The Water-Energy-Food-Ecosystems (WEFE) Nexus

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Water in the Nexus

The last few years have witnessed an increasing attention to water beyond its environmental role and looked at water crises as a major global risk to social and economic stability. An example is the report on Global Risks released by the World Economic Forum (WEF, 2018) or the World Bank report "High and Dry" (World Bank, 2016), which predicts that some regions in the world could see their growth rates decline by as much as 6% of GDP by 2050 as a result of water-related losses. Indeed, demand for water from agriculture could increase by 50%, for urban uses by 50% to 70%. According to FAO (2018), feeding a global population expected to reach 9 billion people by 2050 will require a 60% increase in food production. Global energy consumption is projected to grow up to 50% by 2035 (IEA, 2010). However, constraints on water can challenge not only the physical, economic and environmental reliability of future projects, but also that of today's existing operations. The Californian "almond case" is a striking example of this challenge (Le Monde, 2015). In California, which is heavily affected by drought since a few years, the 900 tons of yearly production of almonds uses the same amount of water necessary to quench the thirst of the inhabitants of Los Angeles, San Diego and San Francisco, which, together, represent two thirds of the entire Californian population, while almond production represents just 2% of the State's GDP. In Poland, the summer of 2015 experienced a heatwave that drained the rivers supplying water to cool power plants resulting in problems of electricity supply (Reuters, 2016). In 2015, the European Parliament released a report on the implementation of current EU water legislation and confirmed that there are still implementation gaps with missing economic benefits estimated in the order of 2.8 billion euro per year (EPRS, 2015). One of the reasons is that the goals of water protection policies and related policies, particularly energy and agriculture, are occasionally incoherent or even in conflict.

Constraints to water supply/availability can then occur naturally, or be human-induced, as a result of growing competition among water using sectors. The examples above show that securing resilience of global energy and food systems needs to build on better and nontransient fairness of water allocation strategies across the energy and the food sectors, especially in light of the expected growing of pressures in the coming decades also associated to climate change. What we need is to overcome stakeholders' view of resources as individual assets by developing an understanding of the broader system. This points to the interdependency of policies and introduces the notion of Water-Energy-Food Nexus.

From Concept to Implementation

The Water-Energy-Food Nexus is a cross-sectoral perspective which requires that response options go beyond traditional sectoral approaches. It means that the three sectors or securities—water security, energy security and food security (Sustainable Development Goals or SDGs 6, 7 and 2)—are inextricably linked and that actions in one area have impacts in one or both of the others. However, a fourth leg that we should consider in the Nexus is that of ecosystems, as they are central in providing and sustaining these three securities, through the services they deliver to the human being and society. Exploitation of water, agricultural and energy resources should not undermine the provision of these services, especially considering that they are often at the basis of the only resources available to poor people in different parts of the world. **Fig. 1** shows these interlinkages. At the same time, some of the impacted ecosystem services may support combinations of both built and natural infrastructure that in turn provide water services or can be considered solutions to water resources management challenges from sedimentation in reservoirs to water purification (Baker *et al.*, 2015; UNEP, 2014). The Nexus is about understanding and managing often-competing interests, while ensuring the integrity of ecosystems.

According to FAO (2002), food security is defined as "availability and access to sufficient, safe and nutritious (nutrition security) food to meet the dietary needs and food preferences for an active and healthy life." Food is defined as a human right. The end products for food security encompass edible agricultural crops, livestock products (meat, dairy and eggs), freshwater fish (wild and aquaculture), wild foods (e.g., berries, mushrooms, fruits, nuts, game and bushmeat, insects), but also marine fish and seafood. The International Energy Agency (IEA) defines energy security as "the uninterrupted availability of energy sources at an affordable price." The UN defines it as "the access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses (end products)." Primary energy is generated by means of fossil energy, nuclear energy and renewable energy. Water security is defined as "access to safe drinking water and sanitation," both of which have recently become a human right (UN, 2010). One of the most frequently resources required for realizing the nexus, that is, minimizing tradeoffs and maximizing synergies across resource securities, is water. **Fig. 2** shows the links between available water resources (green and blue) and food security, energy security and water security. Interlinkages are many and consequently possible tradeoffs too. The nexus between energy and food security is, for example, very visible in the amount of energy required for food security, which is about one third (32%) of global energy end consumption (from farm to fork) (FAO, 2011). The primary production of crops, livestock and fisheries accounts for 6.6% of global energy end consumption.

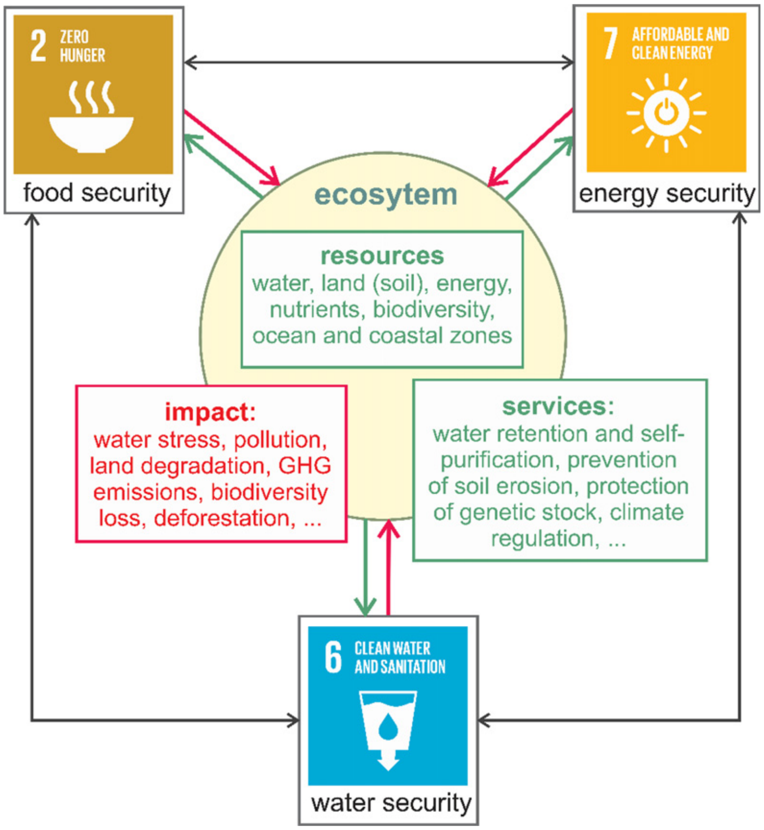

Fig. 1 Schematic representation of the WEFE Nexus.

Generally, national governments and international organizations have separate departments/ministries dealing with water, energy, and agriculture. They often define and implement policies for each sector separately (SEI, 2014). The same is true for research on these issues: expertise on energy, water and food systems is clustered in separate groups, with often limited interaction (SEI, 2014). It is on this basis that the cross-institutional planning of water resources referred to as integrated river basin management is often conducted. The Nexus approach recognizes that water, energy, food and ecosystems are closely linked, through global, basin and local resource use and impact cycles. In developing an effectively integrated nexus approach it is important to recognize that many activities take place at the very bottom of the grassroots, at the level of, for example, households, farmers. An array of options and measures adapted to the specificity of local conditions need then to be developed.

Terminology in the Nexus Communication

The Nexus is often accounted for in different terminologies or even defined in different ways, but addressing the same concept. Different authors use the terminology FEW (Food-Energy-Water) Nexus, especially in the United States (Chini *et al.*, 2017). Others mix the components in a different order, for example, the EFW Nexus (Owen *et al.*, 2018; Liu *et al.*, 2018), as often referred to by energy experts, putting the E first. Other authors define the Nexus in a variety of combinations, like the Land-Water-Energy Nexus (Silalertruksa and Gheewala, 2018), the Water-Land-Food Nexus (Rulli *et al.*, 2016), the Land-Water-Energy-Food Nexus (Siciliano *et al.*, 2017), the Water-Land-Energy-Food-Climate (WLEFC) Nexus (Munaretto and Witmer, 2017; Sušnik *et al.*, 2018) or many others. These terminologies try to describe the complexity of the Nexus, however they often differ from the original definition (Hoff, 2011) by including elements like land or climate that are not securities, but resources or impacts.

Exploring WEFE Interdependencies

Water, energy and food resources are linked through many interactions: we need water for power generation (hydropower, cooling, biofuels, etc.), while at the same time large amounts of energy are required to pump, treat and desalinate water, and both water and energy use are required for food production and distribution. Using water to irrigate crops can increase food production, but also reduce river flows and hydropower potential as well as affect water quality and ecosystem health and services. Growing bioenergy crops under irrigated agriculture can increase overall water withdrawals and also affect food security. Converting surface irrigation into high efficiency pressurized irrigation may save water, but also result in higher energy use.

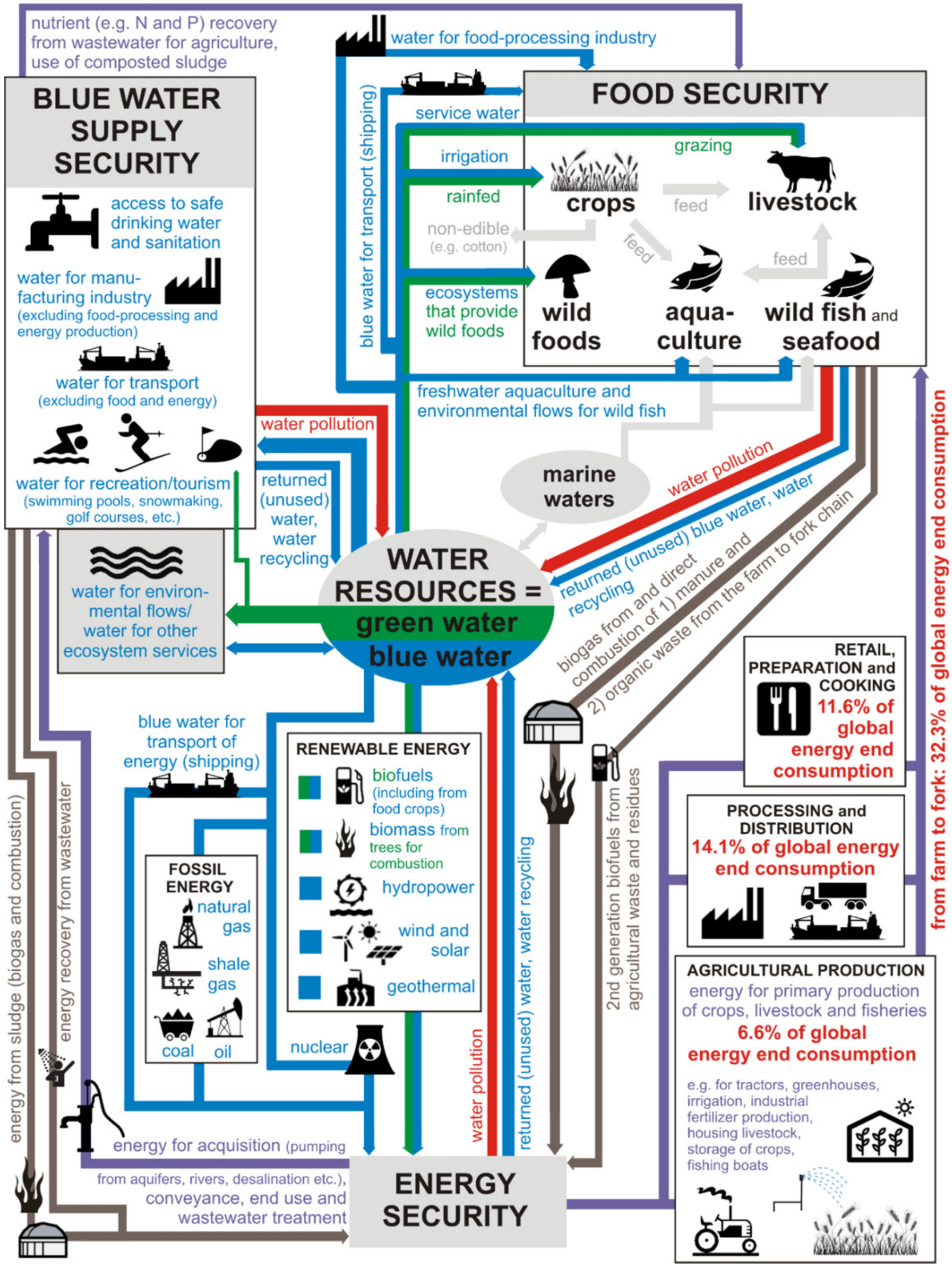

Fig. 2 The WEFE Nexus for blue and green water, as presented in Vanham (2016).

The modernization of the irrigation sector that took place in Spain in the years 1950–2007 offers a paradoxical example of the energy-water interdependency (Tarjuelo *et al.*, 2015; González-Cebollada, 2015). During this period, water consumption by agriculture has quadrupled, due to a shift of cropping patterns with greater water needs, also influenced by subsidies. Efforts mostly focused on irrigation efficiency (from 67% to 82.5%) resulting in a 19-fold increase in energy consumption, which has led to an increase in water costs. Irrigation systems modernized in a climate of strong public support without giving much thought to the significant energy dependence they would introduce may then represent a barrier to economic sustainability for certain crops and irrigation regions.

Hydro-economic interdependencies exist also between distant global geographies via trade, especially of agricultural and manufactured goods (Vanham and Bidoglio, 2014). This makes local consumption dependent on foreign water resources and increases virtual water exports from other regions.

The Water-Energy-Food-Ecosystems (WEFE) Nexus highlights the need of a joint management of bundles of resources, rather than of individual resources, if we want to achieve sustainable development (Biggs *et al.*, 2015). The Sustainable Development Goals (*SDGs*) of the 2030 Agenda set by the United Nations promote a crosscutting understanding of the interdependencies of the goals and targets as opposed to their individual consideration. It follows that the implementation of the Nexus helps meet the SDG commitments. Indeed, accounting for tradeoffs and synergies of the WEFE Nexus contributes to the achievement of a number of interdependent SDGs. The WEFE Nexus directly addresses a number of SDGs: SDG 6 (clean water), SDG 7 (clean energy) and SDG 2 (zero hunger), while the last E of WEFE refers to other SDGs like 14 (life below water) and 15 (life on land). Resilient communities better prepared to react and recover from water resources crises are those that have identified crucial interdependencies and built relationships between the water-using sectors.

Ecosystems as Fourth Pillar of the Nexus

Aquatic ecosystems offer a wide array of benefits to human society, such as water retention and self-purification, the prevention of soil erosion, the protection of genetic stock. Preserving these services guarantees the maintenance and improvement of water quality and quantity, increases the resilience of ecosystems to natural and man-made alterations making floods less severe, food and energy production more reliable (Russi *et al.*, 2013; UNWWAP, 2018). Ecosystems have then to be considered as water using sectors on an equal ground as food and energy production. The practical instrument for achieving these interdependent goals is the deployment of green–blue infrastructure, or "natural infrastructure." This refers to the network of green (land) and blue (water) spaces that provide services to people, can help decision makers and infrastructure managers address interconnected challenges facing water, energy and food systems. The value of ecosystems is explicited in the EU policy-making process (e.g., Water Framework Directive, Common Agricultural Policy, EU Biodiversity Strategy) by promoting nature-based solutions (NBS). The EU has promoted a Green Infrastructure Strategy to become an integral part of spatial planning and territorial development whenever it offers a better alternative, or is complementary, to standard gray choices (EC, 2013). This is reflected in certain research projects on NBS in the urban environment (EC, 2015; GrowGreen, 2018), another key scale for Nexus implementation considering that cities are where global and local resource constraints meet. The potential of nature-based solutions to address water management across the agricultural sector, sustainable cities, disaster risk reduction and improving water quality is also addressed by the 2018 UN World Water Development Report (UNWWAP, 2018).

What makes natural infrastructure particularly attractive is its multifunctionality, that is its ability to perform several functions and provide several benefits on the same spatial area. The challenge is to build on the knowledge gained from the traditional and local sustainable water management practices, link the green–blue infrastructure or "natural capital" part to ecosystem services and their role in river basin management plans, including investment in these natural solutions instead of purely technical ones. While in some cases planners may directly compare the advantages of "green versus gray" water infrastructure solutions, greater emphasis should be placed on understanding how green solutions can be integrated within an overall system of water management, composed of appropriately sited and designed elements of both green and gray water infrastructure (UNEP, 2014). Any methodology for developing combined portfolios consisting of green and gray alternatives, or mutually supportive green and gray elements, should therefore provide meaningful evaluation of all water infrastructure options, including in monetary terms to the extent possible. This then leads to the development of adequately informed strategies for investing in natural infrastructure. For these to be incorporated into broader infrastructure packages, appropriate mechanisms for investment are however needed that can unlock financing for ecosystem management that also supports empowerment of stakeholders to participate in and enable implementation of these options (Bennett *et al*,. 2016). Forms of investment in natural infrastructure are sustainable dam management for the Nexus, certifiable standards for watershed stewardship, and public–private partnerships for Payments for Ecosystem Services (PES). These are established instruments, not without hurdles, to direct private and public investments to sustain provisioning services in ecosystems and watersheds (Bennett and Carroll, 2014). As an example, a water conservation project along the Cauca River near the city of Cali in Colombia pooled money from downstream water users to pay upstream stakeholders who have the ability to impact water quantity and quality and to implement projects and practices addressing the interdependent, downstream's needs for food, energy and water (Madre Agua Water Fund, 2018). Ozment *et al.* (2015) examine reasons and ways to include natural infrastructure in the Nexus along with challenges that have prevented increased investments and recommendations for moving forward. For example, they present recent studies that estimate that the global community invests about 12.3 billion $ per year to protect, manage and restore natural infrastructure to secure water resources. Yet, the energy and agriculture sectors collectively contributed less than 1% of all natural infrastructure investments in 2013. Partnerships are still needed that proactively identify more opportunities to invest in green–blue infrastructure, leverage new sources of financing, and reform policy and standards to broaden investments.

In Search of Appropriate WEFE Nexus Indicators

By their nature, water, energy, food and ecosystems require integrated and transdisciplinary approaches for addressing the peculiarity of their interlinked temporal and spatial variabilities. However, integration goes beyond these pillars and should include social, political and governance aspects. In addition, the Nexus approach should consider tradeoffs, not only across sectors, but also among different users of the same sectors (Sønderberg Petersen and Larsen, 2016). Moreover, solutions valid in a place do not necessarily apply under different bio-geographical and socio-economic conditions (Liu *et al.*, 2017). In this context, data and appropriate methodologies are needed to inform on these complex interlinkages, in the present situation and also under different future scenarios, to help policy makers in decision making. Most of the existing WEFE Nexus analyses have been performed at large scale ranging from global, to regional and national (Martinez-Hernandez *et al.*, 2017), however at very coarse resolution. As international and regional decisions have significant impact at the local level, the local specificities need to be considered when designing efficient management strategies (Aarnoudse and Leentvaar, 2015). However, the local scale is rarely addressed even though it is the relevant scale at which policy implementation is usually taking place and where synergies between the food, water and energy can be enhanced (Martinez-Hernandez *et al.*, 2017). As stressed by Mohtar (2016), it is at the local scale that also the SDG targets deliver their benefits. Different assessment levels are then needed to address the WEFE Nexus.

Addressing the WEFE Nexus or the achievement of the associated SDGs requires a holistic approach and a systems view (Bazilian *et al.*, 2011; UNECE, 2015; de Strasser *et al.*, 2016). Endo *et al.* (2017) classified the tools used in Nexus studies in two broad categories including qualitative and quantitative approaches. Qualitative approaches are used to identify the priorities and understand the types of environmental, economic and societal tradeoffs. Quantitative methods are used to assess baselines and carry out scenario analyses for the evaluation of the impact of alternative proposed interventions. Examples of how an assessment of the four pillar Nexus can be operationalized are offered by Tesfaye *et al.* (2016) and Karabulut *et al.* (2016). These authors investigated spatially explicit tradeoffs and co-benefits for two large transboundary river basins, the Blue Nile basin in Ethiopia and the Danube River basin in Europe. A wide range of the facets of the water-food nexus have been analyzed in a series of multidisciplinary papers edited by Laio *et al.* (2017). A coupled simulation and optimization tool with which stakeholders can define their own objectives was proposed by Karnib (2017). A systematic review of Nexus-specific methods by Albrecht *et al.* (2018) shows that mixed-methods and interdisciplinary approaches are needed that incorporate social and political dimensions of water, energy and food. Dai *et al.* (2018) found that fewer approaches are designed to support governance and implementation of water-energy nexus technical solutions. In general, most of the published Nexus studies are considering two sectors, rarely the three components of the WEF, leaving repeatedly ecosystems outside the analysis (Martiner-Hernadez *et al.*, 2017). Moreover, our understanding and representation of the interactions and tradeoffs are often limited by data availability, collection and management thus failing to encompass a comprehensive overview of the interlinkages between the pillars of the Nexus.

Nexus Solutions for Sustainable Development

Already today different control variables within the planetary boundary framework show human-made disruptions (Steffen *et al.*, 2015). Climate change and global socio-economic developments like population increase, rapid urbanization, changing diets and economic growth are among drivers that will increase the demands for energy, food and water. Can we afford continuing in this way? Certainly not if we consider that about 78% of the world's total active workforce is water-dependent globally (WWAP, 2016).

These considerations place the Water-Energy-Food-Ecosystems Nexus at the core of resilience strategies (Smith, 2016). To implement the Nexus we need actions for the development of a multilevel governance, the investment in human and social infrastructure, the enrollment of technologies across water-using sectors, and the leveraging of public–private cooperation. Governance deals with the ability of institutions to manage water use through different sectors and propose policies that are socially acceptable and can address competition through an analysis of tradeoffs. To this end, rules and regulations are necessary, but not sufficient if not integrated with constructive engagement of social actors, as good WEFE Nexus practices that work in a place do not necessarily apply to different social, economic and geographical conditions. The organizational model must accommodate creation and diffusion of technology tools that span multiple applications and innovate solutions across water-using sectors. This will require creating incentives for public–private partnerships to cultivate the innovative operational models, policies, strategies and technologies.

The circular economy dynamics based on reuse and recycling offers the framework for conserving and saving water, energy and materials by ensuring the balance between supply and demand from the different sectors. If supply decreases, we have to find ways of reducing demand or decrease losses. Opportunities exist especially in the field of efficient irrigation techniques, sustainable water pumping, crop refinement techniques, water efficient appliances and processes, technologies for aquifer storage as well as water treatment and reuse. The IGN Group and the Ellen McArthur Foundation released a report addressing the concept of circular economy in relation to the water sector (IGN, 2017). For the investigated countries, circular water economy has the potential to save 412 billion m^3 of water a year, which is equivalent to 11% of annual global water demand, or almost the entire water consumption in the United States. Of course, this does not equally applies everywhere. The concept of circular economy is very much different from regions to regions in the world. The report shows that effects are different, for example, from California to the Emirates. In addition, circular economy measures can look appealing when viewed in isolation. However, circular economy requires a system approach to be developed not only for water, but also for its nexus with energy and materials.

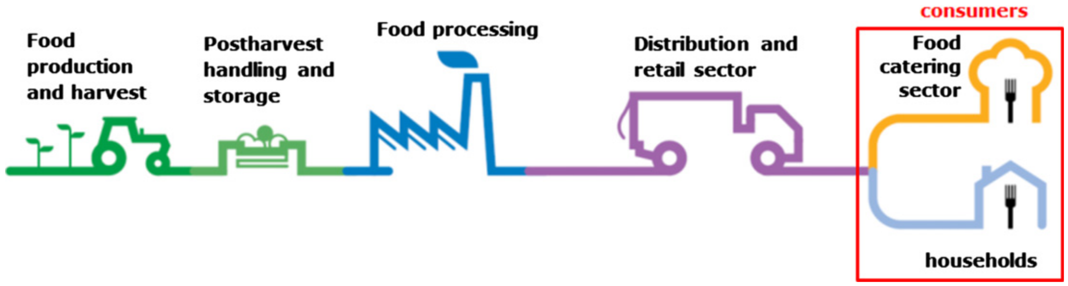

Fig. 3 Graphical representation of the food supply chain. Solutions to address the Nexus need to come from all stages within supply chains. Different processes can take place in different geographical regions.

Policy, science and technology can bring about change, but this change takes place in a specific local ecological, economic and cultural context. In order to provide water, food and energy security to a growing and urbanizing global population, within global planetary boundaries with limited resources availability (Rockstrom *et al.*, 2009; Steffen *et al.*, 2015), solutions need to come from all stages within supply chains (**Fig. 3**), that is, from the production to the consumption side (Godfray *et al.*, 2010; Foley *et al.*, 2011).

Production side solutions may include (Godfray *et al.*, 2010; Foley *et al.*, 2011):

- The sustainable intensification of agriculture (Garnett *et al.*, 2013). In order to close yield gaps, nutrient management and integrated land and water management on existing agricultural lands (rainfed and irrigated) are key to this development (Mueller *et al.*, 2012). Often the increase in water productivity is referred to as "more crop per drop." In the wider context of the Nexus, the expression "more biomass per drop" (apart from crops also fish, livestock, fiber, tree biomass …) is more appropriate.
- Production processes along the supply chain need to become more resource-efficient, energy-efficient, circular and sustainable. For instance, installation of new hydropower plants in existing water infrastructures is an attractive Nexus solution in that it can save construction costs and minimize environmental and social impacts. Moreover, it may contribute to the reduction of the global footprint of these infrastructures. Examples of how hydropower can be incorporated in existing hydraulic infrastructures where electricity generation was not a primary objective are municipal and agricultural water systems, for example, for wastewater treatment and irrigation canals, hydraulic circulation systems for cooling and heating of plants, and hydropower dams themselves where there are ship navigation locks or fish passages that need dissipation of energy (Marence *et al.*, 2018). Existing infrastructure in the water sector has a high potential for additional renewable energy production from solar as well, for example, the installation of photovoltaic (PV) systems on the face of existing dams and the coverage of irrigation canals with solar PV systems (Szabó *et al.*, 2018).

Demand side solutions may include:

- Consumer behavior in water use, energy consumption, food consumption and (food) waste generation. In the EU, for instance, citizens can decrease their current food-related water footprint by 24% when shifting to a healthy diet and by 40% when shifting to a vegetarian diet (Vanham *et al.*, 2013). EU consumers waste on average 123 kg of food per person annually, of which 80% is avoidable (Vanham *et al.*, 2015). A reduction in food waste as envisaged by SDG target 12.3 would have an influential impact on the Nexus.
- Some scholars also state that family planning to lower per capita fertility should be part of the solution (Potts, 2014; Speidel *et al.*, 2009). Especially in Africa a population explosion is projected for the next few decades (UN, 2014). There are consequently more frequent calls to address environmental problems by advocating further reductions in human fertility (Bradshaw and Brook, 2014), including in the second notice of "World Scientists' Warning to Humanity" (Ripple *et al.*, 2017).

It is clear that the provision of water, energy and food security for people within a geographical region relates to the consumption side of this geographical region and not the production side. Trade between regions is thus essential to provide these three securities. Sustainability does not mean self-sufficiency.

See also: Human Ecology and Sustainability: Tragedy of the Ecological Commons; Ecosystem Services Evaluation; The Sustainable Development Goals

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