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Nature-based solutions addressing the water-energy-food nexus: Review of theoretical concepts and urban case studies

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ABSTRACT

An increasing world population is projected to increase water, energy and food requirements, three vital resources for humankind. Projected climate change impacts will aggravate water availability, as well as flood risks, especially in urban areas. Nature-based solutions (NBS) have been identified as key concepts to defuse the expected tensions within the Water-Energy-Food (W-E-F) nexus due to their multiple benefits. In this paper, the authors outlined the theories and concepts, analyzed real-life case studies, and discussed the potential of NBS to address the future W-E-F nexus. For this purpose, we performed a systematic literature review on the theories of NBS that address the W-E-F nexus, and we summarized 19 representative real-life case studies to identify the current knowledge gaps and challenges. The quantitative and qualitative data was used to differentiate and discuss the direct and indirect potential benefits of NBS to the W-E-F nexus. The study further expanded on the challenges for the implementation of NBS and highlighted the growing possibilities in the context of circularity and the implementation of NBS in urban planning. It was concluded that the potential impacts of NBS on the W-E-F nexus have been identified, but the quantitative effects have not been analyzed in-depth. Moreover, indicators are mostly single-purpose and not multipurpose, as required to fully characterize the W-E-F nexus and circularity holistically. Overall, there is a need to adopt systemic thinking and promote the multipurpose design of NBS.

1. Introduction

The Water-Energy-Food (W-E-F) nexus addresses the consumption of ecosystem resources, namely water, energy, food, land, and soil, and socio-economic factors (FAO, 2014). Namely, it describes the interaction of resources exploitation between the three essential elements (Water, Energy and Food) for human society. Energy production, for example, may need water, while water is also essential for food production. To ensure security in agriculture one might put pressure on energy production and vice-versa (Bennett et al., 2016). In industrialized countries, over half of the freshwater resources are needed for energy production (Bauer et al., 2014). While the tradeoff between the three nodes is case-dependent, on average about 0.6–4 kWh are needed to produce and treat 1 m^3 of consumed water (Nakkasunchi et al., 2021; Sharif et al., 2019). Nearly 30% of global energy is consumed in food production, however, food or food waste can be used as an energy source (Chamas

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et al., 2021). On average approximately 100 m^3 of water is needed to produce one ton of durum wheat pasta (Lowe et al., 2020). The W-E-F nexus as a concept, therefore, considers the complexity of interactions and interrelationships between the three nodes of the system - water, energy and food (Endo et al., 2020; Zhang et al., 2018). The W-E-F nexus should be approached in a holistic and circular manner in order to address the growing scarcities under economic, climate change and urbanization pressures (Zhang et al., 2019). Urban communities are particularly vulnerable to the future demand for food, energy and water, meaning that solutions need to be found also in urban spaces (Yan and Roggema, 2019). Nature-based solutions (NBS) have been pointed as a key to overcoming some of these issues.

NBS are defined by the European Commission as "living solutions inspired by, continuously supported by and using nature, which are designed to address various societal challenges in a resource-efficient and adaptable manner and to simultaneously provide economic, social, and environmental benefits'' (European Commission, 2015). Building on this definition, one can understand NBS as components of green infrastructure aimed at solving specific problems or issues in urban and rural landscapes. The definition of NBS has been recently revisited under the European Cooperation in Science and Technology (COST) Action Circular City as "concepts that bring nature into cities and those that are derived from nature. NBS address societal challenges and enable resource recovery, climate mitigation and adaptation challenges, human well-being, ecosystem restoration and/or improved biodiversity status, within the urban ecosystems" (Langergraber et al., 2020).

NBS consist of highly productive and interconnected subsystems that can save energy, produce food and manage water resources in a highly effective way (Maes and Jacobs, 2017; Rhodes, 2017). However, a large fraction of the available academic literature only evaluates NBS along a single functional dimension, most commonly the water management. Nevertheless, NBS are expected to play a major role in the current EU Green Deal Strategy (European Commission, 2019) and the EU Biodiversity Strategy to 2030 (European Commission, 2020a) aiming at implementing the Farm to Fork Strategy (European Commission, 2020b), which is directly linked to the W-E-F nexus. NBS are also becoming a plausible concept to address circular economy principles and sustainability challenges of cities in the use of resources, such as water, energy and food. Furthermore, NBS can address global challenges, such as urban sustainability, climate change, food resilience, the biodiversity crisis and other emerging challenges (Fan et al., 2017; IUCN, 2016; Finger et al., 2021).

Furthermore, NBS can play a key role in addressing the United Nations 17 Sustainable Development Goals (SDG) and help to promote global development, human well-being, and environmental protection (United Nations, 2020). NBS could be valuable to simultaneously tackle climatic challenges by reducing the risks and implementing a climate-resilient society (United Nations Global Compact, 2019) and a variety of other issues. Thus, NBS are found to be in line with the main global challenges, namely: SDG 3, 6, 12 and 15 (Life support, e.g., nutrient and water loops, primary production); SD2, 3, 6, 7 and 12 (Food, drinking water, sanitation, materials, renewable energy); SDG 11 and 13 (Self-regulation e.g., climate and water cycle, pollination and pest control); SDG 1, 4, 15, 16 (Cultural values e.g., artistic, educational and recreational); and SDG 1, SDG 8, SDG 9 (Urban economy e.g., energy and water savings, land/property value, employment, tourism). Globally, the uptake of NBS is growing due to a shared understanding that the NBS concept encompasses human and ecological benefits beyond the core objective of ecosystem conservation, restoration or enhancement (Sarabi et a. 2019).

NBS that have been primarily designed for water management (Oral et al., 2020) can potentially eliminate trade-offs while enhancing water, energy, and/or food security simultaneously (Langergraber et al., 2020). Healthy forests, wetlands, and floodplains for example filter sediments, toxins, and nutrients and improve water quality while reducing the need for energy-intensive water treatment (Keesstra et al., 2018; Finger et al., 2019) and the flood risk (European Commission, 2013). Sustainable agricultural practices (e.g. organic agriculture, eco-agriculture, agroforestry, agricultural parks and other types of multi-functional agricultural landscapes) can conserve water and improve its quality, improve quality and safety of food, reduce soil erosion and the need for energy-intensive inorganic fertilizers, and mitigate climate change through reducing greenhouse gas emissions (Bennett et al., 2016).

Literature on the beneficial effects of NBS implemented to address different challenges in cities is growing. For instance, Dorst et al. (2019) analyzed the key characteristics of NBS related to green spaces (such as urban trees, forests and other green infrastructure) in a recent and comprehensive literature review, though they did not analyze the impacts of these types of NBS on the W-E-F nexus. Overall, across the major body of NBS literature, in spite of the continuously cited potential of NBS to address the W-E-F nexus, the assessment of this relation is still missing. Based on the systematic literature review carried out in the present study, and to the best of the authors' knowledge, there is no prior review studying how urban NBS contribute to, or can improve the W-E-F nexus. With this in mind, this study aimed to fill this gap by:

- Reviewing the existing literature conceptualizing both NBS and the W-E-F nexus.
- Analyzing examples and case studies of NBS where indicators of at least one sub-nexus (e.g., W-E) were quantified, as complement to the literature review.
- Discussing the quantitative contribution of NBS to the W-E-F nexus, when possible, otherwise identifying qualitative benefits.
- Identifying the challenges and knowledge gaps that may hinder the usage of NBS to improve the W-E-F nexus.

2. Review of NBS publications theorizing the W-E-F nexus

A review of theoretical concepts was necessary to assess the contribution of NBS to the W-E-F nexus. For this purpose, between May and June 2020, both Web of Science and SCOPUS databases were searched using the query string ["nature-based solution (NBS)" AND water AND energy AND food AND nexus"]. In addition, other related keywords were also used instead of "nature-based solution (NBS)": 1) parks and urban trees, forests and other tree-related green spaces, 2) green roof, 3) green wall, 4) constructed wetland, 5) floodable park, 6) retention pond, 7) urban farming, urban agriculture, urban orchard, and urban livestock, 8) hydroponics, aquaponics, and aeroponics. Furthermore, the search term "Water-Energy-Food nexus" was also varied for the different combinations of the nexus key terms "water", "energy" and "food" with and without the word "nexus". It should be clarified that, in spite of the focus of the present paper being urban environments, the authors did not exclude NBS from rural settings when analyzing the outcomes of the systematic approach. The aim was to review as much literature as possible in order to provide the most detailed overview of NBS and the W-E-F nexus publications. After an assessment of abstracts and full texts, the most relevant published works were selected. The criteria for including the manuscripts for the current analysis was that either NBS in general or specific NBS (e.g. green roof) have been studied and any of the nexus potentially quantified or at least discussed. If "nexus" was not present in the main text publications were not considered further.

Selected publications are summarized in Table 1 and the respective theoretical considerations about the nexus described in this section.

The literature review showed that most articles retrieved included nexus as a keyword but did not include nexus in the main text. Table 1 only comprises relevant publications expanding on the nexus in the text. Briefly, green roofs, constructed wetlands and urban farming are mentioned most frequently, while only a few works (twenty articles - Table 1) provide insights into the W-E-F nexus. Only a few articles (five) assessing NBS for stormwater management (among NBS such as grassed swales and water retention ponds, green filter area, floodable park, dry

Table 1
Summary of existing literature on nature-based solutions (NBS) that discusses the water-energy-food nexuses.

Search query Keyword	Water-energy Nexus	Water-Food Nexus	Food-Energy Nexus	Water-energy-food Nexus
NBS	Engström et al. (2018)	n.f.	n.f.	Bennett et al. (2016)
Urban trees, forests and other tree-related green spaces	Livesley et al. (2016)	n.f.	n.f.	n.f.
Green Roof	Engström et al. (2017)	n.f.	n.f.	n.f.
Green Wall	n.f.	n.f.	n.f.	n.f.
Constructed wetland	Kumar and Singh (2020)	(Langergraber and Masi, 2018; Masi et al., 2018)	n.f.	(Avellan et al., 2017; Avellán and Gremillion, 2019)
Floodable park	n.f.	n.f.	n.f.	(Jodar-Abellan et al., 2018; Miguez et al., 2019)
Retention Pond	(Ramos et al., 2013a, 2013b, 2013a)	n.f.	n.f.	n.f.
Urban farming/Urban agriculture	n.f.	n.f.	Nadal et al. (2017)	(Amos et al., 2018; Avgoustaki and Xydis, 2020; Mohareb et al., 2017; Toboso-Chavero et al., 2019)
"Ponics" (hydroponics, aquaponics, aeroponics)	n.f	n.f	Nadal et al. (2017)	Proksch and Baganz (2020)

n.f. - not found.

bioswale, wet detention pond, retention pond, rain gardens, infiltration ponds, managed aquifer recharge) mentioned the nexus while establishing an evident relation to food and energy. Similarly, only a few articles (four) addressing space-related NBS (e.g., forests and urban trees or urban catchment forestry, shade trees, cooling trees, green corridors), stream/river management NBS (e.g., daylighting, re-opened stream, renaturing, floodplain) discussed the nexus.

The main findings of the systematic literature review were summarized in the following sections, organized by sub-nexus.

2.1. Water-energy (W-E) nexus

Different NBS may be used to solve this nexus in terms of the likelihood of tackling both water and energy problems. Green roofs, for example, are one of the most commonly used NBS in the urban context, used in the field of bioclimatic architecture to replace conventional materials used to build flat roofs, which account for approximately 25% of the horizontal surfaces of urban areas (Cascone et al., 2018). Moreover, green roofs could provide a solution to stormwater management and improvement of urban hydrological balance, (Zölch et al., 2017; Czemiel Berndtsson, 2010), to avoid floods (Mentens et al., 2006) and related possible damage to infrastructure and disruption of city services (McPherson et al., 1997; Miguez et al., 2019). Part of the water could be used on-site for cooling the building and improving microclimate while improving runoff water quality (Berndtsson et al., 2009).

Green roofs can reduce surface temperatures (Ng et al., 2012; Pérez et al., 2015), improve thermal insulation of the building envelope (D'Orazio et al., 2012; Tam et al., 2016) and mitigate the heat flux through non-insulated roof material (Bevilacqua et al., 2018; Tian et al., 2017). Besides, green roofs save energy by cooling indoor spaces, especially when used for the energy retrofitting of existing buildings with a low level of thermal insulation (Cascone et al., 2018). Green roofs also provide CO_2 sequestration (Engström et al., 2017, 2018).

Moreover, Livesley et al. (2016) presented evidence from multiple case studies on pollution reduction by adequately designing urban green spaces, including for abatement of nutrient pollution in stormwater (Dochinger, 1980; Nowak and Dwyer, 2007). Furthermore, NBS could represent a valuable solution for river restoration and sustainable urban drainage (SUDs), by reducing peak flows and increasing the ecosystem services resilience, and economic feasibility (Miguez et al., 2019). SUDs, such as retention ponds, could be used as water storage units while enabling renewable hydroelectricity production, constituting innovative solutions to be integrated into future smart water grid's designs (Ramos et al., 2013a, 2013b). However, while the hydraulic and pollutant benefits have been better characterized, only two articles have assessed the hydropower potential of flood protection NBS.

Other examples of improving urban water and energy cycles were provided by Livesley et al. (2016), by demonstrating that urban trees, forests and other green spaces can positively affect the local temperature buffer capacity while reducing the need for cooling energy. Several studies highlighted the importance of implementing urban trees, gardens and green walls as means to reduce the urban heat island intensity through evapotranspiration (Heisler, 1986; Nowak and Dwyer, 2007; Sjöman et al., 2012; Lafortezza and Sanesi, 2019; Naumann et al., 2011) and thus decrease the need for energy for cooling buildings (Akbari et al., 2001; Maco and McPherson, 2003). Furthermore, these solutions were considered more effective and economically viable than traditional approaches (e.g. areas with fountains, water sprinklers or constructed shades) (Lafortezza et al., 2018; Norton et al., 2015; Solecki et al., 2005).

Vegetated vertical systems made of planted containers attached to building walls (Liu et al., 2018) are also promising solutions to mitigate the effects of climate change in urban environments. Among the many benefits (e.g. air pollution reduction or higher quality of living of urban population), urban heat reduction and energy saving by improving the heating and cooling performances of buildings are commonly reported (Lee and Jim, 2019; Li et al., 2019; Nagle et al., 2017). Moreover, such vertical NBS can also contribute for water reuse and consequently the nexus. In the urban water balance, around 70% of the water used in households is made of greywater (low polluted wastewater from bathtubs, showers, washing basins and washing machines) (Masi et al., 2016). Green walls can treat this great amount of greywater and allow its reuse, decreasing the total urban water footprint and determining a reduction of unnecessary costs for the respective treatment by wastewater treatment plants (Pradhan et al., 2019).

Constructed wetlands (CWs), engineered ecosystems mostly used for water pollution control (Vymazal, 2007), have been recently contextualized within the W-E-F nexus (Avellán and Gremillion, 2019). CWs are multifunctional technologies that not only have a great potential in (waste)water treatment but can also be exploited for bioenergy production. The biomass produced by CWs can be converted to energy by direct combustion, biogas production, and bioethanol production (Avellan et al., 2017; Llano et al., 2021a). Direct combustion requires low infrastructure costs and easy operation and maintenance procedures; the energy supplied by a CW can cover part of the energy demand of a small community (Avellan et al., 2017). Moreover, this biomass burning does not increase CO_2 emission since the CO_2 stored in biomass has been absorbed by plants during their growth (Važić et al., 2015). The use of biomass for bioethanol production has been considered as efficient as the corn stover (Lin et al., 2020). More recently, the association of CWs and microalgae provided important added values both to wastewater treatment and in the form of biofuel production (Chavan and Mutnuri, 2020). Moreover, the integration of CWs with bioelectrochemical systems for wastewater treatment started to be studied recently (Kumar and Singh, 2020). As with other technologies using the concepts of microbial fuel cells, there is also a potential to harvest energy from wastewater in hybrid bioelectrochemical-biofilters and/or CWs. Thus, different setups are being tested in order to make such systems either produce energy or become self-sustained by conjugation of microbial fuel cells with microbial electrolysis cells (Kumar and Singh, 2020). Research is still in a very early stage, but such hybrid systems might contribute in the future to the W-E nexus.

Overall, for the wider range of NBS, it is verified that water management has been the main study focus. Energy has been mostly explored in terms of building insulation and energy savings, while interconnection of water and energy endpoints is still scarce. There is a limited understanding of NBS quantitative contribution to the W-E nexus.

2.2. Water-food (W-F) nexus

Water shortage is putting more strain on agriculture and causing disputes between irrigation and other uses of water. In addition, it also limits the feasibility of urban agriculture, as potable water is already a scarce resource in many large urban areas. Hence, alternative water sources for irrigation are in demand. However, although stormwater has the potential to be used for urban agricultural irrigation, contaminants in this water source can pose potential health risks (Ng et al., 2018). Possible solutions to address safe use of stormwater are stormwater biofilters, which have great potential to treat this flow for harvesting and reuse. However, their variable performance in pathogen removal was considered to be limiting the uptake of the technology (Shen et al., 2020). In general, direct water reuse for irrigation has still limited acceptance.

CWs can also play an active role in environmental sustainability through resource recovery (Kisser et al., 2020). Besides the biomass production, these systems can be applied not only for food production (Langergraber and Masi, 2018; Masi et al., 2018), but also for the treatment of sludge (Uggetti et al., 2012) or wastewater for further reuse as fertilizers (Almuktar et al., 2017, 2018). However, both matrices might contain high levels of pollutants and pathogens representing a health risk (Shingare et al., 2019). Nutrient recycling has been also achieved by harvesting aquatic biomass growing in CWs and using it as fodder (Morand et al., 2011) or as food for human consumption (Hultberg et al., 2018; Kouki et al., 2016).

Aquifer recharge, through water treated or conveyed by NBS, can play a key role in groundwater management and support food security (Shah, 2014).

Overall, several NBS have the potential to address the W-F nexus but such assessment seems to have been performed unidimensionally, not from a nexus perspective.

2.3. Food-energy (F-E) nexus

Only one paper from the revised works focused on the energetic sustainability of a rooftop greenhouse, using soil-free farming methods integrated into an urban building. In developed countries, buildings account for approximately half of the world's primary energy consumption, while agriculture and food production are reported to

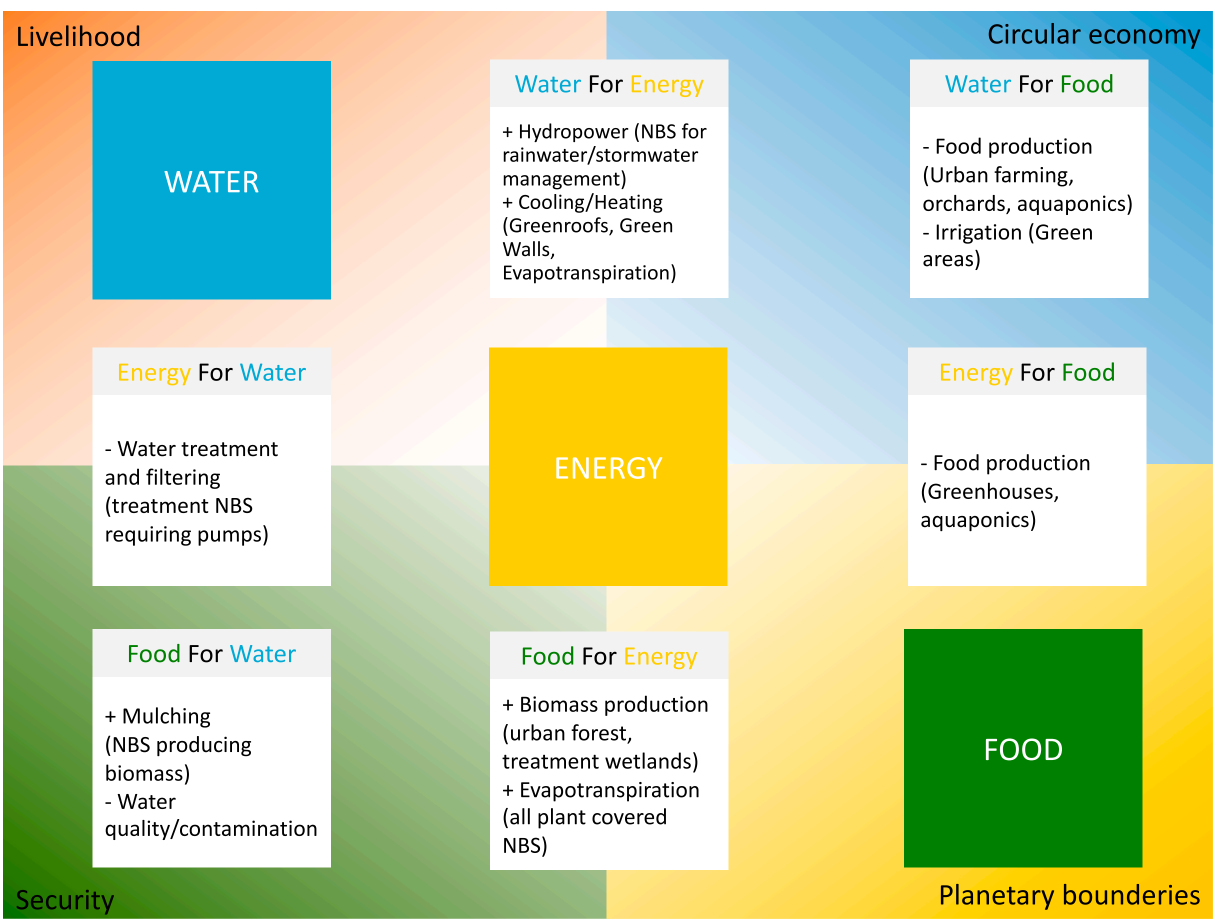

Fig. 1. Nature-based solutions (NBS) and the Water-Energy-Food nexus (W-E-F), inputs and outputs between nodes (water, energy, food) as identified from the analyzed publications on the topic (Table 1). (+) denote gains while (−) loss of water, energy and food/biomass for each node. The dimensions *Livelihood*, *Circular economy*, *Security* and *Planetary boundaries*, are inserted to represent the complexity of our study systems and should be read as totally overlaid and integrated dimensions.

consume between 13 and 15% of total energy. Thus, although potential synergies to be harvested have been identified, empirical data is missing (Nadal et al., 2017).

2.4. Water-energy-food (W-E-F) nexus

Though NBS have received a lot of attention for their role in urban water and temperature (energy) management, their role as a significant solution for food production has remained understudied. Potential synergies have been identified from the reviewed publications (Fig. 1), but the majority of the information available is qualitative. For instance, the floodable park *La Marjal* provided several environmental and economic benefits to the urban area of San Juan (Alicante, South-East Spain), including the possibility for water treatment and reuse of stored water (Jodar-Abellan et al., 2018). However, in spite of the potential additional benefits identified concerning the W-E-F nexus, the assessment and quantification of these benefits and impact is missing.

Rain gardens, shallow vegetated depressions into which stormwater is directed for filtration and/or infiltration and groundwater recharge, allow evapotranspiration and contribute to urban heat island mitigation (Taguchi et al., 2020). Moreover, their potential for water reuse may be relevant for the food-nexus, but reuse in urban agriculture has to be evaluated according to the quality of the water available. Thus, the type of water being managed (rainwater or stormwater) results in different reuse potential.

Green walls might play an active role in relation to self-produce of a large amount of food in cities (Eregno et al., 2017; Nagle et al., 2017; Xing et al., 2017) while reusing greywater. This allows considerably lower consumption of potable water. Moreover, inside and outside temperature conditioning and aesthetic benefits can be provided by a large scale application of this technology in the urban settlement, together with an increase of biodiversity, the amount of sequestered carbon, the acoustic insulation of buildings, and an improvement of air quality (Oquendo-Di Cosola et al., 2020). However, not only green roofs or walls and green spaces can provide a food source within urban boundaries (Bommarco et al., 2013), but can also serve as shelters for pollinators to ensure food production (Bellamy et al., 2017).

CWs can also be used for both saving energy and securing food (Avellan et al., 2017), with potential application at a range of scales from small communities to large cities. This integrated approach may be particularly effective in peri-urban areas, where the interface between urban infrastructure, high population density, and agricultural land has created competition for space and resources (Avellán and Gremillion, 2019).

Urban agriculture (UA) brings the food to the front of the W-E-F nexus examples. There is an increasing global interest in scaling-up UA, from private gardens to sophisticated commercial operations (Mohareb et al., 2017) and metropolitan systems (Tóth and Timpe, 2017). These include practices such as urban vertical farming (Avgoustaki and Xydis, 2020) or aquaponics (Proksch and Baganz, 2020). Much of the interest has been aligned with environmental protection, reduced waste and transportation energy, highlighted as some of the proposed benefits of UA (Mohareb et al., 2017). Aquaponics combine aquaculture and hydroponic cultivation and are interesting for facilitating nutrient cycling between fish and plants aiming to work as closed-loop systems (Proksch and Baganz, 2020). The energy and resources required for food production can be found in urban areas, e.g., water needs can be overcome by rainwater harvesting (Amos et al., 2018), while land use can be overcome by utilizing urban rooftops (Toboso-Chavero et al., 2019). Besides the nexus, UA contributes to environmental, social, and economic benefits; and promotes self-sufficiency (Toboso-Chavero et al., 2019), as well as resilience of urban food systems and landscapes (Toth et al., 2016). A recent approach "Roof Mosaic" merging life cycle assessment with two rooftop guidelines showed that when applied at the neighborhood scale, it allowed optimizing up to 50% of the W-E-F nexus demands while avoiding up to 157 tons CO_2eq/year (Toboso-Chavero et al., 2019). Gains in energy efficiency are expected through the co-location of UA operations with waste streams (e.g. heat, CO_2, greywater, wastewater, compost), potentially increasing yields and offsetting life cycle energy demand relative to conventional approaches (Mohareb et al., 2017).

Safeguarding food security in cities will depend on the implementation of NBS (ICLEI, 2019; Maes and Jacobs, 2017). However, empirical knowledge, including the quantification of the benefits, on NBS contribution to W-E-F nexus is still poorly addressed by existing literature.

3. Review of NBS case-studies addressing the W-E-F nexus

In order to verify the theoretical approaches presented in section 2 we analyzed 19 real-life case studies and reviewed the benefits of NBS addressing the W-E-F nexus. Our search for real-life case studies revealed that NBS addressing the W-E-F nexus are widely spread across all geographic areas and generate a wide variety of primary and additional benefits. In the selection process, we made sure that the case studies have been implemented for several years and that some quantitative impacts of the NBS have been identified. Furthermore, we tried to select case studies that are distributed across the entire world to account for a worldwide representativeness. The selection was also made to investigate possible benefits which could derive from the implementation of different NBSs in full scale application. In each case study, the impacts of NBS on the W-E-F nexus were analyzed by identifying qualitative, quantitative, and secondary benefits. Furthermore, the NBS were classified according to Langergraber et al. (2020) into micro-, meso- and macro-scale NBS. Since each case study may address several nexuses, we believe this classification is most appropriate for the aim of this work. Finally, financing strategies were identified supporting the NBS as well. Table 2 provides an overview of the results from this analysis distinguishing between specific interactions of the dimensions water, energy and food (e.g., W-E; W-F; E-F) in each case study.

3.1. Micro-scale (individual household level)

Individual household-based solutions address different climatic hazards such as heat waves, heavy rainfall, water scarcity and biodiversity loss. Thus, climate change impacts can be tackled and mitigated by introducing natural features in the urban fabric, e.g. green roofs (European Federation Green Roofs and Walls, 2020). Several case studies of green roofs implemented worldwide showed both the capacity to slow down the water during heavy rainfall and a significant water harvesting capacity for further reuse, as well as their capacity to return water to the atmosphere through evapotranspiration (Petsinaris et al., 2020).

In Bologna, Italy, a community urban hydroponic garden was built as a 250 m^2 roof garden (building-scale), which allowed water savings around 25–30%. Concerning the W-E-F nexus, food production could be achieved by using the stored water through a closed-circuit pump. Subsidies were provided by the public regional and local authority budgets (Naturvation, 2017a).

The Southmead Hospital Brunel Building in Bristol, UK, implemented green roofs for runoff water and water consumption reduction. The project, financed by the Hospital, could reduce the runoff water (up to 40%) and water consumption (up to 25% of the total use), which resulted in an annual cost saving of around 130.000,00 £/y (oppla, 2020a).

Moreover, several case studies demonstrated how green roofs are effective also in terms of thermal performance contributing to mitigate the effects of climate change. In this perspective, investigations in Chicago, USA, showed that implemented green roofs could reduce the urban heat island effect, being 7 °C cooler than the nearby roofs (Land8: Land8: Landscape Architects Network, 2015a), thus resulting in lower energy consumption and thus reducing energy costs by about 5.000,00 $/y.

Table 2
The Water-Energy-Food Nexus (WEF) of nature-based solutions (NBS) in representative case studies.

Scale	NBS Projects (units)	Location	W-E-F[a] Potential Impacts	W-E-F[a] Quantitative effects	Sources
Micro-scale (relates to individual household level)	Community Garden of Via Gandusio (Community Garden)	Bologna	W-F: food production W-E: local cooling	W: 25–30% water saving F: 932 g food/(m^2 y)	(Orsini et al., 2014), (Naturvation, 2017a)
	Polderdak Zuidas (Green Roof)	Amsterdam	W-F: food production	W-E: 10–30% energy saving W: 83 m^3 water storage	(Amsterdam Rainproof, 2015; Naturvation, 2017b)
	The Brooklyn Grange (Rooftop farm)	New York		W: >662 m^3 rainwater retained/rainfall event; F: 13.4 t food/y (4.2 kg food/m^2) W-F: 6.4 kg food/m^3 stored water	(Harada and Whitlow, 2020; NYC Environmental Protection, 2019)
	Chicago City Hall (Green Roof)	Chicago		W-E: 7 °C local cooling; W-E: >5000$/y energy saving W: 75% water retention	(Land8: Landscape Architects Network 2015a; City of Chicago, 2020; Dvorak, 2009)
	Rooftop Park B.Bylon (Roof green park)	Amsterdam	W-F: food production W-E: local cooling	W-F: 100% of fallen stormwater for crop cultivation;	Naturvation (2017c)
	ASLA Headquarters (Green Roof)	Washington	W: runoff reduction	W-E: 6.1 °C local cooling; 10% energy saving W: 104 m^3 (77%) of rainfall retention	(Land8: Landscape Architects Network, 2015b), (Green Roofs n.d.; Werthmann, 2007)
	Southmead Hospital Brunel Building (sedum green roofs, therapy gardens, swales and attenuation ponds)	Bristol	W-E: energy efficiency	W: 25% water saving	oppla (2020a)
	California Academy of Sciences's Living Roof (Green roof)	San Francisco		W-E: 10% energy saving; W: 93% runoff reduction; 13249 m^3 absorbed/y;	(Green, 2011; Romancini, 2017)
	Concave Green Roof (flower garden, fish pond and vegetable garden)	Seoul		W-F: vegetable, crops and fruits (e.g. 80 kg honey/y) W-E: 27 °C local cooling; W1: 56% runoff reduction; W2: 6.7 m^3 water stored/140m^2	Baek and Han (2015)
	Greenpoint, - Gotham Greens (urban farming)	New York	W-E: energy efficiency W-F: water savings	F: 20 t/(ha y)	(Ackerman, 2012; Goodman and Minner, 2019; Gotham Greens, 2020)
	Vishvanath urban agriculture	Bangalore	W: water saving, wastewater reduction, local treatment of water and excreta E: local treatment and use F: reuse of nutrients, food production	F:100% rice production (staple food), 100% nutrient recovery, no industrial fertiliser, no energy for fertiliser, no transport, no piping for greywater, no extra treatment	Srikantaiah (2018)
Meso-scale (relates to community, neighborhood and district level)	Tree House Condominium (Green wall)	Singapore	W: water saving W-E: energy saving		Tan (2020)
	Water Decelerating Green Strip (Swales and filter strips)	Amsterdam	W-E: local cooling	W: runoff reduction as buffering capacity of 60 mm/h; 56 m^3 storage	Naturvation (2017d)
	Boeri Project (vertical forest)	Milan	W: runoff reduction, water saving; W-E: local cooling, energy saving;		(Giacomello, 2015; oppla, 2020b)
	Public Orchards and Nectar Gardens	Ljubljana	W-F: fruit trees (e.g. apple, pear, plum, mulberry, quince, persimmon, chestnut)		Naturvation (2017e)
Macro-scale (relates to city level or above)	Green roofs in Basel (Green roof)	Basel	W: runoff reduction	W-E: 4 GWh/year energy saving	(Climate, 2015; oppla, 2020c)
	Gorla Maggiore Water Park (Constructed Wetlands)	Milan		W: 86% peak flow reduction (downstream flooding −8900 m^3)	(Naturvation, 2017f;Rizzo et al., 2020; Liquete et al., 2016)
	Fornebu Stormwater Management System (Green corridor, Lake, Rain gardens, swales & filter strips)	Oslo	W: runoff reduction	W: 60% phosphorus removal; 40% nitrogen removal; 80%t total suspended solid removal; 230 m3/ha water storage	(Astebøl et al., 2004; Naturvation, 2017g; NWRM, 2015)
	Cheonggyecheon River Restoration (bioswales, dikes, drainage corridors, urban river terracing, vegetated revetment, vegetated riprap)	Seoul	W-F: food production	W: sustain 118 mm/h, for flood protection	Asian Development Bank (2016)

[a] W-E-F stands for water-energy-food nexus, W-F stands for water-food nexus; E-F stands for energy-food nexus; W stands for water; F stands for food; E stands for energy.

Energetic benefits were also measured in the green roof of the American Society of Landscape Architects (ASLA) Headquarters in Washington, USA, where the NBS reduced air temperature by up to 6.1 °C during summer, while during winter, the insulation allowed to decrease heating costs by 10% (Land8: Land8: Landscape Architects Network, 2015b).

In terms of food production, the concave green roof in Seoul, South Korea, is a good example of urban agriculture. The roof is exploited for crop cultivation and produces about 40 kg of honey per year (Baek and Han, 2015). The Brooklyn Grange Rooftop Garden in New York, USA, is a good example of food production by means of individual household-based solutions. Water absorption capacity (more than 662 m^3 of rainwater per rainfall event) is exploited to irrigate food crops with a production of about 13.4 t/y (4.2 kg/m^2) (Harada and Whitlow, 2020; NYC Environmental Protection, 2019). New York provides several examples of commercial rooftop urban farms (Ackerman, 2012; Goodman and Minner, 2019; Gotham Greens, 2020). Moreover, examples of urban agriculture can also be found in Bangalore, India, where rice is produced by 100% resource recovery from a dry toilet and greywater treatment (Srikantaiah, 2018).

While the real-life cases on a micro-scale level reveal direct benefits for local residents, the cumulative effects on a meso-scale or even macro scale have not fully been identified or quantified for the above-mentioned case studies. This reveals that the full extent, complexity and interconnectivity of NBS have not yet been fully described.

3.2. Meso-scale (neighborhood and district level)

NBS are also being implemented at the neighborhood and district levels. Partly because they allow an interconnected network of green spaces but also because different NBS units can be complemented with additional benefits, besides overcoming the climatic hazards mentioned in the previous section. Four examples located in Europe and East Asia were identified: i) Singapore, ii) Amsterdam, Netherlands, iii) Milan, Italy, and iv) Ljubljana, Slovenia.

In Singapore the "Tree House Condominium" project was developed, covering an area of 22,700 m^2 and a gross area of 52,437 m^2 of vertical gardens. The energy and water savings were estimated at $500,000/year. Furthermore, energy saving from the air conditioning due to local cooling was estimated to be 15–30%/year. The most important outcome of this project was the reduction of the residence's carbon footprint (Tan, 2020). Bioswales systems were also implemented, allowing rainwater collection for landscape irrigation and thus water saving of about 30,000 m^3 per year (City Developments Limited, 2014).

The Water Decelerating Green Strip located in Amsterdam, Netherlands, has a stormwater storing capacity of 56 m^3 with a buffering capacity of 60 mm/h. The NBS was created along the sidewalk where the storm water is temporarily stored by means of high-grade vegetation and a drainage system. The infrastructure is providing local cooling in summer and was financed by the local authority (Naturvation, 2017b).

The Boeri Project, a vertical forest on buildings in Milan, Italy, allowed the creation of a microclimate, which reduces summer temperatures by 2.5 °C. The project has a ground surface of 1500 m^2, and 20,000 m^2 of vertical green space was created to achieve carbon sequestration and storage. NBS implementation for urban regeneration, funded by the Lombardy Region and the EU, was launched in the project (Giacomello, 2015; oppla, 2020b).

In Ljubljana, Slovenia, the municipality has been implementing several public Orchards and nectar gardens with various vegetation types (Naturvation, 2017c). While providing local food sources these public gardens have increased the livelihood in the city by providing additional green areas, creating recreational areas, and generating a local cooling effect during hot summer periods.

The impact of meso-scale NBS proves to be substantial. However, the co-benefits for local residents on a micro-scale have not yet fully been quantified. This indicates that additional research is needed to provide a full picture of the co-benefits and interconnectivity on a micro and macro scale.

3.3. Macro-scale (city level or above)

On the macro-scale typical NBS include constructed wetlands (CWs), stormwater retention basins and restored natural rivers (Huang et al., 2020; Kabisch et al., 2017; Keesstra et al., 2018; Pagano et al., 2019). Such large-scale NBS require the participation of entire municipalities, in some cases even the involvement of several municipalities or regional governments. While macro-scale NBS require a high approval among the local population, the effects are significantly larger, especially in regard to flood events, as illustrated in the following examples.

In Milan, Italy, the 3 ha large Gorla Maggiore Water Park (GMWP) was inaugurated as a NBS for flood protection and is able to reduce flood peaks by over 80% (Naturvation, 2017d; oppla, 2020b). The GMWP also provides a wide range of educational services on the local fauna. Monitoring of the effectiveness of GMWP revealed: i) 86% peak flow reduction, ii) reduction of 11.7 t/yr of dissolved organic carbon and 0.4 t/yr nitrogen, iii) rich natural habitats iv) high social acceptance and v) only 29,590 Euro maintenance costs in 20 years. While food production has not yet been scientifically assessed, GMWP potentially offers opportunities for community gardening, adding to the W-E-F nexus.

In Oslo, Norway, the closed Fornebu airport has been redeveloped to a mixture of residential and industrial land use with a focus on green space and natural stormwater management, now known as the Fornebu Stormwater Management System (FSMS) (Astebøl et al., 2004; Naturvation, 2017e; NWRM, 2015). The FSMS is composed of permeable surfaces, swales, filter strips, detention basins, and retention ponds. The direct effects of FSMS are significant: i) 60%, 40%, and 80% of phosphorus, nitrogen, and suspended solids removed, respectively; and ii) the total water retention amounts to 230 m^3/ha. Accordingly, the FSMS provides significant flood protection, while reducing the energy demand for wastewater treatment. Furthermore, the large green areas could also create opportunities for community gardening, reducing the pressure on the W-E-F nexus.

In Seoul, South Korea, the Cheonggyecheon River has been restored and re-naturalized to provide a NBS for flood protection (Asian Development Bank, 2016). The restored river protects from 200-year flood events or precipitation events of up to 118 mm/h. The restored natural habitats have a tremendous effect on biodiversity with an increase of 639% between 2003 and 2008. The re-naturalized areas have a local cooling effect, reducing energy needs for cooling and are expected to enhance fishing possibilities in the future.

Green roofs have also been rolled out at city scale in Basel, Switzerland. Such green roofs have reduced the heat gain in buildings, lowering indoor temperatures by up to 5 °C and thus reducing the need for cooling and the related energy consumption (Climate, 2015; oppla, 2020c).

The NBS implemented on a macro scale level revealed to be efficient, increasing the resilience of local communities against climate change impacts. Our review of the case studies showed that further benefits on a meso- and micro-scale may exist, but have not yet been fully described or quantified.

3.4. Direct, potential and additional benefits of NBS

The 19 case-studies described in sections 3.1 to 3.3 provide a representative overview of the complex and interconnected benefits of NBS for the W-E-F nexus (or sub-nexus). These practical examples also reveal that the full potential has not yet been exploited nor researched, neither regarding the full impact on the W-E-F nexus nor the numerous additional benefits that NBS offer. A summary of these benefits, as provided by the commented case-studies, is combined in Table 3. In the following, we comment on the direct, potential and additional benefits that have been explicitly addressed in the 19 studied examples.

The direct benefits more commonly quantified in the case-studies,

Table 3
The benefits[a] of NBS making the Water-Energy-Food Nexus symbiotic.

Direct and potential benefits			Additional benefits
Water	Energy	Food	
Flood protection; Retention/Runoff reduction; Storage/Saving; Irrigation water; *Fertilizer production; Wastewater reduction & local treatment; Water availability during droughts; Local water balance;*	Temperature regulation supporting cooling effect and energy savings; *Savings in water transport*	Production of crops, vegetables, fruit; Community gardening; Urban agriculture; *Place for urban beekeeping; Fish ponds;*	*Reduce water pollution; Reducing noise, dust and air pollution; Providing bioenergy; Providing carbon uptake and storage; Microclimate; Enhancing connectivity of blue-green infrastructure; Biodiversity increase; Green spaces for recreation;*

[a] Italic text indicates possible benefits that have been mentioned in the examples but have not yet been described or quantified in the reviewed scientific literature.

independently of the scale of the implementation, are those related to water retention (runoff reduction), water storage (or water savings) and temperature regulation (providing energy savings). A large majority of the NBS in the case-studies help to mitigate floods, by controlling the runoff which enters into the sewer system (Petsinaris et al., 2020), while simultaneously allowing the storage and use of water. Examples of quantified water treatment and food production were also found. However, food production was one of the direct benefits mostly mentioned as a potential direct benefit but not exactly quantified, especially at meso- and macro-scale. Water treatment by NBS is commonly studied as an independent topic (Masi et al., 2016; Pradhan et al., 2019) and quite often not linked with the W-E-F nexus.

The additional benefits of biodiversity increase and carbon storage are consistently mentioned in the different examples, as well as the creation of green spaces and reduction of air pollution (Walters and Stoelzle Midden, 2018). Despite the importance of these benefits, few indicators have been used in the literature and the benefits were rarely quantified.

Interestingly, some subtle differences in potential additional benefits could be denoted from the variation in scale. At macro-scale multiple and wide-ranging positive effects were referred to, such as connectivity of blue-green infrastructure, enhanced flood protection and water availability emerged. For instance, in Jakarta, 21% of total green space is used for urban agriculture, community gardens, urban farms, and edible school gardens (Chandra and Diehl, 2019). However, the potential of such urban farming has not been recognized by the local government. A similar potential of urban farming has also been identified in developed countries such as Spain (Yacamán Ochoa et al., 2020).

An additional benefit, not directly mentioned in the case-studies analyzed but important to be highlighted, is the reduction of greenhouse gas emissions compared to conventional engineering solutions. For example, the integration of rainwater harvesting for food production in the roof Mosaic approach could reduce CO_2 emissions by 13.9–18.6 kg CO_2 eq/inhabitant/year (Toboso-Chavero et al., 2019). If the rainwater harvesting would be coupled to energy systems (photovoltaic or solar thermal systems) the CO_2 eq emissions could even be reduced by 177–196 kg CO_2 eq/inhabitant/year (Toboso-Chavero et al., 2019).

4. Discussion: The knowledge gaps and challenges for implementation of NBS to address the W-E-F nexus

The reviewed theoretical considerations gathered from the systematic literature review were critically compared with the knowledge gathered from the case studies to identify knowledge gaps (4.1) and challenges for future NBS implementations to address the W-E-F nexus (4.2), as well as to highlight the growing importance of circularity within the W-E-F nexus and urban needs (4.3). Fig. 2 provides a graphical summary of these issues.

4.1. Comparing the literature with case studies: the knowledge gaps

The literature review (Section 2) revealed that NBS and the W-E-F nexus are poorly assessed and benefits are rarely quantified. The relatively few publications (twenty, Table 1) hint at potential contributions to the W-E-F nexus and elaborate on a few theoretical considerations. The NBS case-studies (Section 3 and respective tables), widely distributed across all geographic areas, showed a wide range of benefits. While water management and energetic benefits were mostly quantified, benefits linked to food production were rather mentioned qualitatively. Table 3 summarizes the data available in the different case-studies (Table 2) that allow quantification of different nexus. The review of the case studies highlighted the scarcity of data available, especially regarding the subset F-E and the W-E-F nexus, particularly at larger scales. Interestingly, this issue herein observed, has been also reported beyond NBS. Zarei et al. (2020) concluded that studies dealing with sustainability in industrial subsystems rarely take into account the complexity of the W-E-F resources, and are generally limited to a binary combination of these three components.

Overall, there is a lack of information, making it difficult to quantify the contribution of NBS to the W-E-F nexus. Moreover, the usage of different indicators, especially related to food production, makes it difficult to highlight productivity or resource-saving. The lack of data may partly be explained by the various barriers towards implementation (Walters and Stoelzle Midden, 2018). It may also stem from a dichotomy between research and implementation of such approaches in cities, either by the public – the classical homestead or allotment garden with rainwater harvesting and possibly a composting toilet – or by city planning offices and urban professionals who are satisfied with the applications and do not see the need to monitor or assess the results.

From a critical comparison of Tables 1 and 2, it became clear that when it comes to practice and full-scale implementation, often, several NBS are fused within one project. For instance, green roofs are simultaneously applied with community gardens, rooftop farms, or green parks. So, several examples can be found for green roofs, while only one publication was found that, from a theoretical point of view, discussed green-roofs in the context of a W-E nexus. In the opposite direction, more theoretical mentions were found with NBS for urban farming, urban agriculture and hydroponics (and other -ponic related systems) than specific applications. Nevertheless, we should recall that while the present literature review was systematic, the analyzed case-studies aim to offer representative examples of NBS implementation in different parts of the world.

It appeared that scale could help organize the discussion of the examples, while for the theoretical exercise, the literature needed to be searched per NBS in order to find a maximum of publications. This is probably linked with the fact that also for the case studies, data for the F-E and W-E-F nexus was more difficult to find at the meso- and macro-scale. While water networks generally cover a whole city and NBS implementations for water management are more common at neighborhood scale, the food production implementations for which we have data are rather localized. This does not mean that they can't be rolled out at neighborhood or city level by multiplication of small implementations, as seen for the case of green roofs and energetic benefits quantified in Basel at a city-scale.

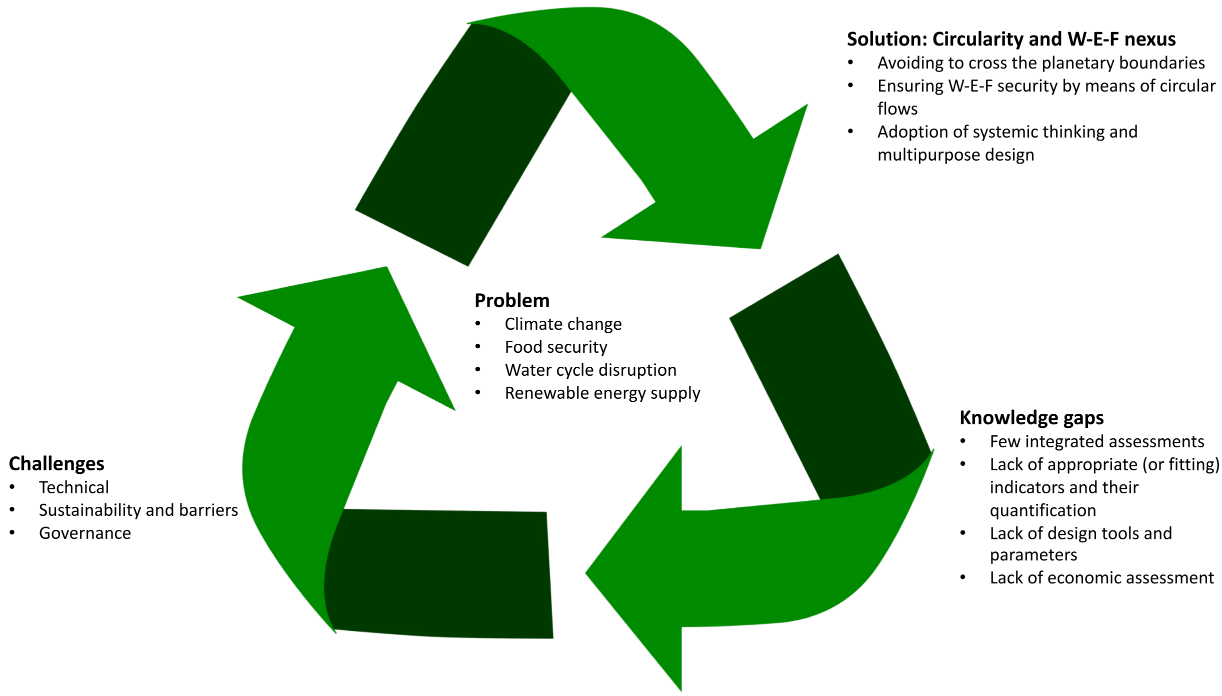

Fig. 2. Overview of the main points covered in the discussion. From the problem to the solution identifying the knowledge gaps and challenges.

Despite the widely discussed ability of NBS to solve issues with the W-E-F nexus, more research is required to thoroughly demonstrate this potential in a detailed and interconnected manner. To date, NBS lead only partly to direct or additional benefits through environmental sustainability, such as water reuse, nutrient recovery, food production and cooling effects. Thus, while it was possible to conclude that there are positive impacts of NBS on the W-E-F nexus, their exact quantification for a detailed design is still missing. One of the reasons might be the lack of well-defined and standardized indicators, an issue being addressed in the COST Action 17133, as well as the project EdiCitNet. In order to make the best use of NBS for the W-E-F nexus, new indicators in the context of sustainable resource management, social engagement, and business model optimization toward circularity have recently been proposed (Nika et al., 2020a, 2020b). These new indicators and new standardized methods of assessment, as well as the state of play in urban implementation of evaluation frameworks (Dumitru and Wendling, 2021) need now to be implemented and translated into new results.

4.2. Challenges for further implementation

It seems clear that the implementation of certain NBS may achieve more efficient and sustainable management of the multidimensional W-E-F nexus in urban areas. With the aim to provide a holistic framework of the problem and solution, identification of possible feedback loops and trade-offs among the multiple dimensions (e.g., technological, financial, political and social), effective participatory schemes (e.g., stakeholders engagement), as well as the development of adequate performance assessments (e.g., monetary and non-monetary valuation of benefits) are much needed (Raymond et al., 2017). This section expands on several challenges for implementation that have been identified and summarized in Table 4.

Table 4
Summary of the identified challenges for further implementation (section 4.2).

Type of Challenge	Identified challenge
General	• Lack of knowledge on feedback loops and trade-offs among the multiple dimensions (e.g., technological, financial, political and social) • Lack of awareness on specific examples and knowledge for large-scale solutions • Lack of examples across different geographical locations with different technical and societal challenges
Technical	• Installation and maintenance costs • Structure weight limitations (e.g., greenroof, greenwall) • Limitations when retrofitting existing buildings (e.g., installation of separated pipelines for grey and black water) • Lack of design standards • Lack of knowledge and examples on how to close loops both under centralised and decentralized solutions including the three W-E-F nexus dimensions • Need to follow the quick expansion of the Internet of Things (IoT) • Water-quality issues for emission/discharge • Water-quality issues for crop production
Governance	• Lack of effective participatory schemes (e.g., stakeholders engagement) • Lack of adequate performance assessments (e.g., monetary and non-monetary valuation of benefits) • Reduced promotion of the multi-functionality of NBS • Cultural practices • Novel perspectives for urban water resource management keep evolving • Complexity of the water sector • Legislative and framework barriers (which can also impose technical challenges) • High realization cost by comparison with "politically" mediated water tariff

One of the current greatest challenges is the lack of awareness on specific examples and knowledge on how to adapt some of the local solutions to larger scales. For instance, city-scale effects of urban rooftop agriculture are still under discussion as hypothetical (Harada and Whitlow, 2020). The integration of single site-specific NBS into an interlinked green infrastructure framework is also a critical challenge. Especially, when specific quantitative indicators are not documented. Furthermore, practice at one place, such as Ljubljana or Milan, applies specifically to this geography, but not necessarily to Oslo or much less to an Asian megacity. Besides climate and scale, the population factor can also be added to this (Ruangpan et al., 2020). Thus, the relationship between NBS and W-E-F nexus is currently not fully resolved, and the issues with geographical locations and specific natural and cultural conditions can hinder further replication of the technology. This can potentially be overcome by increasing the number of studies and demonstration projects, and consequent available data and documentation.

4.2.1. Technical

On the technical dimension, several obstacles to urban farming implementation have been listed by Walters and Stoelzle Midden (2018) and include installation costs, roof weight limitations, media composition and depth, cultural practices, potential water-quality issues of effluent runoff, and influence of crop production. In addition, maintenance costs could constitute a barrier to the production of cultivated green roofs (City Farmer, 2006). A particular challenge in some countries is the retrofitting of existing buildings and related infrastructures, i.e. the installation of separated pipelines for grey and black water (Liu et al., 2018). In terms of food production, NBS are important, but it is also known that to ensure food security in urban areas, complementary sources of food production are needed (Walters and Stoelzle Midden, 2018). Moreover, one should mention the potential hazards dealing with the reuse of stormwater (contaminated rain water in cities), highlighting the importance of properly handling rainwater for food production.

Nowadays the quick expansion of the Internet of Things (IoT) is making it feasible to remotely and continuously monitor NBS, further reducing the need for direct interventions (in person) for their management. A study recently conducted in Italy on a constructed wetland has demonstrated excellent performances in describing the effluent pollutant concentration by an online sensor (Rizzo et al., 2020). Thus, IoT can play a role in facilitating the integration of decentralized treatment NBS options within the smart cities developments, but it also demonstrates that it is possible to extend remote monitoring and control to other types of NBS more focused on energy or food production.

Most of the NBS are still missing design tools or parameters to guarantee effectiveness or to facilitate the expression of the multiple benefits/ecosystem services they can provide (Kumar et al., 2020). As an example, a general guideline for sizing green walls aimed to treat and recycle greywater is still missing (Boano et al., 2020), despite the first appearances of such products on the market. This kind of technical gaps can be mitigated by initiatives like the COST Action CA17133 and its Green Walls Cluster working on design criteria and replicability. The lack of guidelines for new solutions can prevent their application because such solutions do not get a permit (Cipolletta et al., 2020). However, one should keep in mind that guidelines can also limit innovation and disruption of established concepts, which is needed towards fulfilling the W-E-F nexus in an efficient and circular way.

To allow for effective cycles and loops, a paradigm shift is needed: from "wastewater treatment" to "irrigation water and fertilizer production from wastewater". New sanitation systems, that are specifically designed for water and nutrient recovery, can and should be merged with the implementation of NBS. As urban food production tends to be decentralized, local decentralized NBS solutions for water management will be particularly appropriate. The shift from waste treatment to production of a system feed may not be limited to water, but equally to other resources, e.g., organic matter or heat, ultimately encompassing all the aspects of the W-E-F nexus.

4.2.2. Governance

A wide adoption of urban NBS can provide numerous and consistent additional benefits and services (such as microclimate improvement, provision of open spaces for recreation, enhancing the quality of life in urban areas and others) beside their main function (e.g., treating polluted wastewater, draining impervious surfaces) and surely a higher flexibility and resilience to climate changes. These additional benefits can be decisive in the choice of an alternative and a detailed study of alternatives including environmental, economic and social aspects - substantially a Multi-Criteria Analysis - should be conducted in the preliminary design phase (Liquete et al., 2016; Llano et al., 2021b).

Despite the capacity of NBS to provide multiple benefits and fulfil multiple functions, these solutions are frequently considered as mono-functional solutions. Thus, there is a need for targeted promotion of the multi-functionality of NBS, in order to raise the awareness of the general public, as well as local and regional governments and to support the understanding of the benefits and acceptance of the solutions.

Governance issues may impose significant limitations for an efficient management of the W-E-F nexus. As an example, demand for water keeps expanding, consequently requiring novel perspectives for urban water resource management (Zhou et al., 2021). Water reuse, resource recovery, and water-related loops are increasingly popular issues (Cipolletta et al., 2020; Zhou et al., 2021; Oral et al., 2021) to which NBS can provide specific contributions. However, the development and implementation of these concepts, including by NBS, is hindered by the complexity of the water sector, making the sustainability of the sector primarily a governance issue (Franco-Torres et al., 2021). NBS faces the same challenge as other innovative technologies to increase water reuse, by having to deal with varied legislative and framework barriers (Cipolletta et al., 2020). Moreover, technical issues also arise from the legislation. For instance, the latest EU regulation on water reuse has an indicative technology target with disinfection (European Parliament, 2020) and is limited to agricultural reuse. This leaves domestic loops like greywater recycling, regulated by very different national norms. The latter are making the elaboration of valid business models very difficult, with a lot of uncertainties and unpredictable patterns (Fogarassy and Finger, 2020).

The last decades have shown us an efficient adoption of regulations that promote a sustainable approach to the urban water cycle (Oral et al., 2021). For instance, green roofs uptake has benefited from the widespread implementation of legislation (Susca, 2019) as well as from positive examples and incentives from local authorities (Tóth et al., 2019).

A relevant issue for the real-world application of NBS technologies is the realization cost, often too high when compared to the still often "politically" mediated water tariff. The low cost of water is making the payback time too long for attracting private investors, as families, even when the investment cost is not particularly expensive. As pointed out by Dinar (2000) and Massarutto (2020), certain socio-political factors (i.e. the reason for pricing reforms, parties involved, existing institutions and the power systems) constitute important challenges to be addressed since they prevent the implementation of pricing reforms for a more sustainable use of water resources and the promotion of NBS. Nevertheless, investment costs can be very high (depending on the scale and the population served) and usually need an adequate mix of public (i.e., taxation and subsidies, environmental taxes, payment for ecosystem services and other economic instruments), private and social (e.g., community and social institutions) financial sources with the appropriate market and fiscal incentives.

From local and national public institutions, subsidies to stimulate NBS implementation and innovation in the real estate sector are being widely used. In the private sector, the adoption of circularity and resource-efficient measures is providing an adequate framework for the development of NBS in urban areas. Finally, neighboring crowdfunding has been shown to be another significant source of financial resources in urban communities. Regardless of the financial sources used, some common challenges are observed, such as longevity and maintenance of the infrastructure, the scale of the NBS investment, risks associated to the return of NBS investments, land ownership in urban areas, impact assessment and monitoring of linkages in the W-E-F nexus, and insufficient stakeholders' engagement. To promote public participation (e.g., policy-makers, citizens), several tools have been shown to be effective, such as the Adaptation Planning Support Toolbox (van de Ven et al., 2016) and public participation GIS (Raymond et al., 2017).

Related to the fiscal and financial challenges, the economic assessment of NBS benefits represents a practical governance challenge for the design of adequate policy instruments for its promotion (e.g., taxation, subsidies). A wide range of methods for monetary and non-monetary valuation can be applied in the economic assessment of NBS (Derkzen et al., 2017; Nika et al., 2020a), Life Cycle, Cost-Benefit Analysis and Eco-Efficiency being the most used methodologies (Ghafourian et al., 2021). In the last decade, important efforts have been made to develop integrated methodological frameworks for the economic assessment of NBS considering social, environmental and economic impacts (Le Coent et al., 2021; Ghafourian et al., 2021). Despite these recent promising advances, and as pointed out by Kumar et al. (2021) and Wishart et al. (2021), among others, holistic models that integrate the functions, benefits and costs of NBS are not readily available. Therefore, further research is needed to produce integrated and holistic assessment methods of co-benefits across different scales and multiple stages of NBS implementation (Raymond et al., 2017; Kumar et al., 2021) as well as to dynamically evaluate the feedback loops in the W-E-F nexus. Such methods would facilitate the assessment of impacts under different NBS scenarios, as well as the upscaling and replication of these solutions.

4.3. NBS are essential to address the future W-E-F nexus

The benefits of NBS to address the W-E-F nexus, identified in section 3, reveal the potential for efficient, affordable solutions to address future environmental challenges. Since the 1950's concerned scientists have been warning that global resources are limited and that modern society may be jeopardized if planetary boundaries of the exploitation of natural resources are reached (Hubbert, 1956; Meadows et al., 1972; Rockström et al., 2009). NBS have the potential to reduce the pressure on the W-E-F nexus and the planetary boundaries. The presented case-studies illustrate that it has become essential to adopt circular economy solutions (Fogarassy and Finger, 2020) in order to address the W-E-F nexus.

Another scenario where NBS can play a relevant role in the modern urban centers, is the one just observed recently with lockdowns for a pandemic. The forced presence at home coupled with issues with local water supply, could bring severe problems of intermittent or even very partial service. NBS able to generate "new water" can help in reducing the local water demand, especially when emergency causes, such as climate change, are creating dramatic shortages.

Overall, NBS deal well with different challenges due to their multifunctionality, possibly the main driving force to address the SDGs (Gómez Martín et al., 2020). Moreover, NBS are in line with the major current European strategies to preserve biodiversity and reduce environmental impacts. Specifically, within the framework of the European Green Deal, the European Environmental Bureau (EEB) proposes NBS as a way to support the transition towards a more sustainable food production while preserving biodiversity and natural resources (European Environmental Bureau (EEB), 2020). In this perspective, NBS could be part of a sustainable strategy, supporting every step of the food chain, from "field to fork to field".

5. Conclusions

NBS can make the W-E-F nexus synergetic and circular if smartly embedded into urban systems. This is necessary for environmental, political (e.g., EU Green Deal) and social reasons, to ensure that we stay within the nine planetary boundaries. In summary, this study has highlighted that often the W-E-F nexus is included as a keyword in publications, but rarely mentioned or discussed in the work. Moreover, theoretical concepts of NBS addressing W-E-F nexus are frequently driven by technical solutions and less by system analysis. Our review of case-studies has also shown that examples of NBS addressing W-E-F nexus are easily found for microscale, while macroscale examples are mostly related to water management. Regarding the potential benefits of NBS at addressing W-E-F nexus, these have been demonstrated by the reviewed literature, with a special emphasis on direct benefits (e.g., water retention, food production, temperature regulation). On the contrary, indirect benefits have been poorly studied in connection to the W-E-F nexus. Additionally, quantification of benefits is mainly carried out by using not well-established indicators, thus lacking an in-depth and holistic analysis.

Several knowledge gaps and challenges in the use of NBS in urban areas to address the W-E-F nexus have been identified, covering technical, sustainability, and governance issues. There is a need for systemic thinking to achieve a multipurpose design in order to improve livelihood while providing services at a lower cost. The potential benefits of NBS for the management of W-E-F nexus need to be comprehensively assessed taking into consideration all relevant components, including Natural Capital losses and recovery. Although NBS can potentially achieve circularity objectives, further aspects of NBS should be explored, such as the development of assessment frameworks and indicators. In this sense, future research should develop a specific framework of W-E-F indicators that need to be multidisciplinary and cross-sector in order to assist decision making.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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