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Nature-Based Solutions as Building Blocks for the Transition towards Sustainable Climate-Resilient Food Systems

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Abstract: Food systems—encompassing food production, transportation, processing and consumption, including food losses and waste—are currently not delivering what is expected or needed to ensure their full contribution to societal well-being and ecological sustainability. In this paper, we hypothesize that nature-based solutions (NBS; solutions that are inspired by, supported by, or copied from nature) can overcome system challenges related to the functioning of the biosphere, society, or economy (including governance arrangements), and support a transition to sustainable climate-resilient food systems. We develop a conceptual framework to assess NBS contributions to such transitions. Three types of NBS are evaluated: *intrinsic* NBS which make use of existing ecosystems; *hybrid* NBS which manage and adapt ecosystems; and *inspired* NBS which consist of newly constructed ecosystems. We show that inspired NBS in particular will increase opportunities to achieve sustainable development in food systems. NBS can facilitate the much-needed transition to a different way of using our natural resources to reach the SDGs by 2030. We identify the knowledge gaps that impede the development of NBS to support a transition towards sustainable, climate-resilient food systems.

Keywords: food system transformation; climate change adaptation; ecosystem services; circular food systems

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1. Introduction

Food systems—encompassing food production, transportation, processing, and consumption, including food losses and waste—are facing challenges that threaten their ability to feed the population, deliver a healthy diet, sustainably maintain the environment, and produce equal and equitable benefits [1]. New transition pathways need to be developed that address one or more of these food systems challenges and transform how food is produced, processed, transported, and consumed.

Climate change will add further stresses on food systems that already need to respond to current and future trends of increasing population, changes in diet, and urbanisation. The increase in frequency and severity of extreme weather events such as floods, storms and droughts will impact all aspects of food security [2], including land degradation [3,4].

The Food and Agricultural Organisation of the United Nations [5] estimated that at least 26% of the costs of damage and loss from climate-related disasters were absorbed by the agricultural sector [5]. The increasing impacts of climate change are likely to threaten current food systems' resilience and will hamper their ability to adapt and shape their operations in response to change and buffer shocks. To address this threatening situation, researchers are studying how we can intentionally stimulate transformations in our food systems and increase their climate resilience [6,7].

Only recently, nature-based solutions (NBS—in this paper, we use the acronym NBS for nature-based solution (singular) and nature-based solutions (plural)), have been explicitly mentioned in relation to food security and particularly agriculture. NBS are solutions for environmental and societal challenges based on processes and functions of nature. The concept of NBS was introduced to promote nature as a source of inspiration [8] or as a means [9] to provide solutions to climate challenges. NBS are accepted in the water sector as measures to reduce disaster risk and improve water security [10–12]. Sonneveld et al. [13] highlighted the potential of NBS to positively contribute to food security under water-stressed conditions. Other studies looked at NBS addressing multiple societal issues such as biodiversity decline and sustainable development, in addition to issues of food security [14–16]. Design of NBS that address multiple challenges needs to consider the biophysical aspects, the socio-economic opportunities, and the limitations of a system [17]. While the role of NBS has been studied in the context of disaster risk management, water security, and landscape conservation, there is limited information on how NBS can contribute to sustainability of entire or parts of food systems [18].

In this paper, we propose that NBS can achieve sustainable food systems under a changing climate. We use the food systems framework [19] to demonstrate how NBS can provide building blocks for the transition towards climate-resilient and sustainable food systems. In earlier studies, frameworks have been used to assess the benefits of NBS for other goals, such as flood prevention [20] or landscape planning [21], often in the context of climate change adaptation. However, these studies have not looked at the benefits NBS can provide for food and nutrition security. In the next section, we first explain the concepts of NBS, followed by a definition of food systems and transformation pathways. Section three presents the conceptual framework that is used to analyse how NBS can contribute to transition pathways to food systems that can provide food and nutrition security and a healthy diet, maintain and restore natural resources, and produce equal and equitable benefits. The use of the food systems framework [19] is illustrated with examples to highlight supporting and hindering factors in the implementation of NBS. In Section four, we present the major knowledge gaps impeding implementation and scaling of NBS in food systems. Section five concludes the paper.

2. Definitions and Methodology

Before discussing the contributions of NBS towards more climate-resilient food and circular systems, there is a need to better understand (i) the underlying mechanisms of NBS and the ecosystem services they can deliver; and (ii) the opportunities and limitations for (implementation of) nature-based solutions in supporting food security and circularity under climate change conditions.

2.1. Defining Nature-Based Solutions

Although some practices that are now seen as NBS have been used for centuries, there is no consensus on the definition of the concept of NBS. Different descriptions are used by organisations and communities in diverse contexts [22]. Water engineers tend to describe NBS as sustainable engineering solutions such as sand nourishment underpinned by a 'building with nature' principle to reduce flood risks, coastal protection, and create opportunities for other sectors like recreation [23]. The IUCN and the European Commission have developed their own definitions of NBS that share the overall goal of addressing major societal challenges through the effective use of ecosystem processes and ecosystem services. The IUCN defines NBS as *"actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits"* [24]. The definition of the European Commission is somewhat broader and places more emphasis on applying cost-effective interventions that are *"inspired by, supported by, or copied from nature"* and *"simultaneously provide environmental, social, and economic benefits and help build resilience"* by bringing *"more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes"* [25]. This study follows the EC definition.

The NBS concept builds on and supports other closely related nature-based concepts, such as the ecosystem approach, ecosystem services, ecosystem-based adaptation/mitigation, green and blue infrastructure, and biomimicry [25]. Applying NBS to address food systems' challenges means going beyond considerations of productivity, trade, and socio-economic issues, and including biodiversity, climatic stresses, inclusiveness, and equity [26].

To better understand how NBS can address food security challenges under climate change conditions, we distinguish three major types of NBS (Figure 1).

1. *Intrinsic NBS* make better use of existing natural or protected ecosystems and processes with no or minimal human intervention involved. This type of NBS promotes better use of natural ecosystems for the delivery of multiple ecosystem services. Because of the minimal intervention in intrinsic NBS, the performance is highly dependent on uncontrollable factors.
2. *Hybrid NBS* are solutions related to managed ecosystems, for example (re-)establishing agro-forestry systems based on commercial tree species, grazing, and arable systems.
3. *Inspired NBS* involves the creation of new ecosystems or process technologies mimicking natural processes to provide sustainable solutions. Examples mimicking natural processes are a constructed wetland, the use of UV radiation for disinfection as an alternative for solar disinfection and bleaching, and the use of residual heat to purify water by thermal processes.

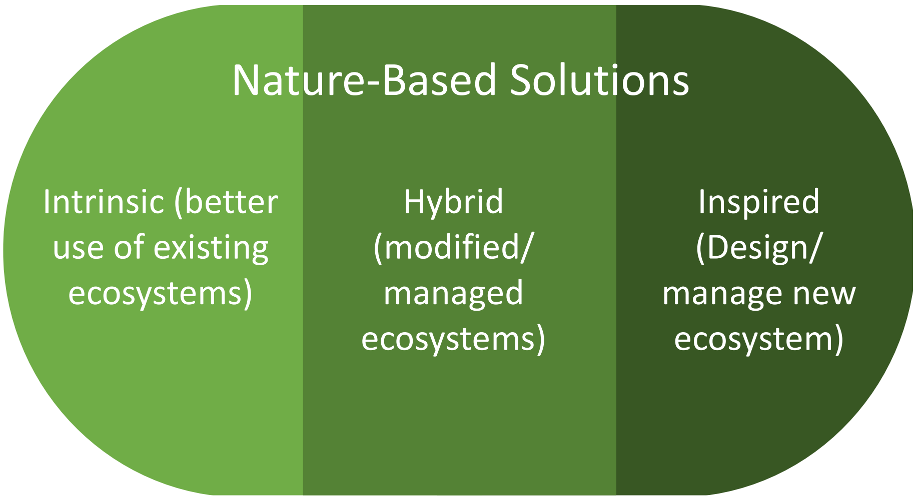

Figure 1. Typology for nature-based solutions: intrinsic, inspired and hybrid solutions.

This typology should not be considered a static representation of possible NBS interventions but as dynamic benchmarks for many hybrid NBS that exist along the gradients used. The three types of NBS are determined by site-specific natural, cultural, and socio-economic and institutional contexts, and draw on experiential and scientific knowledge. They can be implemented alone or integrated with other solutions for societal challenges, and are applied at different levels and scales.

2.2. Food Systems and Food System Transitions

Food systems reflect how societies are organised to produce and consume food, including social and environmental values and interactions [27]. In its simplest form, producers and consumers will be the same person or household [28]. Today's food systems are, however, often diverse and complex (Figure 2). In particular, markets and institutional networks to govern food systems for health, livelihoods, and the environment are complex [29]. The food systems' framework presented in Figure 2 encompasses [30,31]:

1. Drivers including:
    a. socioeconomic drivers such as urbanization, technological change, climate change, and economic growth that lead to a change in food production and consumption patterns, and
    b. environmental drivers, such as climate, biodiversity, freshwater availability and quality, natural reserves etc.;
2. Activities such as input supply, food production, transport, retail, and consumption;
3. Livelihood outcomes such as food security, including safe and healthy diets, and sustainable and equitable food supply.

A systems approach to food systems maps activities, drivers, and outcomes, and how they are linked. This helps us to understand how specific interventions or actions might affect other parts of the system. Using a systems approach can help to identify solutions in other parts of the system, sometimes far from the area where the problems are manifested [32]. Moreover, the food systems' framework clearly demonstrates the links between food system outcomes and non-food related Sustainable Development Goals (SDGs), see Figure 2. The SDGs provide an international set of targets for future food systems. Food system targets of inclusiveness and equal benefits are linked to SDG 8 (decent work), SDG 9 (industry, innovation and infrastructure), SDG 10 (reduced inequality), and SDG 12 (responsible consumption and production). The key targets of food security and safe and healthy diets are linked to SDG 2 (zero hunger), SDG 3 (health), and SDG 6 (clean water). Finally, sustainable and resilient food systems (lower right in Figure 2) are connected to SDG 6 (clean water), SDG 13 (climate), SDG 14 (life in water), and SDG 15 (life on land).

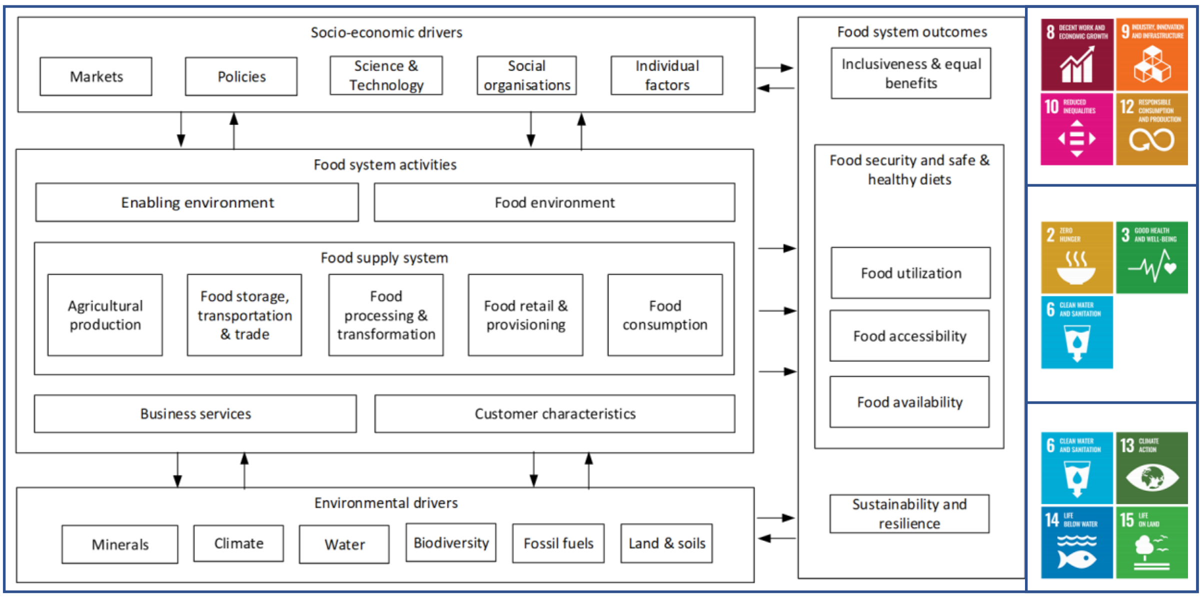

Figure 2. Food systems framework [19] and the link with the Sustainable Development Goals.

Climate change is one of the *drivers* shaping the performance and outcome of food systems. Climate change impacts such as prolonged droughts, unreliable rainfall patterns, and floods have made the development of resilient food systems a top goal on development agendas. A climate-resilient food system anticipates and acts on external shocks [1] and retains essentially the same function, structure, identity, and feedbacks [33]. The list of attributes that are considered to promote resilience of food systems under climate change conditions is rapidly growing and includes increasing absorbing buffer capacities (resources), reactive flexibility, restorative capacity, disturbance exposure, learning capacity, robustness, redundancy, response diversity, autonomy, and independence, being modular (not over-or under-connected), being able to respond quickly to shocks and changes in the system, and being ready to transform if necessary [34–36].

Providing nutritious and affordable and healthy diets for all are the desired key functions or *outcomes* of the food system. There is a constant need to have physical and economic access to sufficient amounts of safe and nutritious food to meet global dietary needs and food preferences for an active and healthy life [10,37]. Currently, food systems are challenged to produce higher quantities to nourish the growing world population [1]. In addition, the produced food may have a low nutritional quality with serious implications for human health [38–40]. Affordable and nutritious diets for good health are, however, not always the only or even the most dominant outcome. Depending on political and societal priorities, other desired outcomes can be defined. Therefore, food production might be inadequate because production is focused on calories rather than micro-nutrients (too many calories, too little micro-nutrients). Nutrition may be inadequately distributed due to affordability and accessibility issues.

Food systems' activities also generate *socio-economic outcomes* such as jobs and incomes. Gaitán-Cremaschi et al. [41] highlighted the need for addressing food systems' diversity to produce equal and equitable benefits. Present food systems increasingly show inequality and inequity not only in relation to food access, but also in relation to the economic and social inequalities and inequities due to, for example, gender issues, land tenure systems, food processing multinationals and market power over activities (e.g., increasing control of the agro-chemical or seed sectors—[42]). Food systems have environmental outcomes; they are sometimes positive, but predominantly negative. Most human activities related to food systems such as consumption, production, processing, and retail will impact the environment through food waste, misuse of agrochemicals, deforestation, soil degradation, depletion of freshwater, reduction in biodiversity, and greenhouse gas emissions.

Different pathways to support a transition to climate resilient food systems have been proposed, including a need for dietary changes, climate smart agriculture, circular agriculture, and regenerative agriculture, among others [1,43,44]. However, a food systems transition will require a reconfiguration of the system [45], including alternative possible trajectories for knowledge, interventions, and change, which prioritize different goals, values, and functions ('transition pathway') [46].The literature shows that transition pathways do not follow a linear and predictable pathway, but are unpredictable and complex processes in which diverse societal forces come together [47–50]. Transition pathways typically follow several phases (green curve in Figure 3). First, new sustainable strategies are developed in an 'experimental phase', followed by 'acceleration' and 'emergence' [47], Figure 3). The 'experimental' phase is characterised by niche innovations: new approaches that challenge dominant patterns and paradigms. In the 'acceleration' phase, the new approach is picked up by a larger part of the market or society, but remains a niche approach. In the 'emergence' phase, the approach takes off and new connections are made, but, perhaps due to lock-ins at individual, institutional, or external levels, implementation can be impeded e.g., [51]. To make the next step to the upper part of the green curve in Figure 3, enabling conditions at all levels are needed to allow the new strategy to scale up to become the new normal by institutionalizing and finally stabilizing the new approaches.

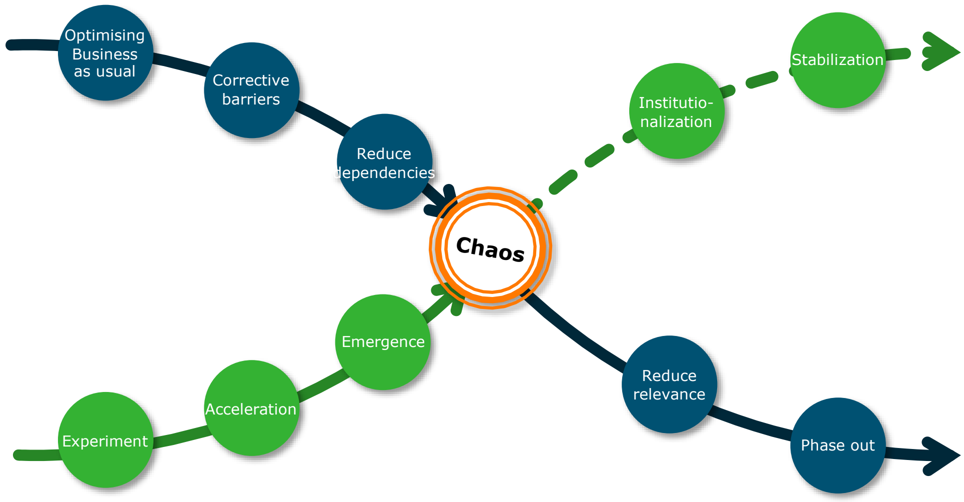

Figure 3. The X-curve transition cross (source [47,52]).

However, promoting only the transition process (green curve in Figure 3) is not enough. The new sustainable management strategies need to replace the old ones in most cases, and therefore it is important to pay attention to the phasing out of old, unsustainable strategies (blue curve in Figure 3). Dominant shared ways of thinking and acting that go largely unquestioned can potentially hinder the emergence and growth of alternative approaches. In a reaction to societal challenges, attempts may be made to optimize the business-as-usual system, to correct current approaches to make them less damaging to the environment, or to reduce social and economic dependencies of people working with the old systems [34,53]. These barriers and dependencies can often be for economic reasons but can also stem from the lack of awareness of the damages that unsustainable management is causing [54], or a lack in social acceptance or perception of a new production system [55].

The transition towards a new sustainable food system is not as linear or smooth as the two curves suggest; examples are present everywhere in the curve at the same time, and the actual transition may be chaotic. In this paper, we argue that nature-based solutions (NBS) can be a successful component in a variety of transition pathways supporting a wider food systems transition process.

2.3. Research Methods and Approach

Different types of NBS can be used to support the transition needed to address food system failures and reach the SDGs. We illustrate the potential contributions of NBS to improved food system outcomes (Figure 2) with three case studies of NBS, representing intrinsic, hybrid, and inspired NBS. Using the conceptual framework presented in Figure 4, we evaluate the potential of NBS to support a transition towards more climate-resilient food systems. The three case studies used in this paper originate from a project running at Wageningen Research (see acknowledgements) that focuses on NBS in food systems. The project used a mixed methods approach including in-depth literature research and dialogue with experts. Workshops held during the project were attended by a broad scope of experts from different backgrounds, including economics, social science, animal science, and environmental science. In addition, the project worked with policy makers, farmers, farmer organisations, and water boards to consider NBS as possible building blocks for their implementation plans to transition to a sustainable climate-resilient food system. We developed a framework that integrates food systems' outcomes and different NBS to explore their potential in achieving desired food systems' goals. Based on the workshop's outcomes, a set of specific NBS were chosen to be studied in the field. From these field sites, three examples were selected to showcase different types of NBS: an intrinsic, inspired, and hybrid one; in combination with the food system elements we wanted to address: For each of the three different types of NBS, we discuss the following four aspects:

(i) what food system failures are addressed (inclusiveness and equality, food security, and sustainability and resilience), (ii) what sort of NBS is used in the transition (intrinsic, inspired, hybrid), (iii) what the multiple benefits for the system are (and links to SDGs), and (iv) in what phase of the transition process we are, and what the enablers and challenges to (further) NBS implementation are. For each example, the impact of the NBS within the food systems framework was determined to be a direct positive effect; an indirect positive effect (as a consequence of implementing the NBS); an ambiguous or negative effect; or no (known) effect. These impacts were qualitatively assessed during workshop session within the project.

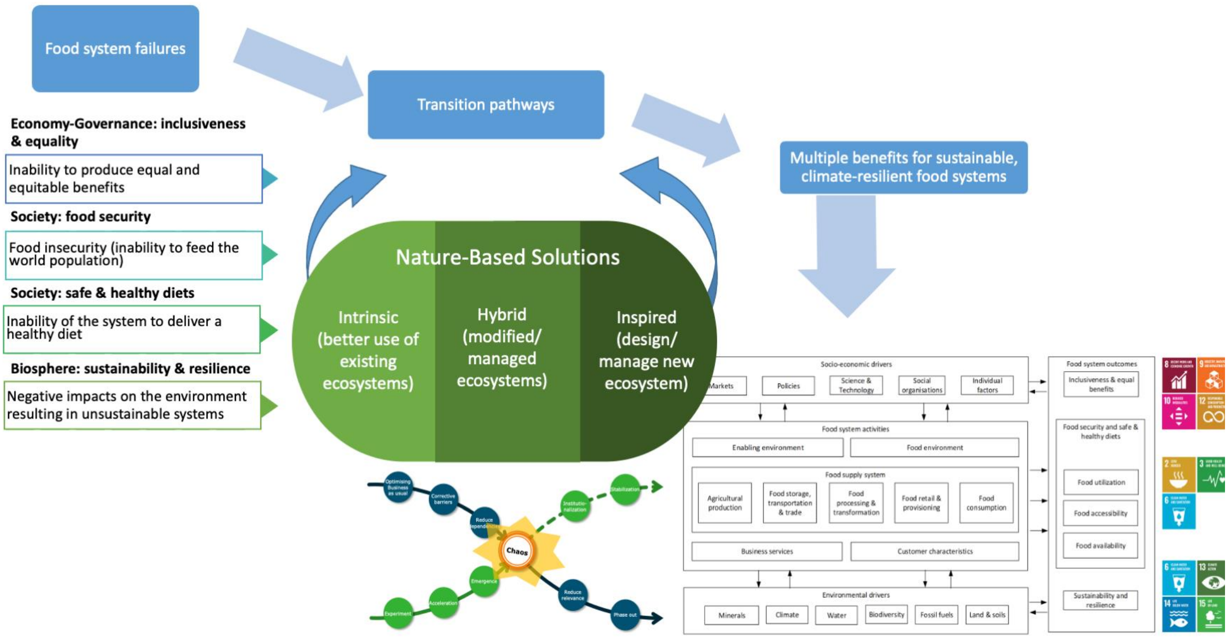

Figure 4. Assessment framework to evaluate the potential of nature-based solutions for supporting the transition of food system (elements) to become more climate resilient and circular.

The limitations of our methodology relate to the fact that the framework we developed was only explored with the examples to assess the potential of the framework. This has shown the links between food systems and NBS, but solid testing of the framework on case studies has not been done. The framework has the potential to be used as a guiding principle to design and/or select the most suitable NBS. Furthermore, the framework could be developed into a monitoring and evaluation tool. Future research will need to test the framework using data-rich case studies, where the benefits of NBS for mitigating food system failures can be measured.

3. Conceptual Framework: How Nature-Based Solutions Build Climate-Resilient Circular Food Systems

In the three examples in this section, we illustrate our framework by describing how different types of NBS (intrinsic/hybrid/inspired) can help to make the transition towards climate-resilient and circular food systems.

In the first example, we present how an intrinsic NBS can help to create a more climate-resilient agricultural system by using rainwater harvesting techniques. The second example shows a hybrid nature-based solution that advocates for Integrated Pest Management (IPM) as a holistic strategy to combat plant pests with minimal applications of chemical pesticides. The third example is an inspired NBS of water- and nutrient-reuse between agro-food industries and agriculture. Green elements indicate positive impacts, grey elements indicate that the impact is undefined or might even be negative. When implementing the NBS, these negative impacts might have to be overcome during implementation. We focus on NBS examples in the primary production domain of food systems. Examples of using

NBS in storage, processing, retail, packaging, and consumption are beyond the scope of this paper.

3.1. Intrinsic NBS: Rainwater Harvesting as a Nature-Based Solution

3.1.1. Food System Failures and Targets

Rainwater harvesting is a practice that dates back to prehistoric times, and still forms an integral part of many domestic and agricultural systems in arid and semi-arid regions where rainfall is insufficient for crop growing [56,57]. It is practiced in many different ways and for several purposes [58]. As we are mainly interested in the linkages between NBS and the food system, we focus on Rain Water Harvesting practices for Irrigation (RWHI), which implies harvesting, storing, and conserving rainwater directly at the farm or the run-off derived from a catchment area or reservoir from which individual farmers can benefit [59,60]. The main food system challenge targeted by RWHI is overcoming food security risks for smallholder farmers posed by climate change (e.g., more extreme weather events, less rain, longer periods of droughts, and higher temperatures). With that, the NBS is aimed at reaching societal targets like improving food security, but also creating opportunities for decent work and economic growth (SDG 2, 8,9,10,12).

3.1.2. Description of NBS

RWHI is based on the natural event of precipitation, and it relies on characteristics of the landscape such as the slope of the land [60,61], and the texture and structure of the soil [62,63]. Its objective is to collect run-off during the rainy period of the year and from outlying areas where the water is not used, store it, and make it available where and when there is a scarcity of water [57,60,64] for crop growth (agricultural production in green in Figure 5). Less (ground)water will be abstracted from the water system (water in green in Figure 5). Some infrastructure may be required to collect rainwater (e.g., stone or earth bunds, small terraces, or Fanja Juu—Figure 6). RWHI improves the efficiency of available water and is often implemented to secure agricultural production in case of water scarcity (resilience in green in Figure 5). Nature and biodiversity might be affected as well, although whether this impact is positive or negative is not yet clear [65], see grey box in Figure 5.

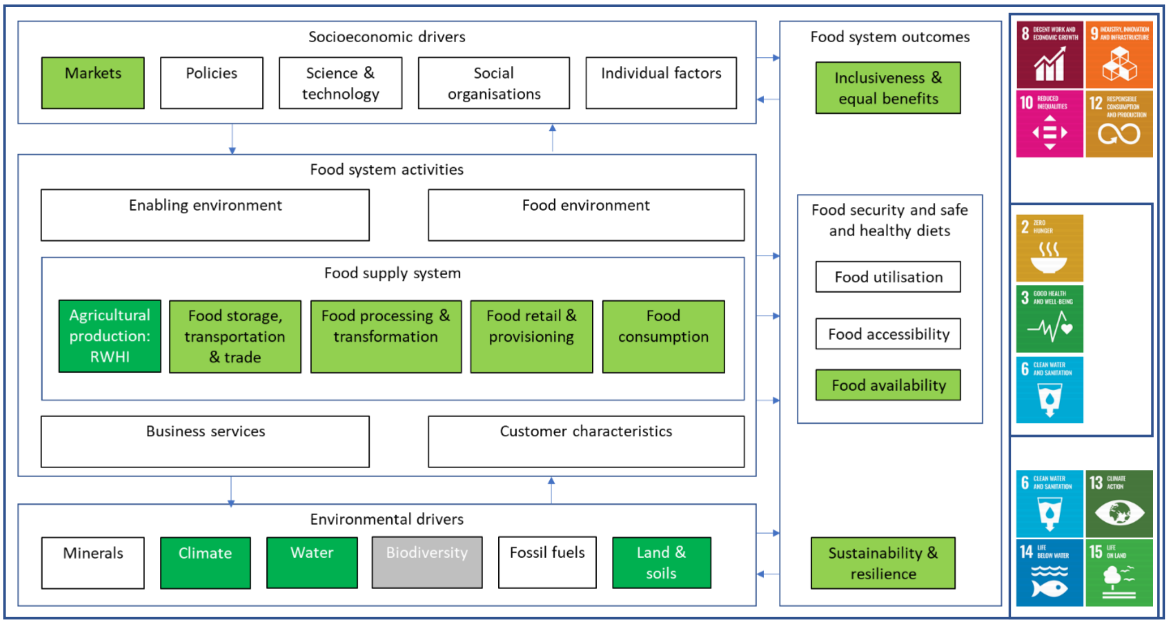

Figure 5. Impact of Rainwater harvesting for irrigation (RWHI) within the food systems framework (dark green = direct positive effect; light green = indirect positive effect (as a consequence of implementing the NBS); grey = ambiguous or negative effect; white = no (known) effect).

Figure 6. Terraces build up by vegetative strips over several decades in humid-tropical Ethiopia (photo by Saskia Keesstra).

3.1.3. Multiple Benefits of NBS to Support the SDGs

Rainwater harvesting is a well-proven concept in many countries, especially in the developing world. The implementation of RWHI has multiple benefits [63,66], particularly targeting SDG 2 (Food Security) by: (i) making agricultural production possible in dry areas which rely on rainfall; (ii) increasing agricultural productivity in areas with high variability of precipitation; and (iii) facilitating the cultivation of water-intensive, higher value crops on a commercial basis or for personal use [67]. In addition, the landscape variability associated with rainfall harvesting infrastructure reduces flood risks by reducing overland flow and related erosion [68]. It also contributes to the improvement of soil health (defined as the capacity of a soil to provide the maximum amount of ecosystem services at that location) over the long term [69], as soils with more nutrients and higher water holding capacity result in higher yields for farmers (Land and soils in Figure 5). The reduced erosion and nutrient losses due to higher infiltration help the soil maintain its health and even improve it through the build-up of organic matter. This creates a positive feedback loop, as a healthier soil will increase the infiltration capacity of the soil, providing better water harvesting.

3.1.4. Phase of Transition, Enablers and Challenges to NBS Implementation

The fact that rainwater harvesting is a relatively well-accepted technique means that this NBS does not suffer from the niche innovation problems that new technologies experience in the first phases of the transition (Figure 3). A challenge in this example is related to the lack of knowledge about the benefits of the NBS for farmers in areas that are newly affected by droughts. Once these land-managers and farmers are more experienced with the cost-reduction benefit that RWHI can bring, the transition towards accepting this methodology in new regions will be easier. Another challenge to implementing rainwater harvesting structures is the loss of land which, in many food-insecure countries, is predominantly used for agricultural production. Furthermore, it may take time to reap the likely benefits of improved soil health because the soils need time to recover [69]. We can enable the implementation of RWHI by providing financial support and training to farmers to build and maintain infrastructure, or to compensate for the loss of land, particularly in early stages where benefits may not be immediately apparent [70].

From a food systems perspective, RWHI are currently mainly used by smallholders in rain-fed areas, who are involved in subsistence agricultural production.

3.2. Hybrid NBS: Pest Management

3.2.1. Food System Failures and Targets

A sustainable food system should be able to provide enough healthy food for consumers and a safe livelihood for producers. The current (over-)use of agro-chemicals in food production systems to combat pests and diseases have negative impacts on human health and the environment. Agro-chemicals often affect natural enemies of pests, may adversely affect pollinators, and lead to development of resistance in pests. The ongoing process of understanding pest management without the use of agrochemicals is called Integrated Pest Management (IPM) and is advocated as a holistic approach to combat plant pests with minimal applications of crop protecting agents. However, most cropping systems still heavily depend on chemical pesticides [71].

In this example, the promotion of natural pest control is presented as a solution for phasing out agrochemicals to mitigate the unsustainable use of the biosphere resources, improving resilience of the system to climate change impacts, and provide safe and healthy diets (SDGs 2, 6, 13, 14 and 15, Figure 7).

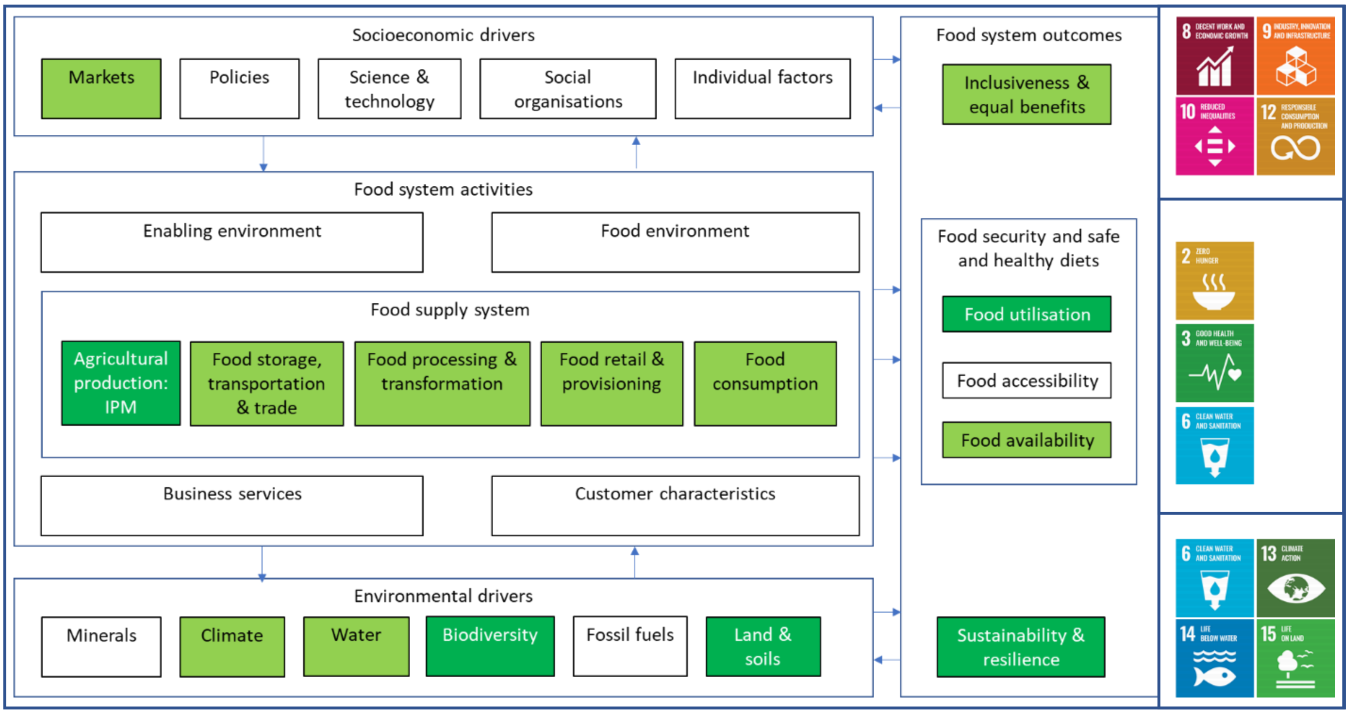

Figure 7. Impact of Integrated Pest Management (IPM) within the food systems framework (Dark green = direct positive effect; light green = indirect positive effect (as a consequence of implementing the NBS); grey = ambiguous or negative effect; white = no (known) effect).

3.2.2. Description of NBS

The re-introduction and implementation of IPM as a NBS that exploits agro-ecological relationships and in some cases, mimic natural systems or landscapes, is now of great importance to sustainably combatting crop pests and diseases. Examples of existing IPM strategies are netting, bird kites, sterile insects, crop rotations, intercropping, and creating natural refuges for predators that feed on pests (Figure 8). Other options are related to landscape management to attract predator species (e.g., insects and birds), by managing hedges and flower strips, or by creating wind profiles and crop diversity through, for example, strip-cropping that are unfavourable to crop pests [72,73]. Crop characteristics play a role in attracting natural enemies of pest insects [74,75]. Research on characterising such important factors for pest control; and subsequently breeding for improved attraction by crops, could lead to novel approaches in IPM. This will also improve the quality of the agricultural products as well as the safety of the food consumed (Figure 7).

Figure 8. Orange orchard and vineyard with natural refuge for predatory fauna (**left**) and treated with agro-chemicals (**right**) (photos kindly provided by Artemi Cerdà).

3.2.3. Multiple Benefits of NBS to Support the SDGs

With increased understanding of the risks and scales needed to manage pests, the potential for a nature-based approach is extensive and not confined to agricultural land. IPM can be applied to nature reserves and can integrate ecosystem services at the landscape level. For successful IPM, a landscape management approach is needed. The impact of wider landscape management on the relationship between crop, pest, and natural enemies has the potential to reduce or eradicate crop pests (and diseases) to minimal levels, where farm-scale IPM may have previously failed.

An IPM technique that has proven to be successful in arable land is strip-cropping. Strip-cropping has the benefit of retaining the area of productive land. The higher diversity of crops in one field attracts natural predators, which reduces the amount of pesticides needed. Hence, IPM does not only address the sustainability of food production, but can also increase biodiversity (SDG 15). As a result, the risk of polluting water resources and will be diminished (Figure 7).

3.2.4. Phase of Transition, Enablers and Challenges to NBS Implementation

The use of natural predators for crop protection is still in its emerging phases in many areas, and still needs to be fine-tuned in terms of effectiveness and scale of implementation. Although the system has proven its usefulness and success, the transition to institutionalising the NBS (Figure 3) still needs to be facilitated. Adoption of IPM by farmers will require a change in management, including—in some cases—new machineries to enable no-till or strip-cropping. Furthermore, implementing IPM involves a change in mindset for farmers, who may prefer to keep their field 'clean' and have control over their pest management instead of relying on natural predators. Local champions, demonstration sites, and capacity building will be essential to encourage institutionalisation of this NBS.

Earlier studies on farm and field strategies in Europe indicated that compensation could incentivise farmers to use field margins and hedges to host and attract predators e.g., [76]. This could be turned around, by requiring farmers to pay a fee for the environmental damage caused using agrochemicals. Such a push mechanism could provide an immediate incentive to manage the land differently; and transfer the real costs of environmental damages onto farmers and, in turn, consumers. Other regulatory drivers, such as the EU's ambition to have 25% of all farms organically managed [77], will further institutionalise new methodologies for crop protection and associated land management [78,79]. The current knowledge gaps are still impeding large scale uptake, but under push from policy, this NBS has high potential to bring the trust in ecosystem services of the landscape back to farmers. This NBS needs to be supported by enabling policies and governance for upscaling of the new sustainable methodology and phasing out the old unsustainable management strategies and technologies.

3.3. Inspired NBS: Wastewater Reuse in the Netherlands

3.3.1. Food System Failures and Targets: Increasing Access and Availability of Freshwater for Agricultural/Agro-Industrial Use

In many river delta regions, water availability for food production is coming under increasing pressure from climate change, sea-level rise, and related increased saltwater intrusion. This is especially the case in regions where water supply is mainly dependent on rainwater [80]. The risk of yield reduction and drought damage within the food supply chain increases as a result. In the Netherlands, freshwater supply from rivers for agriculture is good under average climatic conditions. However, in situations with a low river discharge and high precipitation deficits, freshwater supply cannot meet agricultural freshwater demand during the growing season [81]. In this example, the NBS aims to reduce the amount of water and nutrients used for agricultural production as well as by food processing industries and drinking water production. The drinking water supply factory EVIDES uses a water reservoir, situated in a bird and habitat directive area, as a pre-purification (5 months) of water from the river Meuse. These reservoirs, including the marshland borders, could be seen as a constructed wetland. Pilots are currently conducted at other drinking water plants to improve these systems [82], not only to pre-purification, but also biodiversity values [83]. Another specific example concerns a sugar factory in the south of the Netherlands. Wastewater from this factory is used as irrigation water for nearby greenhouse horticulture. Sugar beets are processed in autumn and winter, while horticulture irrigation water is processed in spring/summer. Since 2016, the purified wastewater is stored within the aquifer during winter, and the water can be recovered in spring and summer by aquifer storage and recovery (ASR) technology for irrigation [84]. The temporary storage of water in the subsurface can also be regarded as an inspired NBS. Wastewater and nutrients in the wastewater are re-used to increase circularity, reduce the ecological footprint, and improve the food system's quality, which makes food production more sustainable and resilient and contributes to life on land and below water (SDGs 2, 6, 12, 14; Figure 9).

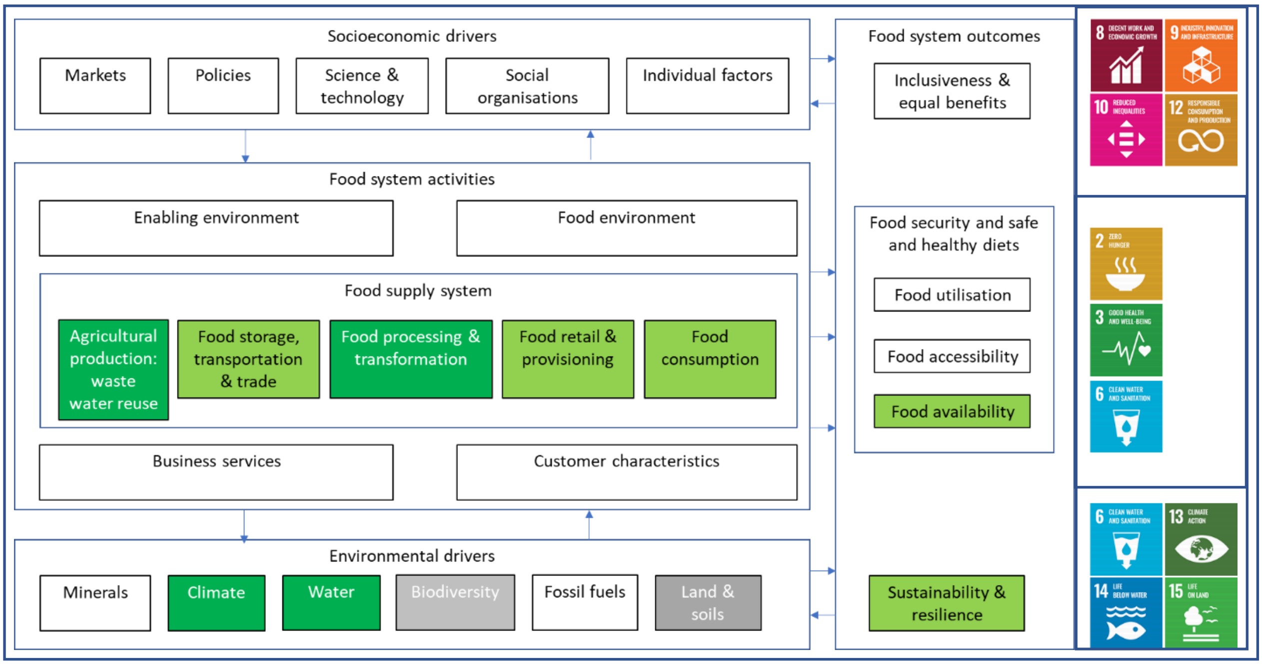

Figure 9. Wastewater reuse in the Netherlands within the food systems framework (Dark green = direct positive effect; light green = indirect positive effect (as a consequence of implementing the NBS); grey = ambiguous or negative effect; white = no (known) effect).

3.3.2. Description of the NBS

Current, conventional wastewater treatment plants are large installations where all the water is collected and treated to a defined quality standard fit for discharge. Water quality for reuse is not yet considered. The example of an inspired NBS uses constructed wetlands or microbial systems to enable the reuse of wastewater streams. Wastewater purification that NBS uses resembles ecological nutrient uptake processes and sedimentation of suspended solids that occur in aquatic ecosystems. In constructed wetlands, these uptake processes can be optimized [85].

The NBS links actors in the food system that can reuse wastewater from residential or food processing streams within the factory or by primary producers (e.g., horticulture, livestock, onshore aquaculture, cattle). This reuse of wastewater reduces the dependence on groundwater and surface water, and can be used as a climate adaptation strategy. Regarding circularity and sustainability, it is interesting to explore trade-offs between, for example, water reuse and energy requirements between food industry, nature, and agriculture.

3.3.3. Multiple Benefits of NBS to Support the SDGs

When freshwater sources (river water, rainwater, groundwater) do not meet (future) water demands in terms of quantity and quality, nature-based treatment options can provide alternative water resources. Reuse of wastewater and components present in the water (raw or partially treated) for crop production, industry, or environmental flows prevents the discharge of nutrients and other valuable components into nature as occurs in conventional wastewater plants. When food processing industry and farming activities become less dependent on natural water resources, there is more water available for other purposes (Figure 9), such as restoring or protecting estuarine dynamics. Depending on the design, regional biodiversity could also benefit from these constructed wetlands.

3.3.4. Phase of Transition, Enablers and Challenges to NBS Implementation

While using wastewater for irrigation is still in its emerging phases in the Netherlands, the technology is becoming more mainstream in countries like Tunisia and Israel [86,87].

However, food industries are interested in the technology and are considering making this part of their normal business [88].

At present, social acceptance of using wastewater for agricultural food production and processing is still low [89]. People may have the perception that produced food may be contaminated, hampering adoption of these types of NBS. Therefore, more research and communication must show food safety and the applicability of this methodology to convince all stakeholders involved. In this context, it is important to distinguish different uses of the water. Reusing wastewater for cooling or cleaning processes may be more easily accepted than reusing water for food production and processing. We expect that the use of NBS treated wastewater will increase for at least some processes as regions experience more frequent dry summers—putting pressure on traditional water sources.

A potential second constraint lies in the availability of space to realize constructed wetlands for the food processing industry (especially in densely populated countries like the Netherlands). One potential could be vertical flow constructed wetlands, whose design reduces their footprint [90]. Furthermore, the accumulation of substances like residues from medicines and pesticides may pose a threat to these systems. Finally, legislative requirements could present a barrier to the development of NBS. Some environmental regulation, like the EU Water Framework Directive, requires continuous functioning of water treatment processes, which may be challenging in a constructed wetland that is exposed to natural dynamics. Because of this, it is necessary to retain back-up systems through water buffers and technological purification methods.

4. Discussion and Knowledge Gaps

4.1. Main Benefits and Challenges of NBS for Food Systems

The examples show the potential of NBS to help overcome the challenges of food system in terms of food security, safe and healthy diets, and sustainability and resilience, contributing to the transition to a climate-resilient food system. The main benefits of NBS lie in the fact that NBS can serve multiple goals at the same time. For instance, the rainwater harvesting techniques in Example 1 will contribute to food security, but also provides many other ecosystem services: lower flood risk, better soil health, carbon sequestration for climate change mitigation, aesthetic landscapes, and higher soil biodiversity. The hybrid NBS example of pest management not only focuses on the transition from chemical to nature-based crop protection, but also delivers enhanced biodiversity benefits and a more attractive landscape. Another benefit of NBS is their longevity. If set up properly, natural process will serve to maintain the NBS [17].

NBS also have several challenges. For example, they use space that cannot be used in another way anymore, and it will take some time for natural processes to be established—which means that the sustainability benefits of NBS are not immediately experienced. NBS are also more difficult to accurately manage, which may lead to a sense of loss of 'control' for farmers. Moreover, managing NBS needs new skills that, in some cases, farmers do not yet have. Capacity building and trials to demonstrate the benefits of NBS will be required to overcome such challenges. Combining NBS with technological innovations (e.g., robotics, Internet of Things) may also help to overcome barriers related to precision farming, space requirement, and time management.

An interesting feature here is that the intrinsic NBS that uses existing ecosystems target societal or economic goals (food security), while the hybrid and inspired/newly developed ecosystems aim to improve biosphere conditions, at least in the evaluated examples in this paper. The inspired type of NBS will be a valuable addition to the 'toolbox' of NBS, as it specifically seeks to improve the delivery of multiple key ecosystem services. Therefore, finding NBS that potentially use aspects of all three types of NBS appear promising in the strive for climate-resilient and circular food systems.

4.2. Knowledge Gaps Impeding the Implementation of NBS in Food Systems

In this section, we offer our view of what NBS offers to food systems when transitioning into more climate-resilient and circular systems, and which major knowledge gaps are impeding implementation (and scaling) of NBS.

Mechanisms: To be able to implement NBS successfully, we need to improve our understanding of the underlying mechanisms of nature-based solutions to support food systems' transformation. We need to address different forms of diversity: crop, genetic, social, and financial.

Effectiveness and diversity in NBS: We defined three types of NBS, ranging from making better use of an existing ecosystem (intrinsic NBS), to designing and managing a newly formed ecosystem (inspired NBS), and an intermediate form where an adapted ecosystem is used (hybrid). These three types will vary in their applicability to different food systems and sectors. Identifying the long-term (biophysical, socio-economic, and governance) potential and limitations of different NBS (be they intrinsic, hybrid, or inspired) will aid decisions around their implementation in different sectors and biophysical/socio-economic contexts. Mapping the potential contribution of NBS to food systems' circularity, demonstrating how NBS can increase climate resilience in the short and long term, and transdisciplinary collaboration across sectors and NBS are core to increasing learning and adoption.

Develop tools: to improve NBS to make them more acceptable and usable for various stakeholders, thus fostering their uptake and transition towards a sustainable food system. For this it is important to embed NBS-based innovations in multiple networks of societal partners and government institutions. Transition pathways or food systems innovations concern a large variety of stakeholders; hence it is important to develop appropriate boundary-spanning processes, methods, and tools, e.g., a decision tree that supports the selection of NBS at various scales. A collaborative or participatory approach will be the desired approach to the development of such tools. The socioeconomic viability needs to be assessed; potentially by using an economic framework that goes beyond monetary value.

Develop indicators: to monitor and evaluate the functioning, costs and benefits, lock-ins, and trade-offs of an implemented NBS, we not only need a thorough knowledge base of the soil, water, and sediment systems, but also the socio-economic situation of the area. SMART indicators that consider the wider societal and institutional context in which NBS are implemented (including governance arrangements, economic viability, and socio-cultural considerations, such as power imbalances) will enable a full scope assessment of the area.

Barriers and opportunities: it is important to improve our understanding of the factors supporting and hindering the design and implementation of NBS that contribute to food systems' transformation (e.g., lock-ins, leverage points, enabling environments). This includes the development of supportive policies, programmes, and governance mechanisms that foster the transition of food systems and implementation of NBS. Further opportunities may arise from synergies by embedding multiple NBS strategies within a single landscape or system. In addition, to date, very few industries or consultancies specialize in developing or selling NBS for food producing systems. This is likely due to the lacking business models for current industry. Social acceptance is equally important and therefore relevant actors need to be engaged and encouraged to apply/participate in the implementation of NBS to foster acceptance.

Contribution of NBS to circularity and climate resilience of food systems: improve our understanding of the contribution of nature-based solutions to food systems' circularity, climate resilience on the short and long term, and map potential optional NBS for specific needs and situations. Furthermore, it is necessary to develop a decision tree to select the type of NBS (intrinsic/hybrid/inspired) that is best suited in each situation.

5. Conclusions

In this paper, we illustrate how different types of nature-based solutions (NBS) can serve as mechanisms to address a range of food system challenges and achieve more sustainable climate-resilient food systems. In addition to (relatively widely accepted) intrinsic NBS that make use of existing ecosystems, we also evaluated inspired NBS and hybrid combinations that adapt and make use of processes based on nature, but are newly constructed ecosystems. We propose a conceptual framework (Figure 4) that is used to assess: (1) what food system challenge is addressed; (2) what type of NBS is employed; (3) what objectives are targeted and how these link to the Sustainable Development Goals; and (4) what stage of the transition process the NBS may be in. We discussed the multiple benefits that NBS provide and identified challenges to adoption. Based on our evaluation, we conclude that all three types of NBS (intrinsic, hybrid, and inspired) provide solutions for food system challenges. The more 'traditional' intrinsic NBS are often used to address multiple environmental challenges and supply a range of ecosystem services. NBS that are 'inspired' by nature can be of specific interest to the food processing industry, as they are targeted, better manageable, and therefore potentially seen as more reliable. Our framework is a useful tool to facilitate the implementation and scaling of NBS for sustainable climate-resilient food systems because it provides a common understanding of the food system challenges addressed and the opportunities provided by different types of NBS. We argue that the enhanced ecosystem services resulting from better functioning natural systems will directly feed into the realization of the United Nation's Sustainable Development Goals, not only by improving food security, but also by increasing the sustainability of production and strengthening food systems' resilience to climate change. NBS can be used as building blocks for a sustainable climate resilient food system by facilitating the much-needed transition to a better way of using our natural resources to reach the SDGs by 2030.

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