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3rd Report on NBS cases´ implementation and transdisciplinary evaluation in Denmark, Hungary, the Netherlands, and the UK

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Table of Contents

1. Introduction 4
2. Methods and protocols 4
3. Overview of NBS implementation across countries 7
4. Cross-country synthesis and evaluation 24
5. Transdisciplinary and transformation insights 32
6. Conclusions and next steps 41

List of figures

Figure 1. Overview of the analytical approach used for the final synthesis and transdisciplinary evaluation of the Trans4num NBS cases. 6
Figure 2. Drone-based vegetation monitoring illustrating spatial heterogeneity at the Hungarian NBS site. 13
Figure 3. Distribution of total nitrogen (TN), total phosphorus (TP), nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and plant-available phosphorus (P-Olsen) across the four treatments at 0–20 cm and 20–40 cm soil depth. Boxplots represent measurements across all available sampling campaigns; points indicate individual observations. 17
Figure 4. Soil profile demonstration at the Hungarian NBS site, illustrating the role of field-based learning in translating NBS-related knowledge into practice. 36

List of tables

Table 1. Overview of the Trans4num NBS cases included in the final evaluation. 7
Table 2. Potato virus Y infection in seed potatoes at Kollumerwaard (2024) 18
Table 3. Summary of key findings from the cross-country evaluation of the Trans4num NBS cases 31
Table 4. Comparative analysis of co-drivers and mechanisms across case studies 35
Table 5. Cross-country synthesis of transdisciplinary contributions to nutrient system transformation 40

1. Introduction

This deliverable (D2.5) is the third report on the implementation and transdisciplinary evaluation of the Nature-based Solutions (NBS) cases studied within Trans4num. It builds on the work presented in Deliverables D2.1 (initial site descriptions and implementation plans), D2.2 (first report on NBS implementation and early experimentation), D2.3 (second report on NBS implementation), and D2.4 (transdisciplinary evaluation framework and cross-case assessment). Together, these deliverables have documented the progressive implementation of the selected NBS and established the methodological basis for their evaluation. This deliverable represents the final stage of this process, bringing together the evidence generated throughout the project to provide an integrated evaluation of the four country sites and the lessons learned from their implementation.

In Trans4num, we study innovations in four country sites – Hungary, Denmark, the Netherlands, and the United Kingdom – that contribute to more sustainable nutrient management. These innovations are designed, implemented, and evaluated at regional and farm level under real-world conditions. While their impacts are observed at field and farm scale, their significance extends beyond individual farming systems. They contribute to wider transformation by demonstrating approaches that can support nutrient circularity, reduce environmental pressures, strengthen resilience, and inform future agricultural practices and policies.

During the fourth project year (2025–2026), the focus shifted from implementation towards the synthesis and transdisciplinary evaluation of the NBS. Building on the implementation experiences and monitoring activities carried out in previous years, the project consolidated evidence from the different case studies to assess the environmental, social, economic, and governance dimensions of the selected NBS. Particular attention was given to identifying enabling and limiting factors, evaluating implementation processes, and synthesising lessons learned across the different national contexts.

This report presents the final evaluation of the Trans4num NBS cases, combining country-specific analyses with a comparative synthesis across all participating countries. Rather than reporting new implementation activities, it evaluates how the selected NBS performed under different conditions, examines their contribution to circular nutrient management, and identifies the key factors influencing their wider uptake and their potential contribution to long-term agricultural system transformation.

2. Methods and protocols

This deliverable builds upon the methodological framework developed throughout Work Package 2 (WP2) and the evidence generated in the previous project deliverables. The NBS case studies analysed in this report are the same as those presented in Deliverables D2.2 and D2.3, and the site narratives developed through the project's storytelling framework provide the basis for the final synthesis and evaluation presented here. Rather than generating new

case descriptions, **this report consolidates the implementation experiences and monitoring results accumulated over the three years of the project**.

The storytelling framework developed during the previous reporting period remains an important methodological foundation for this deliverable. By combining technical results with social, institutional, and governance perspectives, the narratives provide a structured understanding of the implementation process within each case study. These narratives, together with the environmental, agronomic, and stakeholder information collected throughout the project, form the primary evidence base for the analyses presented in this report.

The evaluation adopts a cross-case comparative approach, examining the different NBS cases across a common set of analytical dimensions. Information from each country case study was analysed using thematic categories covering environmental, social, economic, and governance aspects of NBS implementation. Particular attention was given to identifying common patterns across cases, context-specific differences, enabling conditions, implementation barriers, and the lessons learned from applying NBS under different agricultural and institutional settings. The overall analytical approach, from the integration of previous WP2 outputs and case-study evidence to the cross-case comparison and transdisciplinary synthesis, is summarised in Figure 1.

A transdisciplinary perspective underpins the entire evaluation. Scientific evidence generated through field experiments and monitoring activities is considered alongside the practical experiences of farmers, advisors, researchers, and other stakeholders involved in the implementation of the NBS. Insights emerging from stakeholder engagement activities, project workshops, and discussions held during the General Assemblies have been used to validate and interpret the findings, ensuring that the evaluation reflects both scientific evidence and practical implementation experiences.

The synthesis presented in this report builds progressively upon the previous WP2 deliverables. Deliverable D2.1 established the baseline by describing the case study sites and implementation plans. Deliverables D2.2 and D2.3 documented the implementation of the selected NBS, reported monitoring activities, and developed the country narratives through the storytelling framework. Building on these outputs, D2.5 provides the final synthesis and transdisciplinary evaluation of the four country sites, identifying cross-country lessons, assessing the contribution of the NBS to circular nutrient management, and reflecting on their potential to support broader agricultural system transformation.

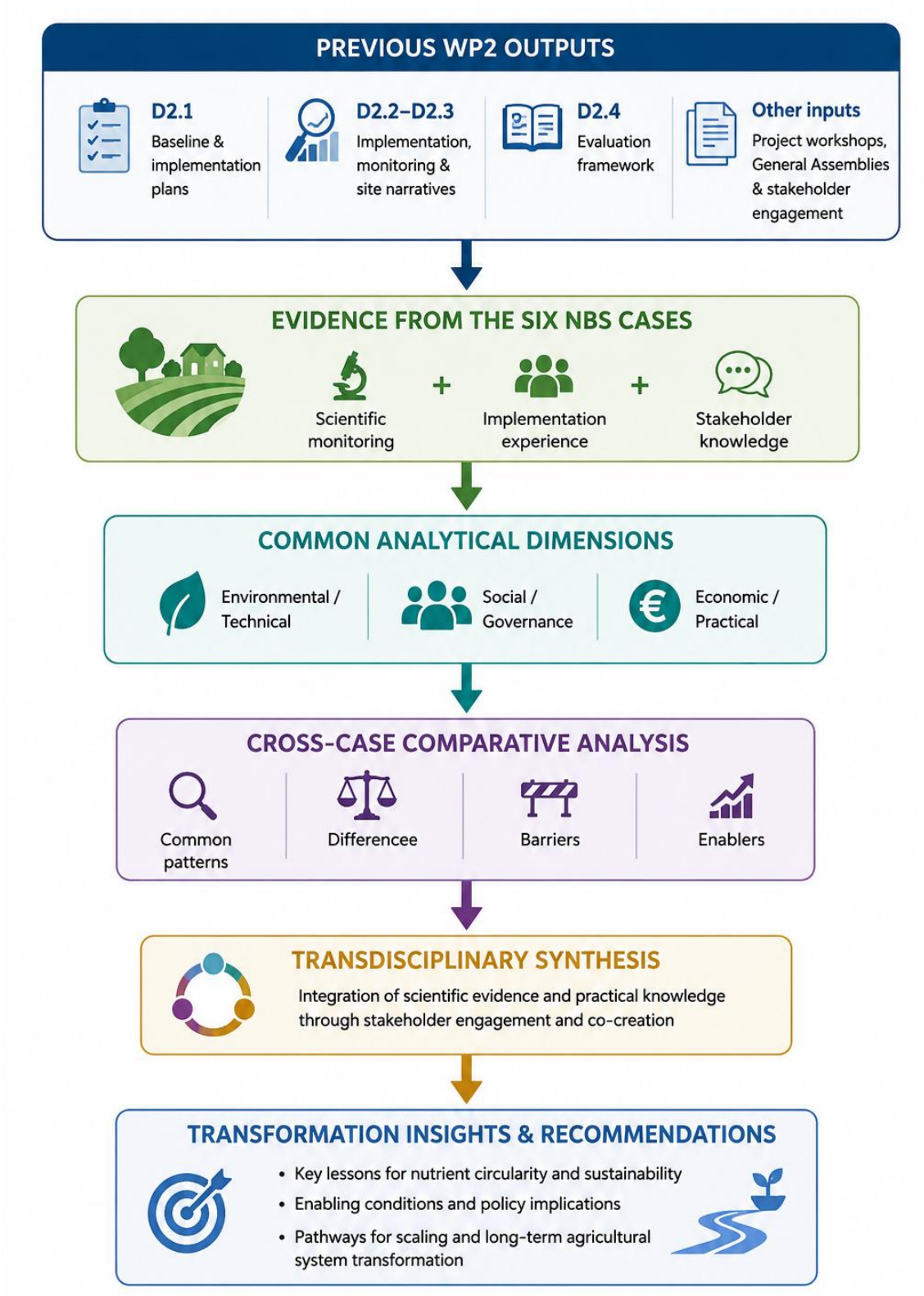


Figure 1. Overview of the analytical approach used for the final synthesis and transdisciplinary evaluation of the Trans4num NBS cases.

3. Overview of NBS implementation across countries

This section provides an overview of the implementation and main outcomes of the different NBS cases studied within Trans4num. The cases differ in their technical approach, spatial scale and implementation setting, ranging from field- and farm-level interventions to regional and value-chain approaches. Table 1 provides an overview of the NBS cases and their main characteristics before each case is presented in more detail.

Table 1. Overview of the Trans4num NBS cases included in the final evaluation.

Country / case	NBS approach	Scale	Main implementation setting	Main circularity mechanism
DK – Limfjord	Perennial biomass + green biorefining + DST	Regional/value chain	Biomass production and processing	Biomass valorisation and nutrient return
HU – Szigetköz	Integrated cropping-system NBS	Field/farm	20-ha commercial field experiment	Soil and nutrient management
NL – Kollumerwaard	Crop rotation, cover crops and plant-based fertilization	Field/farm	Long-term platform + field trials	Plant-based nutrient recycling and reduced external nutrient inputs
NL - Ebelsheerd	Lucerne and grass-clover pellets for winter-wheat fertilisation	Field	Conventional and organic winter-wheat field trials	Substitution of mineral/animal-derived fertilisers with plant-based nutrient sources
UK – Devon	Recycled P fertilizer	Field	Crop and grassland trials	Recovery and reuse of phosphorus
UK – LSRE	Compost, rotations & reduced tillage	Cropping system	Long-term experiment	Organic amendments and improved nutrient-use efficiency

3.1 Denmark NBS Site – Limfjord Catchment

3.1.1 Implemented NBS

The Danish NBS consists of a circular value chain based on the cultivation of perennial grass, grass-clover, legumes and other leafy biomass with high biomass and protein yields and low nutrient leaching. Green biorefining separates a protein concentrate for feed and potentially food, while press cake, brown juice and other residues can be used for biogas production and organic fertilisation, allowing nutrients to be returned to crop production. A spatial decision-

support tool (DST) complements the value chain by identifying where land-use changes may provide the greatest nitrogen, climate, land-use and economic benefits under user-defined goals and constraints.

The intended transformation is therefore both agricultural and industrial: moving from annual, input-intensive cropping systems associated with imported feed protein and nutrient losses towards place-based perennial biomass and protein production and a more circular regional bioeconomy. This requires crop production, harvest logistics, industrial refining, product markets and side-stream utilisation to function as an integrated system.

3.1.2 Implementation status

At project start, the agronomic and environmental potential of the crop and biorefining concept had already been demonstrated, but Denmark did not have a consolidated grass-protein industry. Biomass logistics, contracts, product markets, side-stream utilisation, facility location and regulatory fit remained unresolved. The DST was also at an earlier stage of development as a concept for connecting spatial data, NBS effects and trade-offs.

During Trans4num, development followed two interconnected tracks. The system focus broadened from protein extraction towards value-chain establishment and local system integration, including consideration of different facility scales, market orientations and levels of integration with biogas. In parallel, the DST developed into an operational prototype used in advisory, farmer-meeting and planning discussions. The tool combines field, crop, soil, yield, retention and distance data to generate maps and indicators based on user-defined goals and constraints, supporting deliberation rather than automating land-use decisions.

Actors across the value chain were mapped, consulted and involved in work addressing regulatory barriers to further development and scaling. The current stage is best described as ongoing demonstration and pathway development rather than completed scaling. Technical processes have matured and the requirements for viable value chains are better understood, but no stable large-scale configuration has yet been demonstrated across the Limfjord catchment. Farmer uptake, investment, offtake and markets for side streams therefore remain uncertain.

3.1.3 Key actors involved

Aarhus University contributes agroecological, nutrient-flow and spatial-modelling expertise and, together with Cordulus and other project partners, has supported development and testing of the DST. Climate Foundation Skive acts as a local boundary organisation, connecting research, industry, public authorities and policymakers and supporting stakeholder engagement.

The wider network includes farmers and farmer organisations, advisory services, biorefineries, biogas plants, feed-industry actors, cooperatives, environmental NGOs, municipalities, national authorities and research organisations. Their involvement brings

together knowledge on biomass production, technology, business models, markets, farm decisions, planning and regulation.

3.1.4 Key results / observations

During the project period, broader Danish R&D and industry experience indicated increasing technical maturity and improved protein extraction. Trans4num contributed primarily by examining how these technical developments interact with value-chain organisation, spatial targeting, stakeholder coordination, markets and regulatory conditions.

The main technical observation is the increasing maturity of the overall system concept rather than a single agronomic result. Project experience indicates improved protein extraction and continuing process optimisation, while showing that viable green biorefining is unlikely to follow one standard configuration. Facility scale, market orientation and integration with biogas may vary depending on local biomass supply, transport distances, nearby industries, side-stream utilisation and market access.

The DST represents a concrete project output, allowing spatial land-use scenarios to be compared using indicators for nitrogen, economy, area and other effects, thereby making regional trade-offs more explicit. Testing showed that its usefulness depends on transparent data sources, realistic constraints, locally credible transition assumptions and appropriate facilitation.

From an environmental perspective, perennial grass and grass-clover can reduce nitrogen losses compared with dominant annual rotations in nitrate-sensitive landscapes. Existing Danish field evidence and modelling show that perennial grass and grass-clover can substantially reduce nitrate leaching compared with dominant annual rotations, particularly on vulnerable soils. The magnitude of the effect depends on soil type, crop rotation, fertilisation and preceding crop. These environmental effects are based on established Danish research and modelling rather than on a new long-term field experiment conducted within D2.5. A complete farm- or regional-scale nitrogen and phosphorus balance, long-term soil carbon stock changes, yield effects, life-cycle impacts and the net effects of processing and transport cannot yet be quantified.

During the project period, Climate Foundation Skive engaged closely with Danish ministries on the development of a regulatory sandbox for green biorefining. In 2025, CFS was appointed as the national anchor point for the Danish Regulatory Sandbox on green biorefining. The sandbox provides a structured setting for authorities, industry, farmers and researchers to examine regulatory barriers and test value-chain solutions under real-world conditions. At the

time of writing, the sandbox has been established, while specific regulatory adjustments, support mechanisms and product approvals remain under development.

3.1.5 Challenges and constraints

The main technical and logistical challenges relate to the bulky and perishable nature of fresh biomass, making harvest timing, transport distance, storage, refinery throughput and coordination with downstream users important determinants of system performance. Locating facilities close to biomass supply can reduce transport requirements, but viable markets are still required for protein and the different side streams.

Governance challenges arise from existing support schemes, nutrient rules and product standards which were largely designed around incumbent crops and value chains. The regulatory sandbox has provided a forum for identifying possible solutions, but concrete regulatory changes remain under development.

From 2027, Denmark's targeted nitrogen regulation is replaced by a new discharge-based regulatory model that also accounts for differences in nitrogen losses associated with different crops. This increases the relevance of crop choice and spatial targeting in nitrogen management but does not in itself ensure biomass demand or the commercial viability of green biorefineries.

The competitiveness is influenced by biomass supply and quality, labour, transport, processing efficiency, regulation and feed-protein prices. stakeholder discussions indicate that several environmental benefits associated with perennial biomass production are not directly remunerated through current product markets. This may weaken the private business case even where the system could generate wider water-quality or climate benefits. These wider economic effects were not quantified within D2.5.

Moreover, full-scale facilities require substantial investment, and viable business models are unlikely to depend on green protein for feed alone. Potential higher-value food applications, subject to regulatory and market approval, together with value creation from side streams such as pulp, brown juice, biogas and fertiliser products, may therefore be important for the overall business case.

3.1.6 Enabling factors

A favourable policy window connects water quality, climate, land-use conversion, green proteins and the transition towards emission-based nitrogen and climate regulation. Existing Danish research and pilot experience provide a strong knowledge base, while Skive's regional bioeconomy and energy ecosystem facilitates connections with municipalities, industry and biogas actors.

Trusted intermediaries are another important enabling factor. Climate Foundation Skive and other actors connect technical, commercial and administrative communities. Stakeholder engagement involved farmers, biorefineries, biogas actors, farmer organisations and advisors,

environmental NGOs, feed-industry actors, municipalities and national authorities through workshops, interviews, bilateral dialogue and other forms of interaction. These activities helped identify missing links, barriers and potential scaling pathways. The DST has supported this process as a boundary object around which farmers, advisors, planners, researchers and authorities can explore alternatives.

3.1.7 Lessons learned

The Danish experience shows that the NBS needs to be designed and evaluated as a whole system. Optimising protein extraction alone is insufficient if biomass supply, transport, side-stream valorisation, markets and regulation are misaligned. Similarly, environmental targeting is unlikely to lead to implementation without a viable value proposition for farmers and investors.

Participatory scenario development should begin early, with stakeholders contributing to the definition of goals, constraints and realistic alternatives. Future DST use should therefore combine transparent data and uncertainty with local validation and trusted facilitation.

Scaling should prioritise transferable principles over replicating a single facility model, including place-based targeting, efficient biomass logistics, diversification of revenue streams, robust contractual arrangements, integration with regional industries, and policy recognition of public benefits. However, assessments of scalability must distinguish between anticipated and demonstrated outcomes: stakeholder engagement does not necessarily indicate adoption, regulatory proposals do not constitute formal approval, and modelled benefits should not be presented as empirically verified impacts.

3.2 Hungary NBS Site – Szigetköz Region

3.2.1 Implemented NBS

The Hungarian NBS site is located in Kimle, in the Szigetköz region of north-western Hungary, where a 20-hectare field experiment was established under commercial farming conditions. Rather than testing individual measures in isolation, the site applies an integrated NBS system combining a durum wheat–sorghum–soybean crop rotation, no-tillage, reduced pesticide use, bio-based fertilisation with poultry manure pellets, biostimulants, winter cover crops, and integrated crop and soil monitoring.

The objective is to enhance soil health and nutrient cycling while maintaining productive and economically viable farming. The system therefore combines measures addressing nutrient management, soil disturbance, crop diversification and biological processes within a single practical farming approach.

3.2.2 Implementation status

The planned NBS interventions were fully implemented in a three-year crop rotation comparing the integrated NBS system with conventional intensive farming. Monitoring included soil, plant, yield, CO_2 and remote-sensing measurements throughout the implementation period, allowing agronomic performance to be evaluated together with changes in soil functioning and nutrient dynamics.

The site has now completed its demonstration and evaluation phase within Trans4num. Implementation and monitoring across the three project years provide the basis for assessing the technical performance, environmental effects and practical relevance of the integrated NBS system under commercial farming conditions.

3.2.3 Key actors involved

The site was implemented through collaboration between research institutions, farming practice and local civil-society actors. Széchenyi István University provided scientific coordination, monitoring and data evaluation; Pannon-Mag-Agrár Ltd. contributed practical farming expertise and supported implementation of the field experiment; and Pisztráng Kör Association provided local coordination, stakeholder engagement and knowledge exchange.

Farmers, advisors, researchers and other stakeholders were additionally involved through roundtable discussions, field visits, soil-profile demonstrations and other project events. These activities created opportunities for peer-to-peer learning and for discussing practical experiences, difficulties and potential benefits associated with NBS.

3.2.4 Key results / observations

The Hungarian site demonstrated that an integrated NBS system can support soil functioning and nutrient cycling while maintaining crop nutrition under commercial farming conditions. Soil monitoring after three years showed positive trends in organic carbon, organic matter, potentially mineralisable nitrogen (PMN), total nitrogen, available phosphorus and cation exchange capacity, with the clearest tendencies in the biologically active 0–30 cm layer. Compared with conventional management, NBS increased mean topsoil organic carbon by 6.8% (15.07 vs. 14.11 g/kg), organic matter by 7.3% (2.61 vs. 2.43%), PMN by 12.2% (74.11 vs. 66.07 mg/kg), total nitrogen by 10.0% (1.96 vs. 1.79 g/kg), available phosphorus by 28.4% (49.0 vs. 38.15 mg/kg), and CEC by 1.6% (188.63 vs. 185.74). The strongest trends towards statistical significance were observed for PMN ($p = 0.062$) and total nitrogen ($p = 0.084$).

The 12.2% higher PMN under NBS suggests greater microbial activity and a greater capacity to mineralise organic nitrogen and release plant-available nitrogen. The 10.0% higher total nitrogen concentration in the 0–30 cm layer suggests improved nitrogen retention and potentially reduced nitrogen losses under NBS management. Available phosphorus was also 28.4% higher in the upper soil layer, potentially reflecting enhanced microbial and rhizosphere-mediated phosphorus mobilisation. At 30–60 cm, treatment differences were

generally smaller; notably, available phosphorus was 19.4% lower under NBS, supporting the interpretation that the positive phosphorus response was concentrated in the topsoil.

Leaf analysis showed no significant differences between NBS and conventional treatments for any nutrient or crop (all p-values > 0.13), indicating that plant nutrient status was maintained. Yield responses varied by crop and year: in 2024, NBS increased yields by 4.85% in durum wheat (4.76 vs. 4.54 t/ha), 2.74% in soybean (3.38 vs. 3.29 t/ha), and 4.83% in sorghum (7.82 vs. 7.46 t/ha). In 2025, durum wheat maintained a 6.81% yield advantage (3.93 vs. 3.676 t/ha), whereas soybean and sorghum yields under NBS were 3.44% and 5.09% lower, respectively, than under conventional management. This demonstrates both the agronomic potential of the NBS and its sensitivity to crop and seasonal conditions.

Natural field heterogeneity also strongly influenced crop development and sometimes made treatment and site effects difficult to distinguish. As illustrated in Figure 2, drone and remote-sensing observations revealed substantial spatial variability across the experimental site, associated with differences in clayey, sandy and gravelly soil layers and water-holding capacity. These observations also demonstrated the value of spatial monitoring for supporting more targeted nutrient, irrigation and crop-management decisions.

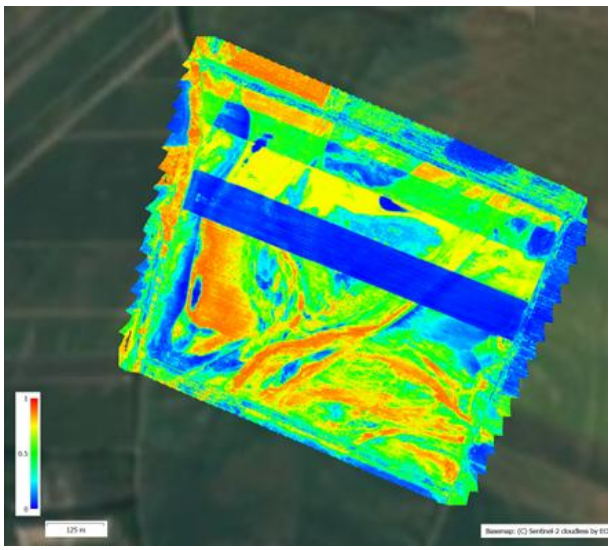


Figure 2. Drone-based vegetation monitoring illustrating spatial heterogeneity at the Hungarian NBS site.

Overall, the results indicate potential improvements in soil functioning and more sustainable nutrient management, while reinforcing the need for long-term monitoring and site-specific interpretation of agronomic and environmental outcomes.

3.2.5 Challenges and constraints

Year-to-year climatic variability strongly influenced crop performance and complicated separation of treatment effects from weather-related impacts. Natural heterogeneity of the

alluvial soils generated additional spatial variability, requiring intensive monitoring and careful interpretation.

The transition towards integrated NBS also requires a longer-term perspective than many agricultural management and support schemes provide, as soil and environmental benefits may take several years to become visible. Farmers can be cautious about adopting unfamiliar practices when the economic consequences are uncertain, making confidence-building and practical evidence important for wider uptake.

Economic feasibility was not assessed through a dedicated economic analysis. Potential reductions in external inputs therefore need to be considered alongside labour, machinery, monitoring, knowledge requirements and production risks. The return on investment may also be difficult to estimate where environmental benefits develop gradually and depend on weather, soil conditions and crop choice.

3.2.6 Enabling factors

A key enabling factor was the integrated systems approach, combining crop rotation, reduced tillage, bio-based fertilisation, cover crops, biostimulants and monitoring rather than evaluating each practice in isolation. Close collaboration between researchers, farmers and local stakeholders ensured that scientific objectives remained connected to practical farming needs.

Comprehensive soil, crop and remote-sensing monitoring provided an evidence base for interpreting field variability and management outcomes. The presence of a trusted local partner was also important for reaching farmers and creating an open environment for discussion.

Field demonstrations and peer-to-peer activities helped translate scientific concepts into visible and locally relevant examples. During demonstrations farmers showed particular interest in practical measures such as cover crops, reduced or no tillage, drought-tolerant crops and observable soil-health outcomes, suggesting that engagement is strongest when environmental objectives are connected to concrete farm-management benefits.

3.2.7 Lessons learned

The Hungarian case indicates that NBS can be particularly relevant to farmers when demonstrated as an integrated farming system rather than as isolated practices. It also confirms the importance of a long-term perspective. The three-year evaluation provides evidence of initial trends, but continued monitoring would be needed to assess longer-term soil biological activity, carbon dynamics, nutrient cycling and yield stability.

The case also shows that spatial heterogeneity and seasonal variability are not simply experimental complications but important components of practical NBS implementation. Scaling should therefore involve site-specific adaptation supported by soil and crop monitoring rather than replication of the same management package across farms.

Environmental performance also needs to be considered together with economic and practical feasibility. Future evaluation should give greater attention to input costs, labour requirements, operational risks and yield stability. Field demonstrations, soil-profile presentations, trusted advisory support and peer-to-peer learning should be further encouraged, while one-size-fits-all approaches should be avoided.

3.3 the Netherlands NBS Site – Kollumerwaard & Ebelsheerd

3.3.1 Implemented NBS

In the Netherlands, the NBS activities are implemented at SPNA (*Stichting Proefboerderijen Noordelijke Akkerbouw*) agroresearch and focus on plant-based nutrient management in arable farming, aiming to reduce dependence on synthetic fertilisers and livestock manure while increasing nutrient self-sufficiency and maintaining productive and resilient cropping systems. The main approaches include long-term cut-and-carry fertilisation using grass-clover biomass, green manure, cover crops, compost, and plant-based fertilisation in conventional and organic winter wheat.

Field experiments at SPNA also investigated organic materials such as straw and grass-clover biomass as alternative crop-protection strategies against aphid-transmitted viruses in seed potatoes. These activities were supported by long-term monitoring of soil physical, chemical and biological properties.

3.3.2 Implementation status

The Dutch case combines a long-term experimental platform with project-specific field experiments. Planty Organic originated from an initiative of organic arable farmers in 2011 seeking alternatives to increasingly scarce and costly livestock manure. Its cut-and-carry fertilisation system has operated since 2012 and provided the foundation for the Dutch NBS evaluation.

Within Trans4num, this platform was complemented by trials replacing mineral nitrogen fertilisers with plant-based alfalfa and grass-clover pellets in conventional and organic winter wheat, as well as experiments evaluating cover crops and organic materials for nutrient supply and crop protection in seed potatoes. Extensive soil, crop and microbial monitoring was conducted between 2023 and 2025.

Planty Organic continues as a long-term experiment, while the Trans4num field trials have reached their final implementation stage. Knowledge generated through Trans4num is expected to inform future activities within SPNA's Agrifuture platform, where integrated NBS can be further evaluated under practical farming conditions and at a larger scale.

3.3.3 Key actors involved

Implementation was based on close collaboration between Wageningen University (WU) and SPNA combining scientific monitoring and analysis with long-term field experimentation and practical agricultural expertise. Farmers contributed practical feedback and participated in field meetings and evaluation of the NBS under commercial conditions, while agricultural advisors helped connect scientific findings with farm-management decisions.

Plant breeders, regional and water authorities, students and other stakeholders were also involved through workshops, dissemination events and knowledge-sharing activities. Together, these interactions supported a long-term farmer–researcher learning network linking scientific evaluation with practical and regional relevance.

3.3.4 Key results / observations

After three years of monitoring at the long-term Planty Organic site in Kollumerwaard, plant-based fertilisation strategies maintained key soil properties, including pH, soil aggregates, bulk density, water availability or some nutrient-related parameters, at levels comparable to conventional farming while relying on lower external nutrient inputs. Environmental variability, soil depth and sampling timing often had stronger effects on soil parameters than fertilisation strategy, particularly in the highly buffered Dutch clay soils, highlighting the importance of long-term monitoring.

Planty Organic at Kollumerwaard generally showed lower total nitrogen and phosphorus concentrations than conventional fields at both soil depths (0–20 and 20–40 cm), while differences in plant-available nutrient concentrations among treatments were less pronounced (Figure 3).

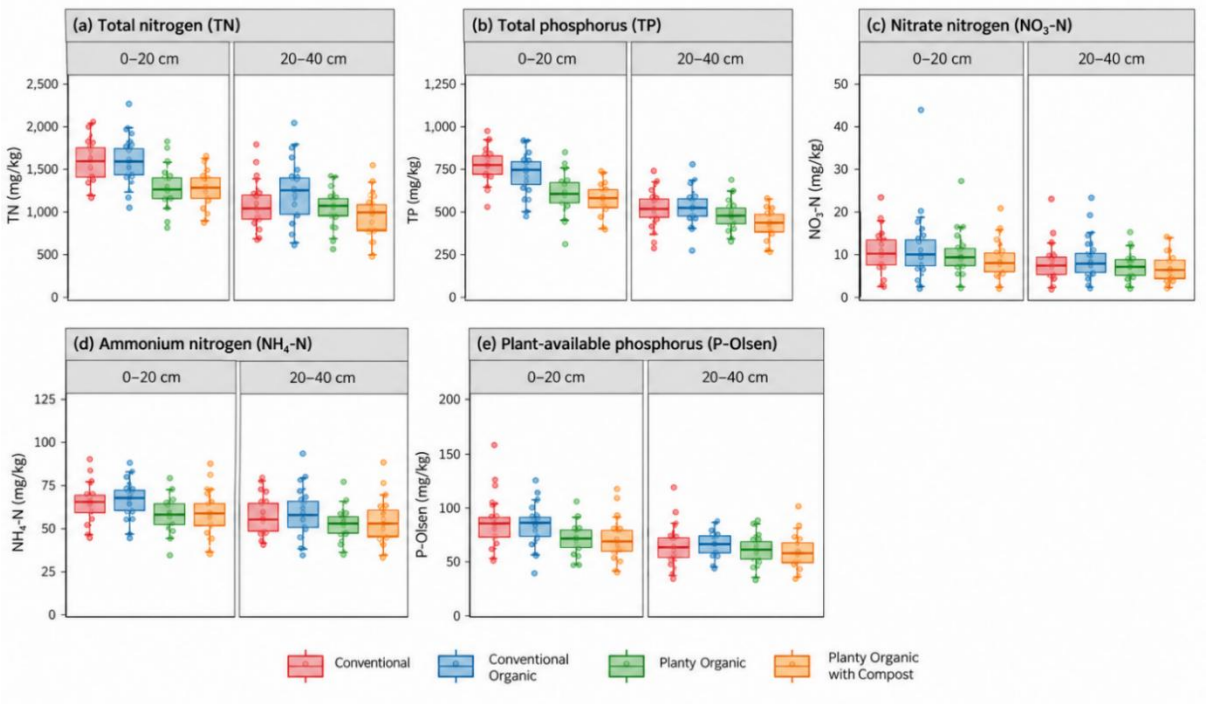


Figure 3. Distribution of total nitrogen (TN), total phosphorus (TP), nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), and plant-available phosphorus (P-Olsen) across the four treatments at 0–20 cm and 20–40 cm soil depth. Boxplots represent measurements across all available sampling campaigns; points indicate individual observations.

In the winter wheat trials at Ebelsheerd, crop-yield responses varied by crop, treatment and season. This response was attributed to potential delays in organic nitrogen mineralisation during early spring crop development, whereas conventional systems provided readily available mineral nitrogen regardless of early-season soil temperatures. Different amendments tested at Ebelsheerd also affected nutrient dynamics differently, with grass-based materials generally providing faster nitrogen availability than straw, which temporarily immobilised nitrogen during decomposition.

In seed-potato trials at Kollumerwaard, organic surface materials showed potential to reduce reliance on chemical crop protection, although their effectiveness varied between seasons depending on aphid pressure and weather conditions. Under the relatively low aphid pressure observed in 2024, the combination of straw mulch and oil spray significantly reduced post-harvest Potato virus Y (PVY) infection, with an infection rate of 2.2%, , compared with 11.3% in the untreated treatment and 9.3% with straw mulch alone (Table 2).

Table 2. Potato virus Y infection in seed potatoes at Kollumerwaard (2024)

Treatment (description)	Application rate	Potato virus Y infection rate (%)	90% confidence interval
Untreated (A)	–	**11.3**	7.1 – 15.0
Grass (B)	12 t/ha	–	–
Straw (C)	4 t/ha	9.3	5.3 – 13.3
Straw + oil (D)	4 t/ha + oil	**2.2**	**0 – 4.4**
Vetch (E)	120 kg/ha	–	–

Note: Infection rates were determined by post-harvest tuber testing. "-" indicates that no post-harvest infection rate was available for this treatment.

Overall, the results indicate that NBS can contribute to more circular nutrient management while maintaining productive farming systems, although some effects may require longer monitoring periods to become fully apparent.

3.3.5 Challenges and constraints

A major technical challenge was synchronising nitrogen release from plant-based fertilisers with crop demand. Because mineralisation depends on microbial activity, cold spring conditions can create a temporary mismatch between nutrient supply and early crop nitrogen demand. Soil-quality responses also developed gradually and were often masked by weather variability, while annual differences in aphid pressure influenced ecological crop-protection performance.

Plant-based nutrient systems additionally operate within regulatory frameworks largely designed around conventional fertilisation and livestock manure, which do not always recognise or incentivise circular plant-based nutrient management.

Adoption also requires changes in farm practices and decision-making. Feedback from farmers showed particular interest in the practical and economic implications of plant-based fertilisation, including potential effects on weed pressure, fertiliser application strategies, input costs, expected yield reductions, and challenges associated with implementation at farm level. Farmers also questioned the broader sustainability of producing crops specifically for use as fertiliser. These concerns highlight the importance of long-term demonstration, practical guidance and clearer evidence on agronomic and economic trade-offs to support informed adoption decisions. An ageing farming population and limited succession opportunities may further affect uptake.

From a practical implementation perspective, biomass-based fertilisation requires biomass production, harvesting, transport and application, as well as suitable infrastructure. Its feasibility therefore depends on the availability of biomass and on how these activities can be integrated into the existing farm system. While these requirements may have economic implications, these were not quantified within the case study and no dedicated economic analysis was undertaken.

3.3.6 Enabling factors

The limited availability and increasing cost of livestock manure on organic arable farms provided a practical incentive to explore plant-based nutrient strategies. The long-term Planty Organic platform enabled cumulative effects to be evaluated under realistic conditions, while collaboration between WU and SPNA combined scientific and practical expertise.

The NDICEA model supported interpretation of nitrogen dynamics and nutrient supply–crop demand relationships, while experienced crop advisors helped translate scientific evidence into management decisions. Regular stakeholder meetings, field demonstrations and dissemination activities further supported knowledge exchange. By December 2025, fourteen events involving farmers, advisors and other stakeholders had been organised.

3.3.7 Lessons learned

The Dutch case demonstrates that transition towards plant-based and circular nutrient management is technically feasible, but that measurable changes in soil quality require long-term monitoring. Maintaining soil functioning with lower external nutrient inputs may itself represent an important environmental benefit even when improvements in individual indicators are not immediately detectable.

Future implementation should continue optimising plant-based fertilisation to minimise potential yield penalties and improve economic feasibility. A gradual transition, combining plant-based fertilisers with faster-acting nitrogen sources where appropriate, may be more practical than relying exclusively on plant-based fertilisation for all crops. Long-term experiments remain important for capturing delayed soil responses and generating evidence for policy and practice.

The case also highlights the importance of demonstration under realistic commercial conditions. Follow-up initiatives such as Agrifuture can evaluate integrated NBS at larger and more commercially relevant scales. Scaling should focus on transferring underlying principles while adapting them to local farming systems, supported by stakeholder engagement, field demonstration and collaborative learning.

3.4 UK NBS Site – Devon (Novel P-based Fertiliser)

3.4.1 Implemented NBS

In south-west England, the NBS focused on Thallo, a recycled phosphorus-based fertiliser developed as an alternative to rock phosphate used in conventional fertiliser production. The approach offered three potential advantages: creating a domestic source of a key plant nutrient and reducing dependence on imports from geopolitically sensitive regions; recycling a previous waste product back into agriculture; and reducing cadmium inputs to agricultural soils because Thallo contains lower cadmium concentrations than rock phosphate.

3.4.2 Implementation status

Previous controlled-environment pot experiments with arable and grassland crops had shown the potential of Thallo under stable growing conditions. Trans4num therefore provided an opportunity to examine its performance under more realistic and variable field conditions.

Field trials were conducted with winter wheat in 2025, winter oats in 2026 and grassland, for which two summer harvests were undertaken. This enabled comparison of the recycled fertiliser with conventional phosphorus fertilisation across different crop types under field conditions.

3.4.3 Key actors involved

Researchers at Rothamsted Research worked in collaboration with Elemental Digest, the company that developed the recycled phosphorus fertiliser. However, Elemental Digest was liquidated in 2024. This substantially changed the innovation pathway and prevented continued engagement with the commercial developer during the later stages of the project.

3.4.4 Key results / observations

Field-trial results have so far been consistent with previous controlled-environment experiments: crops fertilised with Thallo performed broadly similarly to conventionally fertilised crops, with average winter wheat grain yield of 11.1 t/ha for Thallo fertilized crops, 11.6 t/ha for conventionally fertilized crops and 6.4 t/ha for the nil fertilized control plots. Total grass silage yields similarly illustrate that the Thallo fertilized plots yield a comparable total to conventional fertilizers, with 12.5 t/ha for Thallo, 13.3 t/ha for conventional and 7.7 t/ha for the nil control plots.. Total phosphorus uptake was comparable with triple superphosphate, suggesting broadly similar bioavailability of the different phosphorus forms.

Further chemical analysis of harvested plant material and soil samples is intended to assess differences between fertiliser treatments and support calculation of nutrient-use-efficiency budgets. The available evidence therefore supports the technical potential of recycled phosphorus fertilisation, although additional analysis is required for a more complete evaluation of nutrient performance.

3.4.5 Challenges and constraints

The main constraint was not agronomic but commercial and institutional. The liquidation of Elemental Digest meant that the company could no longer contribute to evaluation of farmer and advisor engagement, product development or market introduction. As the product was never commercially available, actual social acceptance, willingness to purchase and economic performance could not be evaluated under real market conditions.

The case therefore illustrates a broader challenge associated with circular-economy innovation: technical feasibility alone does not guarantee that a novel product will reach the market. Commercial continuity and a viable pathway from experimental validation to production and adoption are also required.

3.4.6 Enabling factors

Field validation represents an important enabling factor for future recycled-fertiliser innovations. Stakeholder engagement within Trans4num indicated that farmers and agricultural advisors place considerable value on field-trial evidence comparing novel products directly with conventional alternatives.

Although Thallo itself did not reach the market, the evidence generated by Rothamsted Research remains relevant. Should comparable products be developed in the future, these data can contribute to building confidence and supporting progression from experimental testing towards larger-scale agricultural application.

3.4.7 Lessons learned

The field trials demonstrate that a recycled and a conventional phosphorus fertiliser can produce broadly similar crop performance under the conditions tested, supporting the technical feasibility of this circular nutrient-management approach. However, the case also demonstrates that technical performance is only one component of successful innovation: the loss of the commercial partner prevented assessment of market uptake, social acceptance and economic feasibility.

Further trials across additional soil types would strengthen understanding of the consistency of recycled phosphorus fertiliser performance. More broadly, future development of comparable technologies should connect agronomic validation with a viable commercial pathway if technical evidence is to translate into practical adoption.

3.5 UK NBS Site – Rothamsted LSRE (Compost & Rotations)

3.5.1 Implemented NBS

The Large-Scale Rotation Experiment (LSRE) is a long-term systems experiment established at two sites with contrasting soil types: a clay-loam and a sandy-loam. It evaluates multiple NBS in different combinations, including diversified crop rotations, green compost application with or without cover crops, and reduced tillage. Outcomes monitored include fertiliser-use efficiency, greenhouse-gas emissions, soil properties and crop yields.

The systems approach allows individual NBS to be assessed not only separately but also in combination, providing evidence on interactions and trade-offs within the wider cropping system.

3.5.2 Implementation status

The experiment was established at Brooms Barn, the sandy-loam site, in 2017 and at Harpenden, the clay-loam site, in 2018. Baseline sampling quantified spatial variability in soil properties, weeds and soil microbiology before treatments were implemented.

The experiment compares three-, five- and seven-year crop rotations, with every phase of each rotation represented annually across combinations of compost application and inversion or zero tillage. Soybean, initially included in one rotation, was replaced by field beans because of its late maturation. The 2025 harvest marked the first completion of the seven-year rotation at both sites, providing an increasingly strong basis for evaluating longer-term system responses.

3.5.3 Key actors involved

Rothamsted researchers work closely with local agronomists on management and interpretation of the experiment. The LSRE is also regularly used as a demonstration platform for groups interested in NBS, more commonly discussed as regenerative agriculture in the UK.

The sites have hosted farmers and agronomists as well as policymakers from the UK Department for Environment, Food and Rural Affairs and representatives of food-processing companies, including Nestlé and Unilever. The platform therefore connects long-term systems research with agricultural practice, policy and value-chain interests.

3.5.4 Key results / observations

Two major findings have emerged from the first eight years. First, **NBS performance is strongly dependent on local soil type**. Second, **individual NBS can have negative consequences** for particular components of the system, but these effects can sometimes be

mitigated by combining practices.

Reduced tillage generally resulted in lower yields (for winter wheat, an average of 8% lower on the sandy loam and 15% lower on the clay loam over the last five years), but the penalty was reduced when compost was applied. At the clay-loam Harpenden site, reduced tillage also increased weed pressure, although this was less pronounced within the more diverse five-year rotation. Reduced tillage and compost had an additive effect on soil carbon, with increases occurring more rapidly and consistently in the clay-loam soil because of its greater carbon-storage capacity (an increase of 0.24% over the first six years). Increased soil carbon is expected to improve soil structure over longer timescales and potentially increase yield resilience.

The interaction between management and soil type was also apparent for cover crops: they negatively affected subsequent spring-barley yields at Harpenden by immobilising available nutrients in the clay-rich soil, while this effect was not observed at the sandy-loam site. These findings underline the importance of tailoring NBS combinations to local soil and farming conditions.

3.5.5 Challenges and constraints

Transition from ploughing to reduced tillage creates short-term management challenges, particularly soil compaction and crop establishment. These problems were most pronounced on the heavy clay-loam soil, where the drill used under reduced tillage sometimes resulted in poor crop establishment.

Green compost produced substantial benefits for yield and soil health, but access to compost and transport costs constrain wider adoption because local supply depends on the availability of suitable feed material. At the same time, rising fertiliser and diesel costs and concerns about resilience to increasingly extreme weather have strengthened stakeholder interest in alternative systems.

A remaining challenge is to translate the environmental and agronomic evidence from the experiment into economic terms that farmers can use when assessing the costs, risks and potential longer-term benefits of adoption.

3.5.6 Enabling factors

The long-term experimental infrastructure itself is a major enabling factor, allowing system responses and interactions to be evaluated over timescales that would be difficult to capture in shorter projects. Maintaining flexibility within the experimental design has also allowed management to be adapted and new technologies incorporated as evidence and farming conditions evolve.

Collaboration with crop and environmental modellers is being used to quantify opportunities for reducing synthetic inputs under different NBS combinations. Further development will be required to translate these models into practical decision-support tools for farmers.

3.5.7 Lessons learned

The LSRE demonstrates that NBS should not be evaluated as isolated practices. Reduced tillage, compost, cover crops and rotation diversity interact with each other and with soil type, meaning that an intervention that produces a disadvantage in one part of the system may perform differently when combined with complementary practices.

The experiment also highlights the importance of transition periods and long-term evidence. Short-term yield penalties or management difficulties need to be considered alongside potential longer-term improvements in soil carbon, soil structure, input efficiency and resilience.

Finally, the experience of the LSRE indicates that farmers and other end users should be involved early in the design and interpretation of long-term systems experiments. The platform was originally designed primarily as a research resource; as its value for farmer demonstration and decision-making became clearer, earlier farmer involvement would have helped ensure that experimental design and outputs addressed practical adoption questions from the outset.

4. Cross-country synthesis and evaluation

The Trans4num NBS cases represent different approaches to circular nutrient management and operate at different spatial and organisational scales. The Netherlands, Hungary and the UK primarily provide evidence from field- and farm-level interventions, although the practices and experimental designs differ substantially, whereas the Danish case addresses a broader regional biomass and nutrient system involving production, processing, logistics and multiple value-chain actors. The cases also differ in implementation duration, monitoring approaches and the availability of environmental, agronomic and economic evidence.

4.1 Environmental and technical performance

4.1.1 Nutrient recovery / cycling outcomes

Across the cases, circular nutrient management was pursued through different mechanisms. The field-based cases primarily addressed changes in nutrient inputs, soil management and soil functioning, while Denmark extended circularity to the regional redistribution and valorisation of biomass and nutrients. This diversity illustrates that nutrient circularity can be pursued through multiple pathways rather than through a single NBS configuration.

Across the Netherlands, Hungary and the UK, changes in nutrient and soil management were generally compatible with maintained or improving aspects of soil functioning, although the

direction, magnitude and timescale of responses differed. Hungary showed positive trends in several indicators associated with nutrient cycling and soil functioning, including organic carbon, organic matter, potentially mineralisable nitrogen, total nitrogen, available phosphorus and cation exchange capacity, while crop nutrient status remained comparable with conventional management. In the UK, improvements in soil carbon and aggregate stability became apparent after eight years of reduced tillage and organic amendment application, with stronger responses at the higher-clay site. In the Netherlands, plant-based fertilisation reduced reliance on livestock manure and synthetic fertilisers while soil functioning was generally maintained. However, lower total nitrogen and phosphorus stocks in the Planty Organic system raise an important longer-term question as to whether these reflect improved nutrient-use efficiency or gradual depletion of soil reserves.

Denmark broadens this comparison beyond field-level nutrient management by linking perennial biomass production with protein extraction, biogas production and potential nutrient return through digestate and other fertiliser products. The potential for circularity therefore depends on how effectively nutrients and biomass are retained and redistributed across the value chain. However, a complete measured nutrient balance is not yet available, limiting conclusions about overall nutrient-use efficiency or changes in nutrient stocks.

Overall, the cross-country evidence indicates that reduced dependence on external nutrient inputs can be pursued through different combinations of plant-based nutrient sources, organic amendments, soil management, crop diversification and biomass valorisation. However, lower external inputs should not automatically be interpreted as greater nutrient efficiency. Long-term nutrient balances and soil monitoring remain necessary to assess whether circular nutrient strategies maintain soil fertility and productivity while reducing external dependencies and nutrient losses.

4.1.2 System efficiency and functionality

A common pattern across the cases is that environmental improvements do not necessarily coincide with immediate or consistent agronomic benefits. Instead, relationships between soil functioning, resource efficiency and crop performance depend on crop type, year, soil conditions and the duration of NBS implementation.

This trade-off is particularly visible in the Netherlands and the UK. In the Netherlands, most monitored soil properties remained relatively stable across fertilisation systems, while fully plant-based fertilisation resulted in lower winter wheat yields than conventional or mixed fertilisation. In the UK, improvements in soil carbon and aggregate stability emerged over several years, while reduced-tillage systems could experience lower yields during the transition from plough-based management. In both cases, short-term yield performance alone would therefore provide an incomplete assessment of system performance.

Hungary illustrates the importance of temporal and crop variability. NBS management produced higher yields across all monitored crops in 2024, whereas results in 2025 were crop-dependent: durum wheat maintained a yield advantage, while soybean and sorghum performed slightly below conventional management. At the same time, comparable leaf nutrient status across treatments indicated that crop nutrient uptake was maintained. These

results reinforce the need to evaluate performance across multiple crops and seasons.

For Denmark, system efficiency needs to be assessed at a different scale. Crop production, transport, processing, protein extraction, side-stream utilisation and nutrient return are interdependent, meaning that gains in one part of the system may be reduced by inefficiencies elsewhere. For example, environmental benefits associated with perennial biomass production may be diminished by long-distance transport of wet biomass or limited valorisation of processing side streams.

Taken together, the cases show that NBS performance cannot be adequately assessed through a single indicator such as yield, nutrient input or soil carbon. **Evaluation needs to consider agronomic performance together with soil functioning, nutrient-use efficiency and, where relevant, processing and logistics**. Different timescales also need to be considered, as environmental or resilience benefits may emerge more slowly than short-term agronomic effects.

4.1.3 Operational robustness

Context dependency emerged as one of the clearest findings across the cases. The NBS were implemented under practical conditions, but their performance was affected by environmental variability, site characteristics, management requirements and, in the more complex systems, infrastructure and market conditions.

Among the field-based cases, the sources of variability differed but the implications were similar. In the Netherlands, weather, seasonal pest pressure and crop management affected performance and complicated the separation of treatment effects from year-to-year variability. In Hungary, spatial differences in soil texture and water-holding capacity strongly influenced crop development, while drone and remote-sensing observations helped identify this heterogeneity and support more site-specific interpretation and management. In the UK, soil type influenced the magnitude of soil-health responses, while the benefits of management change need to be considered over a transition period that may extend over several years.

Operational robustness in Denmark depends more strongly on the functioning of the wider biomass system. Seasonal biomass availability, harvesting and processing windows, processing capacity, transport distances, price volatility and uncertain outlets for side streams can all influence performance. Consequently, different technical and business configurations may be appropriate in different locations.

The common lesson is therefore not that one NBS is inherently more robust than another, but that robustness is context-specific. NBS should not be treated as fixed technical packages expected to perform uniformly across locations. **Adaptive management, appropriate monitoring and adaptation to local environmental and operational conditions are central to maintaining performance**.

4.2 Social and governance dimensions

4.2.1 Stakeholder engagement outcomes

Despite the diversity of the NBS, stakeholder engagement emerged consistently as an important component of implementation and evaluation. Across the cases, engagement appeared particularly valuable when scientific evidence was connected to practical experience, field demonstrations and concrete implementation choices rather than being treated primarily as dissemination.

The Netherlands and Hungary demonstrate the value of repeated interaction through established local networks. In both cases, researchers worked with farmers and other local actors through field visits, meetings, workshops and demonstration activities. Hungarian farmers showed particular interest in directly applicable practices and visible outcomes, while trusted local intermediaries helped connect scientific activities with the farming community. In the Netherlands, embedding Trans4num activities within existing knowledge-sharing structures similarly facilitated continuity and access to a wider agricultural audience.

The UK long-term experimental platform provided a different but complementary basis for engagement. The experimental evidence created a platform for discussing both opportunities and trade-offs associated with NBS adoption. Stakeholders recognised increasing pressures to adopt more sustainable practices in response to input costs and weather extremes, but economic costs and agronomic challenges, including weed pressure under reduced tillage, remained important concerns.

The wider system boundaries of the Danish NBS required engagement with a broader range of actors, including farmers, biorefineries, biogas plants, feed actors, advisors, NGOs, municipalities and national authorities. This enabled technical questions to be considered alongside financing, logistics, regulation, markets, collaboration and risk distribution.

The comparison therefore indicates that the appropriate form of stakeholder engagement depends on the scale and complexity of the NBS. Nevertheless, repeated interaction, practical evidence and trusted intermediary actors emerged as common elements supporting knowledge exchange and implementation across the cases.

4.2.2 Institutional arrangements

Institutional arrangements differed substantially, reflecting the different scales and requirements of the NBS. However, all cases depended on combining scientific expertise with practical, local or operational knowledge.

The Netherlands and Hungary relied strongly on partnerships between scientific institutions, experimental or farming organisations and established regional networks. These arrangements enabled scientific monitoring to be connected with farming experience and local stakeholder engagement. The UK case highlights the additional importance of institutional continuity: the ability of Rothamsted Research to maintain long-term

experimental platforms provides the timescale required to evaluate management changes whose effects may only become apparent after several years.

Denmark represents a more distributed institutional arrangement because implementation involves a wider biomass value chain. Scientific and modelling expertise, stakeholder coordination, public planning, processing, market knowledge and farming practice are distributed across multiple organisations and actors. This creates opportunities for integrated system development, but simultaneously increases coordination requirements.

Although these institutional configurations are not directly comparable, they point to a common requirement: NBS implementation benefits from organisations and networks capable of connecting scientific evidence with farming practice and, where necessary, policy, infrastructure and markets. Institutional continuity is particularly important where benefits develop slowly or implementation requires sustained coordination across actors.

4.2.3 Barriers and enabling factors

A particularly strong cross-country finding is that the main constraints to wider uptake are not exclusively, and in some cases not primarily, technical. Once technical implementation becomes possible, economic uncertainty, regulatory conditions, advisory capacity, markets, coordination requirements and confidence in expected benefits become increasingly important.

Economic uncertainty was particularly evident in Hungary and the UK, where willingness to adopt unfamiliar practices was closely related to confidence in their implications for farm profitability. Similar concerns are relevant in the Netherlands, where plant-based nutrient management may reduce dependence on external inputs but can introduce additional land, labour and management requirements and potential yield penalties under some conditions.

Regulatory and coordination barriers were more explicit in the Netherlands and Denmark. Dutch nutrient regulations remain largely oriented towards conventional manure management and may not fully accommodate plant-based nutrient cycles. In Denmark, the wider system configuration introduces additional challenges related to institutional responsibilities, product approval, policy uncertainty, compensation mechanisms and coordination across the biomass value chain.

Against these barriers, a relatively consistent set of enabling conditions emerged: long-term scientific evidence, practical demonstration, farmer–researcher collaboration, trusted intermediaries, advisory support and repeated stakeholder interaction. The relative importance of each factor differs between cases, but together they demonstrate that successful implementation depends on an enabling environment surrounding the technical NBS.

Overall, the cross-country evidence suggests that demonstrating technical feasibility is necessary but insufficient for wider uptake. Farmers and other actors must also have sufficient evidence, confidence, knowledge, institutional support and economic or regulatory incentives to implement the proposed changes.

4.3 Economic and practical feasibility

4.3.1 Economic considerations and evidence gaps

Economic feasibility was not systematically assessed across the cases, and no comparable cost-benefit analysis was undertaken. Nevertheless, implementation of the NBS highlighted several factors that may influence their economic and practical feasibility. These observations should therefore be interpreted as implementation considerations rather than as evidence of economic performance.

In the Netherlands, plant-based fertilisation can reduce dependence on external nutrient inputs, while requiring land and resources for biomass production, cultivation, harvesting, transport and application. Lower yields observed under fully plant-based fertilisation may also be relevant to economic performance. However, these factors were not assessed through a dedicated economic analysis, and their overall effect on costs and benefits cannot be determined from the available evidence.

In the UK, reduced tillage was associated with lower yields in some cases, alongside lower diesel use. These observations indicate potential economic trade-offs, but their net economic effect was not quantified. Similarly, in Hungary, reduced use of external inputs represents a potential source of cost savings, but no dedicated economic assessment was undertaken to determine whether these savings offset other requirements associated with NBS implementation.

In Denmark, the regional value-chain approach identifies a broader set of factors that could affect economic feasibility, including land use, harvesting, transport, processing, storage and the valorisation of side streams. The distribution of costs and benefits among actors may also influence implementation. These factors provide relevant considerations for future assessment but should not be interpreted as results of a cost-benefit analysis.

Overall, the cases identify several factors that would need to be considered in a comprehensive economic assessment, including input requirements, yields, land use, machinery, logistics, infrastructure and transition costs. The available evidence does not, however, support conclusions on the overall economic viability or relative cost-effectiveness of the NBS. Further economic assessment would be required to evaluate these aspects and their implications for wider adoption.

4.3.2 Scalability constraints

Technical feasibility at experimental or demonstration scale did not translate automatically into straightforward scalability in any of the cases. Although the specific constraints differed, wider implementation consistently required adaptation to local conditions and consideration of resource availability, management capacity, infrastructure or markets.

For the Netherlands and Hungary, adaptation is primarily required at farm and field level. Dutch plant-based fertilisation depends on crop rotations, biomass availability, land

requirements and farm-specific nutrient management and therefore needs to be considered within the complete farm business model. Hungarian experience similarly shows that soil heterogeneity, water availability, crop rotation and management conditions limit the value of simply replicating an experimental NBS package across farms.

In the UK, scalability is additionally constrained by access to organic amendments and by limited markets for diversification crops such as lucerne. In Denmark, scaling requires coordination across the biomass value chain: processors require sufficient and predictable biomass supplies before investing, while farmers require credible contracts and outlets before changing land use or crop rotations. Transport distances and processing requirements further influence the feasible geographic scale.

Although these constraints differ, they lead to an important common principle: scaling should focus on transferring and adapting NBS principles rather than reproducing experimental systems unchanged. Demonstration under commercially relevant conditions, advisory support, monitoring and evidence of agronomic and economic performance can support this adaptation. More complex NBS additionally require coordinated development of infrastructure, markets and value-chain relationships.

4.3.3 Dependency on external support

All four cases currently rely to some extent on scientific, advisory, institutional, policy or financial support. However, the type of support required reflects both the maturity and complexity of the respective NBS.

Long-term research and monitoring are particularly important where soil and system responses emerge over timescales exceeding standard project cycles, as illustrated by the Netherlands and the UK. In Hungary, advisory expertise, monitoring tools and peer learning can help farmers interpret results and reduce uncertainty. The Danish system requires a broader combination of research and demonstration funding, investment, advisory capacity, regulatory approval, stable policy signals, data and mechanisms for managing risks across multiple actors.

Policy support also differs according to national context and NBS type. The UK Sustainable Farming Incentive provides opportunities to support practices such as reduced soil disturbance and increased soil organic matter. Dutch implementation could benefit from regulatory frameworks that better recognise plant-based nutrient management, while Danish implementation may require mechanisms capable of recognising collective water-quality and other environmental benefits that are not fully captured through private market returns.

Despite these differences, external support appears particularly important during transition, when uncertainty and investment risks remain high and longer-term benefits may not yet be economically rewarded. The longer-term challenge is therefore to move from project-supported experimentation towards NBS embedded in viable farm or value-chain models, supported by appropriate regulation, advisory structures and markets.

4.4 Key findings from the cross-country evaluation

The cross-country comparison, summarised in Table 3, shows that there is no single pathway towards more circular nutrient management. The NBS operate through different mechanisms and at different scales, and their performance is influenced by local biophysical, agronomic and operational conditions. Differences in experimental design, NBS configuration, implementation duration and monitoring approaches also affect the type of evidence generated and should be considered when interpreting differences between cases. An important consideration in the cross-case comparison is the different monitoring duration across cases, as long-term processes such as soil carbon dynamics and nutrient depletion cannot be assessed equivalently over short- and long-term experimental periods. The cases should therefore not be directly ranked, but assessed in relation to their objectives, system boundaries, evidence base and implementation contexts.

Across this diversity, several common conclusions emerge. Technical and environmental feasibility is currently better established than economic feasibility, while environmental improvements do not necessarily translate into immediate yield or economic benefits. Some NBS require longer transition periods before benefits in soil functioning, nutrient efficiency or resilience become visible. Scaling should therefore focus on adapting NBS principles to local conditions rather than replicating experimental systems unchanged.

Wider uptake also depends on more than technical performance. Economic viability, farmer confidence, advisory capacity, supportive regulation, institutional coordination and, where relevant, functioning markets and value chains all influence the potential for wider implementation. Overall, the Trans4num cases indicate that the key question is not which NBS "works best", but under which environmental, agronomic, economic and institutional conditions different NBS can contribute to circular nutrient management and be sustained at a wider scale. These findings provide the basis for the transdisciplinary and transformation analysis developed in Section 5.

Table 3. Summary of key findings from the cross-country evaluation of the Trans4num NBS cases

Dimension	Denmark	Hungary	Netherlands	UK
Main nutrient-circularity pathway	Perennial biomass, biorefining and cascading nutrient use	Integrated soil and nutrient-management NBS	Plant-based fertilisation and local biomass recycling	Reduced tillage and organic amendments
Key technical/ environmental finding	Potential regional integration of biomass and nutrient flows	Positive soil-health and nutrient-cycling trends while maintaining crop nutrition	Long-term evidence of soil functioning under reduced external inputs	Long-term improvements in soil carbon and aggregate stability
Main technical constraint	Biomass logistics, processing and side-stream utilisation	Soil heterogeneity and crop/year-dependent performance	Nutrient-release timing, yield response and environmental variability	Transition-period yield effects and soil-dependent responses

Dimension	Denmark	Hungary	Netherlands	UK
Key social/ governance consideration	Coordination, regulation and risk distribution across the value chain	Farmer confidence and economic uncertainty	Regulatory fit and advisory capacity	Confidence in medium- to long-term cost-benefit
Main scalability constraint	Biomass–processor coordination and facility location	Site-specific adaptation and advisory needs	Land and biomass requirements, farm-business integration and site-specific adaptation	Organic amendment availability and markets for diversification crops
Key enabling factor	Strong knowledge base, intermediaries and emerging policy opportunities	Trusted local intermediaries and practical demonstrations	Long-term platform and farmer–researcher collaboration	Long-term experimental infrastructure
Long-term support need	Markets, investment, regulation and risk-sharing	Advice, monitoring and peer learning	Evidence, advisory support and enabling policy	Economic evidence, decision support and transitional policy support

5. Transdisciplinary and transformation insights

5.1 Co-creation and stakeholder processes

To ensure that NBS are both scientifically sound and practical for real-world farming systems, transdisciplinary co-creation was embedded across all case studies. Here, stakeholder involvement refers to direct participation in field trials and events, while stakeholder engagement covers broader, ongoing processes like co-designing tools and strategic dialogue. By connecting researchers, farmers, agricultural advisors, and municipal actors, this collaborative approach grounded technical evaluation in real-world agricultural conditions across four European countries: Denmark, Hungary, the Netherlands, and the United Kingdom. The following sub-sections summarize how co-creation influenced decision-making and trial design across three core operational pillars (Table 3).

5.1.1 Nutrient recovery and cycling outcomes

Denmark (DK): The co-creation process expanded the scope of innovation beyond isolated technological questions (such as protein production from grass) toward a holistic regional framework. Stakeholders collaboratively evaluated how biomass, protein, organic residues, biogas, and closed fertiliser loops operate at a regional scale. Practical input from farmers and commercial firms highlighted critical operational variables including logistics timing, transport distances, contractual agreements, and product quality standards. Research and spatial planning frameworks then linked these practical considerations to landscape-targeted nitrogen management.

Hungary (HU): Co-creation was realized through close interaction between research partners, the farming partner, and local stakeholders. The field experiment provided a shared learning platform to evaluate nutrient cycling, soil health, crop performance, and field heterogeneity. Practical stakeholder discussions focused on concrete, site-specific nutrient management solutions, including cover crops, bio-based inputs, and drought-tolerant crop varieties to support sustainable nutrient cycling.

Netherlands (NL): Continuous interaction among researchers (WU), field-experiment specialists (SPNA), and farmers supported the development of plant-based nutrient strategies. This collaborative feedback loop addressed core commercial arable challenges, notably the escalating cost and reduced availability of organic livestock manure, the mandate to reduce synthetic fertiliser inputs, and the necessity of maintaining soil fertility in intensive seed-potato rotations. By combining local agronomic experience with scientific monitoring, the partnership evaluated regional biomass streams, such as grass-clover, lucerne, cover crops, green manure, and compost, as viable circular nutrient sources.

United Kingdom (UK): Stakeholder dialogues revealed a recognized gap in empirical evidence and practitioner confidence regarding the specific nutrient-emission reduction benefits of NBS and regenerative agriculture. Nonetheless, a strong multi-stakeholder consensus exists that diversified crop rotations, reduced tillage, and organic soil amendments effectively lower synthetic fertiliser dependency while delivering broader environmental benefits.

5.1.2 System efficiency and functionality

Denmark (DK): Operational robustness was demonstrated by co-designing spatial tools with local stakeholders, showing that flexible scenario testing makes digital tools practically useful for planners and farmers. Key operational lessons included establishing early data-sharing protocols, separating empirical observations from qualitative feedback, and allowing sufficient time for participatory scenario definition before finalizing technical models.

Hungary (HU): Co-creation helped translate technical monitoring outputs into practice-oriented knowledge for system evaluation. Roundtable discussions, field visits, and soil profile demonstrations enabled farmers, advisors, and researchers to connect environmental performance with everyday management questions. Evaluating soil health, nutrient dynamics, and crop performance together allowed stakeholders to assess the practical functionality and overall applicability of NBS under local field conditions.

Netherlands (NL): Co-creation directly drove the iterative adaptation of experimental field designs and nutrient application treatments over time. Trial protocols were systematically adjusted in response to multi-season field observations, analytical results, and direct farmer feedback. This flexible setup was essential, as plant-based nutrient sources differ significantly from mineral fertilisers in nutrient concentration, mineralisation rates, application windows, and operational handling. Furthermore, joint field evaluations (including demonstration days) broadened the assessment beyond isolated indicators, enabling actors to interpret stable soil properties under reduced-input regimes as positive functional outcomes even when short-term yield parity was not achieved in every crop cycle.

United Kingdom (UK): An ongoing tripartite dialogue among farmers, policymakers, and researchers focuses on how NBS impacts overall farm functionality and efficiency. While compelling individual case studies exist, stakeholder confidence in scaling best practices remains constrained by the strong dependency of NBS performance on localized environmental contexts. Long-Term Research Experiments (LSRE) are currently being leveraged to generate the location-specific evidence required to determine 'what works where '.

5.1.3 Operational applicability and reliability

Denmark (DK): The national engagement framework followed an iterative cycle: investigate, analyze, influence/connect, observe system responses, and re-initiate. While this flexibility enabled the project team to capitalize on emerging contacts and policy windows, it made systematic documentation highly resource-intensive. Key methodological lessons highlight the necessity of establishing a minimum data-collection protocol from the outset, logging activities immediately as they occur, strictly distinguishing empirical observation from qualitative interpretation, and securing formal consent and data governance agreements early. Furthermore, participatory scenario definition requires dedicated allocation of time prior to finalizing technical modelling scripts.

Hungary (HU): Stakeholder engagement proved most effective when linked to visible, field-based evidence. Demonstrating practices such as reduced/no-tillage, soil profile observations, and crop responses directly in the field built practitioner trust and demonstrated operational feasibility. The peer-to-peer exchange format allowed farmers to reflect on practical operational limitations, risks, and real-world implementation constraints under local climate and soil conditions.

Netherlands (NL): Experience confirmed that operational robustness relies heavily on an agricultural system's adaptive capacity in response to adverse weather, pest pressure, variable crop development, and resource constraints. Regular exchanges between WU, SPNA, and participating farmers helped distinguish structural limitations inherent to NBS practices from transient seasonal anomalies. However, trials also revealed vulnerabilities to field-level operational disruptions, particularly spatial soil heterogeneity. Future transdisciplinary experiments require clearer coordination protocols, shared sampling schedules, and early formalization of operational responsibilities.

United Kingdom (UK): Findings from the LSRE underscored the critical importance of identifying unintended side effects when implementing NBS for input efficiency and circular nutrient cycling. For instance, while reduced-tillage plots demonstrated enhanced nutrient-use efficiency, they also experienced higher weed pressure, necessitating increased herbicide application. To foster sustained adoption and safeguard operational robustness, stakeholder communications must adopt a comprehensive whole-system approach rather than presenting isolated single-intervention or single-outcome narratives.

Table 4 provides a comparative overview of the stakeholder networks, co-creation mechanisms and main outputs across the four country case studies, highlighting the different approaches used to support stakeholder engagement and knowledge exchange.

Table 4. Comparative analysis of co-drivers and mechanisms across case studies

Country	Primary Stakeholder Networks	Core Focus & Mechanisms	Primary Co-Creation Deliverable
Denmark (DK)	Farmers, and advisors; Value-chain firms; Climate Foundation Skive; Researchers; Municipalities and national authorities.	Regional system modeling, closed nutrient loops, landscape targeting	Decision Support Tool (DST) as a multi-actor boundary object
Hungary (HU)	Research institutes and research partners; Farmers and farming partner; Agricultural advisor; Local agricultural associations.	Soil profile demonstrations, field visits, peer-to-peer roundtables	Shared learning platforms for field-based NBS evidence
Netherlands (NL)	Farmers and farmer-based organisation; Research institute; Public authorities and governmental actor; Private-sector actors.	Iterative trial adaptations, organic amendment integration, soil health monitoring	Adaptive field-management regimes for plant-based nutrients
United Kingdom (UK)	Private-sector actors; Research institutes and researchers; Farmers; Public authorities and NGOs.	Evidence-building on NBS efficiency, systemic trade-off evaluation	Long-Term Research Experiments (LSRE) data for local contexts

5.2 Knowledge integration

Knowledge integration across transdisciplinary boundaries is essential to bridge scientific validation, practical farming feasibility, and policy development. Within the Trans4num framework, knowledge integration was structured around three core themes across the four national case studies.

5.2.1 Stakeholder engagement outcomes

Denmark (DK): The Danish engagement process generated three main knowledge-integration outcomes: it broadened the case from a primarily technical green-protein innovation to a regional value-chain challenge; it identified logistics, side-stream valorization, regulatory fit, market development and risk-sharing as interdependent bottlenecks; and it helped refine the DST as a shared scenario and dialogue tool rather than a prescriptive farm-level optimization tool. These are process and knowledge-integration outcomes and should not be interpreted as evidence of commercial adoption or large-scale implementation.

Hungary (HU): Multi-actor engagement improved local capacity for data-driven farm decisions by translating complex scientific monitoring (soil properties, emissions, remote sensing) into actionable management knowledge. Interactive field visits and soil profile demonstrations (Figure 4) increased farmer trust in NBS performance and facilitated direct adjustments to site-specific crop rotations and bio-based input strategies.



Figure 4. Soil profile demonstration at the Hungarian NBS site, illustrating the role of field-based learning in translating NBS-related knowledge into practice.

Netherlands (NL): Embedding activities within SPNA's regional extension program built long-term institutional trust and expanded regional awareness of plant-based circular nutrient management. Reaching over 35 participants per session across fourteen structured meetings strengthened the local learning network, connecting growers, agricultural students, and regional authorities around sustainable fertilization alternatives.

United Kingdom (UK): Leveraging the LSRE platform stimulated multi-stakeholder consensus on systemic transitions and the need for standardized NBS monitoring. Structured dialogues among farmers, agronomists, and policy actors enhanced practitioner confidence regarding trade-offs in soil carbon, cover cropping, and reduced-tillage management.

5.2.2 Institutional arrangements

Denmark (DK): Climate Foundation Skive played a pivotal intermediary boundary role, connecting municipal, national, research (Aarhus University), industry, and farming actors. While Aarhus University provided analytical framing and modeling, operational knowledge was contributed by local firms, advisors, and authorities. Process documentation (such as stakeholder registers) highlighted the necessity of managing process data under pseudonymised working protocols and clear legal/governance frameworks.

Hungary (HU): Integration relied on a three-tier institutional structure; Széchenyi István University provided scientific monitoring capacity; Pannon-Mag-Agrár Ltd. supplied practical agricultural infrastructure and operational testing; and the Pisztráng Kör Association facilitated local stakeholder engagement and community outreach. This formal division of responsibilities bridged academic research and local farming networks.

Netherlands (NL): The core partnership between Wageningen University & Research (WU) and SPNA integrated scientific analytical expertise (soil, crop, and microbial dynamics) with practical field trial management and regional grower networks. A major strength was leveraging the long-term Planty Organic experimental platform (established in 2012), which provided an established foundation that extended beyond typical project timeframes. However, private-sector, supply-chain, and policy actor involvement remained secondary, indicating a key focus area for future market scaling.

United Kingdom (UK): The LSRE capitalized on the established research infrastructure of Rothamsted Research farms and its multidisciplinary scientific team. The institutional reputation of Rothamsted provided high stakeholder confidence in the empirical data and evidence presented.

5.2.3 Barriers and enabling factors

Denmark (DK): Transformation remains dependent on policy stability, alignment of competitive conditions across value chains, product approvals, market development, and institutional capacity. The new discharge-based nitrogen regulation from 2027 increases the relevance of spatial decision-support tools for identifying where crop and land-use changes can contribute most effectively to nitrogen-reduction objectives. However, the regulation does not automatically resolve the commercial business case for green biorefineries.

Hungary (HU): The primary enabling factor was the use of visible, field-based evidence (such as live soil profile pits and local trial measurements). Conversely, the main barrier was the discrepancy between biological and decision-making timescales: soil processes evolve gradually over multi-year periods and are subject to seasonal weather anomalies, whereas growers require short-term economic clarity. Consequently, knowledge integration must be conducted as an ongoing collaborative learning process rather than a single data transfer.

Netherlands (NL): The central barrier was the temporal mismatch between scientific monitoring requirements (multi-year detection of soil changes) and farmer decision-making needs (immediate feedback on yields, economic margins, labor, and reliability). Translating complex multi-variable results (varying by soil depth, season, and sampling timing) into simple management guidelines also proved difficult. Key enabling factors were the multi-year history of the Planty Organic platform, complementary WU–SPNA capabilities, frequent interaction, and the involvement of trusted local advisors.

United Kingdom (UK): The primary barrier to widespread NBS adoption is the limited availability of localized, site-specific evidence regarding performance and economic risk. Overcoming this requires combining empirical field observations (from platforms like the LSRE) with predictive simulation modeling, delivering user-friendly decision-support tools that allow farmers to reduce synthetic inputs with confidence.

5.3 Contribution to nutrient system transformation

The transdisciplinary co-creation processes and knowledge integration mechanisms established across the four national case studies demonstrate that systemic nutrient transformation cannot be achieved merely through simple input substitution. Moving toward circular, nature-based, and plant-based nutrient management requires coordinated structural adaptations across economic, operational, spatial, and institutional dimensions (Table 4).

5.3.1 Cost considerations

Systemic transformation requires balancing immediate farm-level operational costs against long-term environmental benefits and system resilience.

Denmark (DK): Nutrient transformation is not achieved by replacing a single input or crop; it demands investment in an entirely new regional supply chain, coordinating land, logistics, processing, markets, and regulatory frameworks. At the farm level, financial viability depends on contractual stability, opportunity costs, and risk distribution. Societally, viability includes water quality, climate mitigation, and import-substitution benefits. Evaluating this transition requires multi-year farm economics and whole-system accounting, encompassing labor, land use, transport, processing, nutrient balances, and the valorization of public goods.

Hungary (HU): The transformation potential of NBS hinges on the balance between input savings, additional management overheads, and yield stability. Practices such as crop rotation, reduced soil disturbance, bio-based fertilization, cover crops, biostimulants, and continuous monitoring reduce reliance on synthetic inputs while safeguarding soil health and yield productivity. However, because adoption requires significant planning, management, and monitoring, growers require concrete evidence of economic feasibility and agronomic performance before transitioning.

Netherlands (NL): Plant-based fertilization and regional biomass recycling reduce exposure to livestock manure scarcity, imported nutrient dependencies, and volatile synthetic fertilizer prices. However, fully plant-based systems introduce financial trade-offs: they may require dedicated land for biomass production, as well as added labour and logistical costs for harvesting, storage, transport, and application. Lower short-term yields under certain plant-based regimes can reduce immediate economic appeal, necessitating improved nutrient-use efficiency and policy mechanisms that reward unpriced environmental externalities.

United Kingdom (UK): Adopting NBS strategies can offer significant long-term cost savings, but growers face increased investment costs during the initial transition period. This transition represents a necessary strategic investment as climate change, extreme weather events, and rising input costs render high-input farming systems increasingly unsustainable over time.

5.3.2 Scalability constraints

Translating experimental farming methods directly into commercial practice is limited by regional differences in infrastructure, soil quality, and local markets.

Denmark (DK): The primary scalable innovation is a flexible process and design logic rather than a rigid refinery blueprint. Scaling requires identifying where perennial biomass yields sufficient environmental value, establishing a viable supply radius, securing downstream market ecosystems, and offering fair risk-sharing contracts to growers. Achieving catchment-scale impacts requires coordination beyond individual farms, supported by locally parameterized Decision Support Tools (DST) and market competitiveness enabled by internalizing environmental externalities or targeted support schemes.

Hungary (HU): Scalability cannot be achieved through simple package replication. Local soil properties, field heterogeneity, water availability, crop selection, and farm management strongly dictate NBS performance. Scaling requires site-specific adaptation, active advisory support, locally relevant demonstrations, and continuous knowledge exchange to foster a gradual transition toward circularity.

Netherlands (NL): The multi-year Planty Organic trial demonstrated that nutrient-self-sufficient arable production is technically feasible, but commercial scaling requires adapting complex cut-and-carry systems to match real-world farm constraints in land, machinery, labor, and yield-risk tolerance. Scaling must focus on core transferable principles such as increasing legume and cover crop usage, recycling regional biomass, and combining plant-based and mineral sources where necessary. Follow-up programs like Agrifuture test these principles at a broader system scale, ensuring relevance and acceptance among a wider group of commercial growers.

United Kingdom (UK): Scaling NBS to landscape and regional scales relies heavily on facilitated knowledge exchange at the farm-cluster scale. Emerging UK mechanisms, such as Landscape Recovery schemes and river catchment plans, provide structured opportunities for this coordination. Long-Term Research Experiment (LSRE) datasets offer crucial empirical evidence for targeting site-specific NBS interventions across varying soil types to meet regional environmental targets.

5.3.3 Dependency on external support

Achieving lasting nutrient system transformation requires robust institutional backing, long-term funding, regulatory modernizations, and market alignment across supply chains.

Denmark (DK): Transformation remains dependent on policy stability, alignment of competitive conditions across value chains, product approvals, market development, and institutional capacity. The new discharge-based nitrogen regulation from 2027 increases the relevance of spatial decision-support tools for identifying where crop and land-use changes can contribute most effectively to nitrogen-reduction objectives. However, the regulation does not automatically resolve the commercial business case for green biorefineries.

Hungary (HU): Long-term scaling relies on sustained, multi-partner cooperation between research institutes, practical farming partners, agricultural advisors, and local intermediary organizations. Continuous technical justification, long-term monitoring, and dedicated advisory networks are vital building trust and supporting ongoing learning cycles.

Netherlands (NL): Transitioning away from external inputs requires ongoing institutional support. Based on the Dutch case experience, policy and advisory frameworks could better recognize plant-based nutrient flows to support circular farm management. Furthermore, long-term research funding is vital to capture multi-year soil health benefits, while market development is needed for plant-based fertilizer products. Embedding Trans4num knowledge into enduring programs like *Agrifuture* ensures that project outputs remain active within established regional learning networks.

United Kingdom (UK): Structural challenges hinder the widespread adoption of organic amendments in the UK due to a geographical polarization of nutrient availability. Livestock production is heavily concentrated in the Southwest (causing high phosphorus and nitrogen loads in local watercourses), while arable soils in the East suffer from organic matter depletion. Integrating livestock into arable rotations presents a key systemic solution, but requires dedicated infrastructure investment and farm business diversification.

Table 5 synthesises the main contributions of the four country case studies to nutrient system transformation, highlighting the economic and operational barriers identified and the institutional and policy mechanisms that could support longer-term adoption and scaling.

Table 5. Cross-country synthesis of transdisciplinary contributions to nutrient system transformation

Country	Primary Systemic Contribution	Key Economic & Operational Bottlenecks	Long-Term Scaling & Policy Mechanisms
Denmark (DK)	Regional biomass & green biorefinery loop integration; parameterized DST boundary tools.	Multi-year supply chain logistics; upfront capital investments; biorefinery commercial viability.	Internalization of environmental externalities; catchment-scale spatial planning; durable DST governance.
Hungary (HU)	Integrated field-based NBS (cover crops, reduced tillage, bio-fertilization) tailored to local soils.	Management overheads; operational risk; delay between biological soil recovery and economic return.	Tri-party institutional networks; peer-to-peer field demonstrations; site-specific advisory adaptation.
Netherlands (NL)	Circular, plant-based nutrient management replacing synthetic fertilizer and manure reliance.	Labor & transport costs of cut-and-carry biomass; dedicated land requirements; short-term yield risks.	Modernized fertilizer regulations recognizing plant-based inputs; embedding outputs into *Agrifuture*.
United Kingdom (UK)	Whole-system trade-off evaluation & evidence-based NBS targeting across soil types via LSRE.	Transition-period investment costs; geographic polarization of livestock (West) and arable lands (East).	Landscape Recovery schemes; river catchment farm clusters; infrastructure investment for mixed farming.

5.4 Cross-case lessons for broader system transformation

Taken together, the case studies show that the contribution of NBS to broader system transformation extends beyond the environmental or agronomic performance of individual interventions. Transformation emerges when NBS become embedded in wider processes of co-creation, knowledge integration, institutional adaptation, and changes in the economic and operational conditions shaping agricultural decision-making. NBS can therefore act not only as alternatives to conventional practices or inputs, but also as entry points for reconfiguring relationships between farming practices, actors, knowledge systems, nutrient flows and supporting institutions.

Across the cases, transformation was iterative and context-dependent rather than based on straightforward replication. Co-creation supported adaptation to local constraints and stakeholder needs, while long-term experiments, field demonstrations and intermediary organisations helped connect scientific evidence with practical knowledge. The experiences therefore suggest that scaling should focus on transferring adaptable principles and strengthening the capacity for continued learning and adjustment, rather than reproducing fixed NBS configurations across different farming contexts.

The cases also demonstrate that farm-level change alone is insufficient. Wider transformation depends on enabling conditions beyond the farm, including viable supply chains and markets, supportive regulation, advisory capacity, long-term research and monitoring, appropriate infrastructure, and mechanisms for managing transition costs and risks. Overall, the transformative potential of NBS lies not only in the outcomes of individual interventions, but also in their capacity to mobilise coordinated changes across technical, social, economic and institutional dimensions.

6. Conclusions and next steps

The Trans4num NBS cases demonstrate that more circular nutrient management can be pursued through multiple pathways, ranging from plant-based fertilisation, recycled nutrients and integrated soil management to diversified cropping systems and regional biomass value chains. Across the field-based cases,, the project provides evidence that external nutrient inputs can, under specific conditions, be reduced while maintaining or improving important aspects of soil functioning and crop production. The Danish case provides a complementary system-level pathway, demonstrating how perennial biomass, green biorefining, spatial decision support and multi-actor coordination can be combined in a regional transition strategy, while large-scale nutrient, economic and life-cycle effects remain to be demonstrated.

However, performance was strongly influenced by soil conditions, crop type, climate, management, implementation timescale and, for more complex systems, logistics and market conditions. The cases should therefore not be interpreted as directly comparable alternatives, but as complementary examples of how circular nutrient management can be developed under different agricultural and institutional contexts. A central lesson from the project is that

successful NBS implementation requires a whole-system perspective. Technical feasibility alone is insufficient: adoption also depends on agronomic reliability, economic viability, farmer confidence, advisory capacity, institutional coordination, supportive regulation and, where relevant, functioning markets and value chains. Transdisciplinary processes were therefore essential for connecting scientific evidence with practical farming knowledge and implementation realities. Long-term experimental platforms, field demonstrations, trusted intermediary organisations and decision-support approaches provided important mechanisms for building confidence, identifying trade-offs and adapting NBS to local conditions.

The findings also indicate that scaling should focus on transferable principles rather than replication of individual experimental configurations. NBS need to be adapted to local soils, farming systems, resource availability, infrastructure and market conditions, while recognising that environmental benefits and improvements in soil functioning may emerge over longer timescales than short-term agronomic or economic costs. Further evidence is particularly needed on multi-year nutrient balances and soil stocks, yield stability, whole-system costs, labour and land requirements, and the distribution of risks and benefits. Strengthening this evidence base will be important for distinguishing genuine improvements in nutrient-use efficiency from potential nutrient depletion and for developing credible long-term business cases for farmers.

Beyond the project lifetime, continued progress will depend on maintaining the research, advisory and stakeholder networks established through Trans4num and embedding the knowledge generated into longer-term experimental, demonstration and policy processes. Follow-up initiatives such as Agrifuture in the Netherlands, the continued use of the Rothamsted LSRE in the UK, and ongoing development of regional planning and decision-support approaches in Denmark provide opportunities to extend this work. For practice, farmers and advisors should prioritise locally adapted combinations of NBS, supported by long-term monitoring, commercially relevant demonstration and whole-farm assessment of agronomic, economic and environmental trade-offs. For policy, enabling frameworks should recognise circular and plant-based nutrient flows, reward environmental benefits that are not fully reflected in market prices, provide stability during transition periods and support advisory, demonstration and coordination structures. Scaling beyond the project should build on these locally adapted approaches and established networks rather than seeking uniform replication of individual NBS. Overall, Trans4num shows that NBS can contribute meaningfully to more circular and resilient European agricultural systems, but their wider transformation potential will depend on aligning biophysical performance, farm-level feasibility, knowledge and advisory systems, markets and enabling institutions over the long term.