic approaches to a nature-positive food system and sustainable development goals are yet to establish" (He et al., 2022)
Ecologic vs Economic Competition	9	Economic	*Desirable ecologic and economic outcomes are seen as direct competitors.*	"Despite variation between ecosystem functions, **profit gains** come at the **expense** of **ecosystem multifunctionality**" (Grass et al., 2020)
Lack of Ecosystem Service Feedbacks	8	Ecologic	*Humans have no direct feedback on ecologic effects; Costs and benefits of ecosystem services/disservices are mismatched.*	*"Increasing use of distant ecosystems marks a regime shift and with that, the transition to "red loops" in which **feedbacks between environmental degradation and human well-being are only indirect**" (Censkowsky & Otto, 2021)*
Traditional Knowledge Loss	6	Social	*Local/traditional knowledge is lost, under-used or under-valued.*	*"[obstacles to the adoption and spread of diversified farming practices] include the broader political economic context of industrialized agriculture, the **erosion** of **farmer knowledge** and capacity, and supply chain and marketing conditions that **limit the ability of farmers to adopt sustainable practices**." (Iles & Marsh, 2012)*

Globalization	8	Economic	*Globalization and rich global actors hinders sustainable agriculture.*	"**Global markets** and **consumption** patterns remain prominent drivers of land **degradation**" (Bosshard et al., 2021)
Demographics	6	Economic	*Demographics hinder sustainable agriculture; food security and demand pressures favor intensive agriculture.*	"Due to capitalist expansion and prevailing conditions of unsecured land tenure, lack of access to basic assets, and **high population pressure on scarce resources**, the peasants have had a intensify production." (Gutberlet, 1999)

Table 4: Links between factors fostering and hindering NBS transformation.

Factor Fostering	Mentions *(Count)*	Description	Factor Hindering	Mentions *(Count)*	Description
Societal Valuation of ES	30	*Agriculture is valued for providing more than just economic renumeration.*	Local Livelihood Strategies	11	*Agriculture is **not** valued, or agriculture provides insufficient economic or other renumeration.*
Participatory Stakeholder Cooperation	25	*Stakeholders cooperate in participatory processes (e.g. of cooperation include shared vision, trust, and shared benefits).*	Poor Stakeholder Management	8	*Stakeholders are **not** involved in participatory processes (e.g. of cooperation like shared vision, trust, and shared benefits).*
Local Institutional Ties	18	*Local institutions support sustainable agriculture.*	Local Socio-Cultural Context	9	*Local institutions do **not** support sustainable agriculture.*
Governance	19	*Governance/Rules/Regulations are clear and enforced.*	Governance	14	*Governance/Rules/Regulations are **not** clear and enforced.*
Local/Traditional Knowledge	22	*Local/traditional knowledge is used & valued. Solutions are local and site-specific.*	Traditional Knowledge Loss	6	*Local/traditional knowledge is lost, under-used or under-valued.*
Farmers' Resources	17	*Farmers have resources for sustainability, including capital, knowledge, and/or experience.*	Lack of Farmers' Resources	14	*Farmers do **not** have resources for sustainability, including capital, knowledge, and/or experience.*
Policy Support	17	*Policy supports sustainable agriculture.*	Competing Policy Support	9	*Policy does **not** support sustainable agriculture.*
Historical land use	10	*Historical land use is linked to sustainable agriculture.*	Status Quo	17	*Historical extent & entrenchment of intensification limits sustainable agriculture.*
Management Intensity	8	*Yields and profits are higher in unsustainable production.*	Management Intensity	12	*Yields and profits are lower in sustainable production.*
Innovation & Tech	13	*Innovation and technology adoption activities are applied to*	Lack of Innovation Support	9	*Innovation and technology adoption activities are **not** applied*

		sustainable agriculture; innovation culture exists.			*to sustainable agriculture; innovation culture does **not** exist.*
Direct Feedbacks on Human Health	11	*Sustainable agriculture provides direct feedback to human health/well-being. Costs & benefits of ES/ED are linked.*	Lack of Ecosystem Service Feedbacks	8	*Humans have **no** direct feedback on ecologic consequences. Costs and benefits of Ecosystem Services/Disservices are mismatched.*
Financial incentives for action	9	*Financial incentives encourage sustainable agriculture.*	Ecologic vs Economic Competition	9	*Financial incentives **discourage** sustainable agriculture.*
R&D	7	*Knowledge or scientific consensus supports sustainable agriculture.*	Lack of Knowledge	11	*Knowledge or scientific consensus is missing.*
Funding	7	*Funding sufficiently supports sustainable agriculture.*	Funding	5	*Funding does **not** sufficiently support sustainable agriculture.*
Infrastructure	4	*Infrastructure sufficiently supports sustainable agriculture.*	Lack of market access / market infrastructure	3	*Infrastructure does **not** sufficiently support sustainable agriculture.*
Holistic Risk Analysis	6	*Long time horizon and broad scope of risk analyses promote sustainable agriculture.*	Lack of Diversification	4	*Short time horizon and limited scope of risk analysis **discourage** sustainable agriculture.*
International Policy	3	*International policy supports sustainable agriculture.*	International Governance (SDGs) Incoherence	2	*International policy does **not** support sustainable agriculture because of incoherent goals.*