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REVIEW ARTICLE

The water-energy-food nexus, its relationship with ecosystems, and its role in supporting society

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Abstract

The water-energy-food (WEF) nexus concept has emerged over the last decade as a way of thinking about and analysing natural resources. Each WEF sector has intimate feedback relationships with the other sectors, forming a coherent, complex system. Through analysis of these relationships and of the impact of policy on the system, more integrated and sustainable resources management is aimed for. The nexus concept is not without criticism, and a concern is that one sector would come to be seen as 'more important' than the others. This paper attempts to break such ideas, describing how each WEF sector is equally essential for the functioning of the other two, and that the WEF nexus is more than the sum of its parts. Going further, the paper shows how the WEF nexus is supported/enabled by 'ecosystems'. Without good ecosystems functioning, the WEF sectors could be compromised with significant consequences. At the same time, ecosystems are degraded by WEF demand and exploitation. Society depends upon ecosystems and the proper quantity, quality, timing, and spatial availability of WEF resources. Societal demand impacts on WEF resources availability and security, and on ecosystems integrity. The paper concludes by stating that the integrity of this WEF-ecosystems system is under significant threat as planetary boundaries are exceeded, ecological overexploitation is accelerating, and global warming impacts become acute. Nothing short of a wholesale societal behavioural and conceptual shift towards WEF sectors, their use, exploitation, and management is required, and that a systems-thinking mentality is central to such a shift.

Keywords Ecosystems · Nexus · Planetary boundaries · Water-energy-food

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Introduction

The water-energy-food (WEF) nexus has re-emerged since the 2011 Bonn Nexus Conference (Hoff 2011) as a concept aiming to promote the holistic management of critical natural resources for sustainable futures. Central to the WEF nexus concept is the idea that the underlying resources of the nexus sectors, such as water, soil, fossil fuels, etc., are tightly and inextricably linked to each other in a complex system of systems. Throughout this paper, the ordering 'WEF' is used, being commonly used in European nexus literature and studies (versus FEW in North American literature) and following the formulation of Hoff (2011). No hierarchy of resources importance is implied in this ordering. The WEF ordering is popular for a few reasons, namely: (1) following from the Hoff (2011) re-popularisation; and/or (2) sometimes being seen as an extension to the Integrated Water Resources Management (IRWM) paradigm in which water is placed as the central resource. Avellan and Roidt (2022) present a timeline of the emergence of the WEF

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nexus, showing that the Hoff (2011) background paper was a pivotal moment in the use of the term. There are studies in which the ordering 'FEW' is used rather than WEF (see D'Odorico et al. 2018; Gragg et al. 2018; Zhang et al. 2019; Liang et al. 2020; Huntington et al. 2021; Clasen et al. 2022; Simonvic and Breach 2023). This paper argues that no single sector should be given centrality and proposes a new framework in which the WEF nexus sits within a wider system comprised of ecosystems and societal system.

In this paper the term 'resource' is used to denote the supply of ecosystem services (e.g. water resources, energy resources, soil resources) that feed the WEF nexus sectors, seen as the productive elements that produce societally desired goods and services. A balanced demand and supply of these resources enable their sectoral securities. The resources that sustain the WEF nexus are themselves conditioned on a healthy, functioning ecosystems base,[1] which in turn is impacted by their demand and extraction. It is recognised that resource security is a much broader issue than merely a provisioning service, encompassing quantity, quality, accessibility, timing, and equity of the resources (e.g. Biggs et al. 2015), and that regulating and cultural services are vital. WEF nexus sectors provide outputs which are products and amenities (raw and derived) demanded, exploited, and used by society for development (e.g. drinking water supply, food provision, electricity generation). Over-demand and exploitation of WEF sectors strains WEF sector security, which degrades ecosystems, hampering their ability to provide resources to the WEF sectors. Ecosystem restoration and maintenance can act to improve resources provisioning and security. At the same time, the WEF sectors are tied to each other through socio-economic connections, for example as the food sector depends on energy and water generation, acquisition, and supply for the generation of food products, which are ultimately governed through interconnected governance systems and policies. Figure 1 demonstrates this coupling, showing how each sector is dependent on the others for its own functioning. Society in its broadest sense (e.g. population, demographics, industry, commerce, health, development opportunities, etc.), depends on the security of the WEF sectors, the underlying resources, and the ecosystems base, which are impacted by societal needs and behaviour (Merz et al. 2023).

While the water community focuses on the IWRM paradigm as the main way forward for sustainable water use and management, experience has shown that there are no one-size-fits-all solutions or blueprints. There are wide debates about how to put IWRM into practice due to its apparent lack of focus and bias towards water (Rogers and Hall 2003; La Jeunesse and Quevauviller 2016). Moreover, with climate and global change increasing the level of complexity to be considered for sustainable resources management, a more holistic and comprehensive systems approach is needed (Pahl-Wostl 2007). The nexus concept has been seen as an improvement over other resources management paradigms (e.g. Brouwer 2022) such as IWRM (Lalawmpuii 2023), Integrated Natural Resources Management and others as it intends to be more holistically integrative (Roidt and Avellán, 2019) and is focused on the three resources most important to societal well-being and the underlying ecosystems. Choosing the WEF sectors simplifies the complexity of managing the whole system and focuses on development of those resources in a sustainable way. The most important connections and sustainability issues then become clear. At the same time, the nexus concept has come under criticism for not delivering reproducible tools, falling short of capturing nexus interactions fully, favouring quantitative assessment at the expense of social science approaches and, ironically, being confined to disciplinary silos (Albrecht et al. 2018). A recent 'review of reviews' has shown that while the multi-resource aspect of the nexus concept is still relevant, there are a myriad of challenges in advancing nexus awareness and research, including conceptual, operational, scale-related, governance, and contextual issues (Brouwer et al. 2024; Mooren et al. 2024). There is the potential danger of falling back to sectorally-biased viewpoints on the nexus if certain natural resources or WEF sectors are deemed more 'important' than others (Sušnik et al. 2023).

To maintain a central tenet of the nexus concept, it is imperative that the WEF sectors stand on an equal footing. In practice this may not be possible due to wider socio-economic/geopolitical drivers and priorities. However, prioritising one sector over others will inevitably lead to trade-offs. The WEF nexus is greater than the sum of its parts as a result of complexity, feedback, delays, and interactions with other systems (ecosystems, societal system, climate system, etc.). It is crucial to understand and appreciate that the WEF nexus is not an isolated system, operating outside the influence of other global systems. Taking this approach, a much wider systems perspective is promoted (cf. Capra and Luisi 2014), which should: (i) recognise and account for planetary boundaries (Rockström et al 2009), some of which have already arguably been crossed (Steffen et al. 2015a; Richardson et al. 2023); (ii) avoid 'tragedy of the commons' behaviour regarding natural resources and ecosystems (Hardin 1968) by stimulating multilevel (Ostrom 1998) and inter-sectoral governance (Lalawmpuii 2023); and (iii) seek for wholesale shifts in societal behaviour and economic models.

A major shortcoming of most WEF nexus conceptualisations is that they neglect ecosystems and/or society and/or their interplay with natural resources. Against this

[1] See https://www.stockholmresilience.org/research/research-news/2016-06-14-the-sdgs-wedding-cake.html.

background, this paper sets out to demonstrate how each WEF sector contributes to the functioning of the other sectors and its interactions with overarching environmental and social systems, using significant literature to support ideas and make the major points. This is done by considering each WEF sector in turn. The contribution of each sector to the others is outlined. In this way, the mutually self-supporting nature of the WEF nexus system is shown. This paper aims to show how no sector should be seen as more important than the others (cf. Mooren et al. 2024). Following from this, extensive literature and nexus thinking ideas are utilised and expanded upon to put forward a new, holistic framework emphasising the placement of the WEF nexus as interacting with ecosystems and society. The argument in this paper shows how the WEF nexus is supported by healthy ecosystems functioning, without which WEF resources could become compromised with significant consequences. In turn, demands from society on WEF resources feeds back to impact upon the ecosystems supporting them, also compromising WEF sector security. Being supported by ecosystems and the WEF nexus is society which depends on proper functioning, timing, quantity, accessibility, stability, and quality of WEF sector outputs (e.g. water, electricity, food products). Thus, this paper conceptualises the WEF-ecosystems-society system as a much broader system along the lines of Lucca et al. (2025), which itself is modulated by demographic, climate, and socio-economic developments. As global changes affect the supply of good quality resources, the demand for these resources to support WEF sector functioning is dramatically increased through socio-economic developments, population rise and urbanisation. This causes friction in the allocation of WEF resources on the one hand but also to society at large and the environment, leading to debates about social and environmental justice (e.g. Malin et al. 2019; Gupta et al. 2024). The paper starts by examining the role of each WEF sector on the other sectors, highlighting interdependencies. Following this, the new holistic WEF-ecosystems-societal framework is proposed.

Watering the nexus

It has been argued that water forms a 'centrality' to the WEF nexus (Sušnik et al. 2023). Water is shown to be essential in almost all aspects of energy generation, being critical in raw fuels extraction and processing (Gleick 1994; Olsson 2021), and subsequently for liquid fuels production and electricity generation. The electricity generating sectors in Europe and the USA account for c. 40% of freshwater withdrawals (United Nations World Water Assessment Programme 2014), in contrast with the global average where 70% of freshwater withdrawals are for irrigated agriculture. Noteworthy is that the water withdrawn for electricity production is often much larger than the amount consumed (i.e. lost from supply locally in space and time; Macknick et al. 2012), with most of the extracted water eventually returned back to the environment, and only a small fraction 'lost' through evaporation. The evaporative loss in hydropower reservoirs is globally significant, yet often overlooked (Scherer and Pfister 2016). Improvements in carbon capture and storage (CCS) technologies at thermal power stations, while potentially beneficial for reducing greenhouse gas emissions and concentrations in the atmosphere, could lead to water use increases of up to 90% (Hoff 2011; Lalawmpuii 2023), leading to an unexpected trade-off emblematic of the WEF nexus. On the other hand, the operational water use of solar and wind electricity generation technologies is close to zero, although water is consumed in raw minerals extraction and processing (Ding et al. 2018). Of note here is the recent growth in green hydrogen. While offering a relatively clean source of energy, the water demand consequence of its production is significant, thus creating new nexus-wide interactions, although there is the potential to use seawater or wastewater in the electrolysis process (Beswick et al. 2021; Newborough and Cooley 2021). Overall, it is shown that the water used to generate electricity varies between about 2–7.5 m^3 kWh^{-1} depending on the location and technology (Feng et al. 2014). It is estimated that globally about 1500 km^3 water is withdrawn every year for energy production, with about 300 km^3 of this being consumed, with these values expected to double by 2100 (Bijl et al. 2016). An additional area where water is used in energy production is in the cultivation of crops for biofuel production. In some countries, (e.g. China, India, South Africa), the stress on water resources as a consequence of cultivating such crops may lead to policy makers being unlikely to pursue biofuel options (de Fraiture et al. 2008; Jewitt and Kunz 2011). This demonstrates the crucial, intimate role that water plays in powering modern society: without it, or with water shortages, energy availability could be curtailed, threatening economic opportunity, transport, infrastructure, communications, and human development.

Water is likewise essential to providing the food that we eat (i.e. the water sector provides water resources used in the food sector to derive a product demanded by society), accounting for 70% of global freshwater withdrawals (Gleick 2011). Currently, over 7000 km^3 are consumed in crop production annually (blue and green water combined; Falkenmark and Rockström (2006), where blue water is that abstracted from freshwater supplies such as rivers, lakes, and groundwater, and green water is that stored in soil moisture; grey water, i.e. reused wastewater not from toilets, was not included in the assessment), a figure that may rise to over 13,000 km^3 by 2050 (de Fraiture et al. 2018). At the same time, irrigated agriculture is shown to produce a vastly disproportionate amount of the world's food relative to the amount of land used for irrigation (Hanjra and Qureshi 2010), demonstrating its outsized importance in feeding over eight billion people and the criticality of ensuring water supply for irrigation. In addition to direct water consumption, the global food trade means that water is moved, being embedded within food products ('virtual water', or the water footprint; Allen 1993; Hoekstra et al. 2009), known as the virtual water trade (Chen et al. 2018). Without this global trade, society and development would arguably not have reached the level currently seen: water is an integral, although often overlooked, part of this. It has been shown that due to demand increases, there could be global competition between water for agriculture and water for cities, however improving agricultural water use could free-up sufficient water for urban use (Flörke et al. 2018).

Water is essential to nexus integrity and resources supply, production, utilisation, and sustainability. Despite this, the safe planetary boundary for freshwater withdrawals (4000 km^3 yr^{-1}; Steffen et al 2015a) is already very close to being surpassed, if not already surpassed (Sušnik 2018; Richardson et al. 2023). It is expected that the demand for freshwater withdrawals will increase up to 20–30% (United Nations World Water Assessment Programme 2019), with even higher rates of demand increase in urban areas in which the global population is expected to double by 2050 (UN DESA 2019). This is expected to put water resources sustainability for cities, and indeed all users, under intense pressure, potentially leading to water security issues (Ahmadi et al. 2020). It is also shown that humanity is driving water scarcity changes across all the IPCC-defined shared socioeconomic pathways (SSPs; O'Neill et al. 2015), suggesting that water security issues will become more acute under almost all development trajectories (Graham et al. 2020). This is important as it has been shown that water is a 'safe' Sustainable Development Goal (SDG) to achieve, meaning it will have very few negative impacts or trade-offs on the attainment of other SDGs (Pham-Truffert et al. 2020), and is arguably an 'enabler' for the achievement of many SDGs (Bhaduri et al. 2016). Other studies have demonstrated the globally-important role of water services access to enabling human development (Amorocho-Daza et al. 2023), something that is shown to be significant over the twenty-first century. Taking the role of water one step further, Sušnik et al. (2023), suggest that water has been historically important for the development of agriculture, cities, and civilisations, and played a central role in the emergence of the Industrial Revolution and subsequent technological and societal advances. All these facets demonstrate that water plays a crucial role in the WEF nexus.

Powering the nexus

Energy forms an integral nexus sector, 'powering' the WEF nexus. The energy sector and its derived outputs enable the production, processing, movement, waste treatment, and consumption of water and food, as well as allowing massive gains in the scale, efficiency, and replicability of work (Smil 2018). Energy supply and demand is critical to every aspect of life, with the shift to electricity being transformational, from providing electricity for homes, hospitals, communications, refrigeration, vehicles, computers, schools, navigation, supply chains, factories, and lighting, taking off exponentially from the advent of the Industrial Revolution. While energy production, consumption, and access have increased dramatically, energy insecurity is still experienced across multiple scales, especially in the Global South (Hostettler et al. 2015). This insecurity hampers economic, social, and human development (Kanagawa and Nakata 2008; Dodds et al. 2009; Phoumin and Kimura 2019). A major global challenge is how to meet current and future energy needs using clean energy while at the same time ensuring equitable access to this energy for all. Sachs (2015) believe, given the global reliance on fossil fuels, that reconciling development with planetary boundaries, is most urgent and most complicated in the world's energy systems. Energy security is fundamental to achieving water and food security. Clean energy sources improve cooking conditions with consequent improvements in household air quality and human health (Odo et al. 2021). Therefore, clean energy contributes to improving health and well-being.

Energy is essential throughout the agricultural production chain, from planting and fertilising to water pumping and irrigation, harvesting, storage, processing, automation, and transportation (FAO 2017; Paris et al. 2022). It is used to refrigerate food, increasing the shelf life of food, being essential in modern society. It has been estimated that 16% of US energy use is food-related (Canning et al. 2010). As a global average, between about 2–2.5% of all energy consumption is in the agricultural and forestry sectors (FAO 2017), a proportion that belies the importance of that energy use. In the EU, the average energy use in 2008 in the agricultural and forestry sectors was 2.2% (c. 1000 PJ), varying from a low of 0.4% (42 PJ) in Germany to a high of 6.2% (132 PJ) in the Netherlands (Gołaszewski et al. 2012). However, according to Gołaszewski et al. (2012), these numbers, derived from the EUROSTAT database, are underestimates as the energy required for fertiliser production is counted in the transport sector and not in agriculture, and the myriad forms of energy required in agricultural production are often not accounted for. More recent analysis suggests that, in the EU, 3.7% of total EU annual energy consumption is related to open-field agriculture (Paris et al. 2022). The total therefore may be even higher once non-field agriculture (e.g. greenhouses) are factored in. The production of synthetic fertilisers (nitrogen, phosphorus) requires considerable amounts of energy, yet this facilitates extraordinarily high yields of staple crops that feed billions (Smil 2018; Olsson 2021; Daramola and Hatzell 2023).

The importance of energy in agriculture provides a counterpoint contrasting with the common view that water is the limiting factor in enhancing agricultural production, especially in Africa (FAO 1995; Salem et al. 2022; Simpson et al. 2023). Water transfers from sources to agricultural areas require a lot of energy, with greater intensity during drought events. Energy insecurity can negatively impact the efficient and productive deployment of natural resources (e.g., water, land) and human capital (e.g., due to disease, lack of training, lack of power) for producing food and fibre for the continent and beyond (through trade networks). Farthing et al. (2023) suggest that at least 2% of the total electricity generation in Africa is utilised in agriculture, though with significant variations between nations (FAO 1995; Farthing et al. 2023). Kebede et al. (2010) place agricultural energy use over the continent at about 1% of the total energy consumption. Similarly, other rapidly developing regions and countries also find energy consumption in agriculture rapidly increasing (Bekhet and Azlina 2010). While many speak broadly of a link between energy access and food security, especially in the sub-Saharan African context, a recent literature review failed to comprehensively support such a hypothesis owing to a lack of data to make a robust assessment (Sola et al. 2016).

Energy is implicitly needed to grow the food that we eat, is of crucial importance in agri-regions globally, and is rapidly growing in criticality developing regions such as sub-Saharan Africa. Although globally and regionally the proportions of energy used in agriculture are relatively small, being of the order of a few percent, the importance is outsized. That energy use ‘feeds’ the nexus, providing economic, health, and development opportunities to hundreds of millions of people worldwide.

Energy plays a core role in the provisioning, access, and treatment of water. Water needs to be pumped from raw sources, filtered, treated, distributed to consumers at different times and in different locations, and often stored if it is to be used beneficially for human development. Wastewater then needs removing from the source location, pumped to a treatment plant, treated to varying degrees, and then be properly and safely disposed of or reused. In some cases, treated wastewater is then pumped back to certain consumers for re-use. All these processes require various amounts of energy (Plappally and Leinhard 2012; Olsson 2021). For example, global wastewater treatment consumes at least 200 TWh or 1% of total electricity consumption, of which 51% is for secondary treatment (International Energy Agency 2016). This relationship is increasingly recognised, with many utilities seeking to make use of “hidden hydro” opportunities to generate energy within their systems and move towards multipurpose reservoirs (Quaranta et al. 2023). Increased access to energy can enhance domestic water supply, sanitation and hygiene services, with positive impacts on human health and development (Dodds et al. 2009; Zakari et al. 2022). Energy, like water, is a crucial human development enabler, supporting socio-economic gains.

The amount of energy used in the water sector can be significant. For example, in the USA, the energy used for water in the domestic, industrial, commercial, and power sectors was evaluated at over 12% of the total national energy consumption (Sanders and Webber 2012). Similarly, Wang et al. (2017) show that significant quantities of energy are used in the Beijing water sector (supply, heating, and treatment). In a global analysis, Liu et al. (2016) estimate that between 1.7 and 2.7% of all global primary energy consumption is related to the water sector, with water resources sourcing and conveyance making up a significant proportion of the total (40%). Heating and cooling are significant end-user water-related energy consumers. At the time of the analysis, China, the Middle East, and India represented the regions with the highest proportions of energy used for water, driven by large populations, desalination, groundwater pumping, and large irrigated agricultural areas. Significant global variations are apparent through the analysis.

As with energy’s importance in food production, energy is likewise central in delivering clean, safe water for users, heating/cooling that water for multiple purposes, and treating wastewater, either to be returned to the environment, or for reuse. Energy is increasingly used for desalination in many parts of the world, helping secure potable and non-potable water for millions of people (Nassrullah et al. 2020) and in some parts, and increasingly so, for the production of green hydrogen. This section has demonstrated that energy, like water and food, is an essential sector within the WEF nexus, without which the other sectors would fail to meet the needs of humanity.

Feeding the nexus

Potentially the ‘weakest’ of the nexus links in Fig. 1, the food sector nevertheless plays a crucial role in the WEF nexus, especially in relation to contributing to energy production and in sustaining humanity through the provision of food. Of importance is the role of biofuels, biomass, and biofuel crops in providing energy sources (i.e. a food sector resource contributing to energy sector security). A thorough review of the role of biofuels for (transport) fuel production

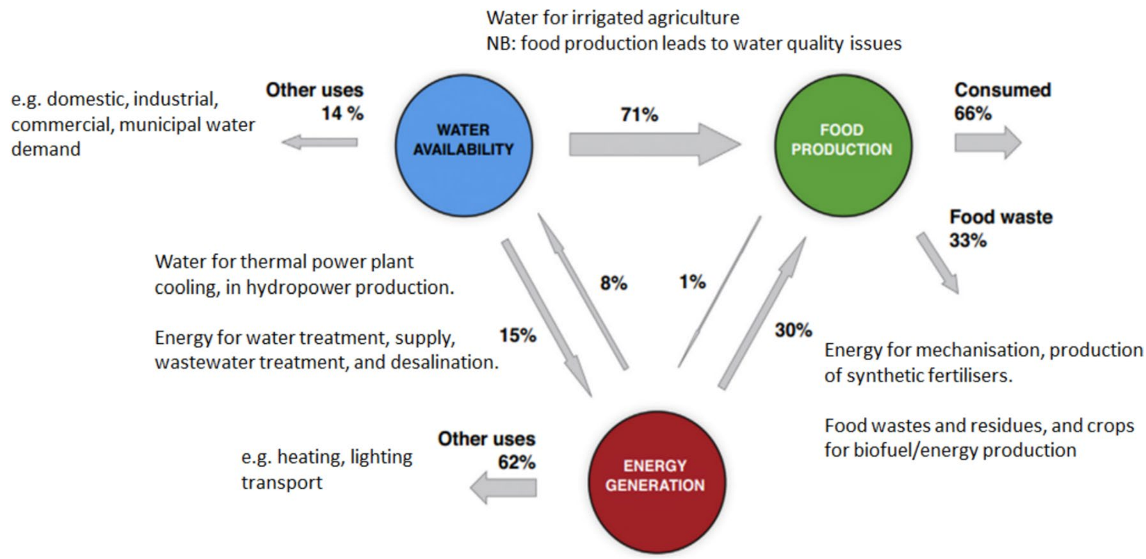

Fig. 1 Global proportions of flows between WEF sectors, with some interlinkages highlighted. These globally-averaged figures have significant regional and national variability, and will change in the future as socioeconomic and energy transitions take place. Adapted after Simpson and Jewitt (2019a, b)

is given in D'Odorico et al. (2018). There is debate around first-generation biofuels (e.g. from crops directly) competing with land for food. Despite this, analysis has shown that potentially 26–55% of liquid fuel consumption could be supplied from biofuels without competing for land for food production through the use of marginal agricultural lands of relatively limited value for food crops (Cai et al. 2011). However, this would compete with ecosystems services and biodiversity on these lands (Jewitt and Kunz 2011). Second generation (e.g. from crop and/or food residues) and third generation biofuels (e.g. from algae, Gerbens-Leenes et al. 2014) cause less concern as they do not compete with land for food production. Rulli et al. (2016) found that approximately 4% of transport fuels globally and 0.2% of all global energy use is utilised from biofuels/biomass.

Liquid fuels are just one energy source from bio-materials. Residues can be burned directly to generate heat/electricity or digested to produce biogas, which is then burned to generate heat/electricity (Kocar and Civas 2013). Kocar and Civas (2013) show that corn, soy, sugarcane, beet, and rapeseed are common staples with which to obtain energy, however they all have the disadvantage of competing with land for food. While liquid biofuels have been popular for some time, the use of biogas to generate electricity is rapidly growing in popularity globally. The potential is considerable, with estimates suggesting that the energy stored in biomass annually produced by plants is 3–4 times total energy demand (Guo et al. 2015), though not all of this could be sustainably exploited. It is estimated that bioenergy will provide 30% of global energy demand by 2050. Biofuels are not expected to contribute more than about 5% of transport-related energy in the near-future (Timilsina 2014), especially as the electrification of vehicles accelerates. Food crops and biomass derivatives are widely used for cooking fuel globally, with biomass being especially prominent in developing nations and in sub-Saharan Africa (Stoner et al. 2021), this being another important contribution of food and food-related products to global energy provision and utilisation.

The rapid development of photovoltaic projects is impacting on agriculture production, both positively and negatively. The advent of small solar powered pumps has been a boon for smallholder farmers globally. However, major photovoltaic projects require large areas, sometimes on agricultural lands. The agrivoltaic concept, which provides use of land for both agriculture and electricity production, tries to reconcile agriculture and photovoltaic production. Many countries are proposing rules maintaining or improving crop production under these systems (Dupraz et al. 2011; Dupraz 2023).

Clearly, food, crops grown on food-productive lands, food/crop residues, and woody products do play a globally important role in energy provision for transport, heat, cooking, and electricity generation. The food → water relationship is asymmetric. Food is not used in the water sector, but food production has a major impact on water quality, in particular via nitrogen, phosphorus, and pesticides run-off and water quantity for the local water cycle, thus impacting the integrity of the water sector. The changes in land use from natural grasslands or forests to agricultural production have shown to enhance runoff into river systems, reduce infiltration rates into groundwater, and cause altered flood regimes (Dale et al. 2015; Deng et al. 2015; Jin et al. 2015). This is a significant and growing global challenge (Lu and Tian 2017; Wang and Liu 2019), along with the food sector contribution to greenhouse gas emissions (Bennetzen et al. 2015, 2016; Liu et al. 2019). Changes in diets towards more meat-based diets, a result of economic development and affluence, are driving land use changes globally thus showing the importance of societal changes on food production and resources pressure (Alexander et al. 2015).

A new water-energy-food nexus framework: a mutually self-supporting system, and relationships with ecosystems and societal functioning

The WEF sectors are mutually dependant (Fig. 1), often in very tightly coupled ways (Sušnik 2018). For many of the interactions discussed, this coupling is so strong that significant alteration in any of the links can disrupt the supply and security of the others. For example, a severe shortage or disruption in the supply of adequate quantities of water would threaten not just irrigated food production, but also energy generation where that is applicable (e.g. with considerable water demand for cooling or with significant hydropower infrastructure). Indeed, this was the case in Europe during the unprecedented 2022 drought (JRC 2022; Toreti et al. 2022; Tripathy and Mishra 2023), when various countries saw either food production decreases and/or power production curtailment (Sušnik et al. 2023). Health and human development can also be impacted, especially over the long term through increased prevalence of waterborne transmissible diseases in floodwaters (e.g. Cann et al. 2013), and during droughts (Lee et al. 2020). Long-term and widespread power outages (energy as a resource) could lead to problems supplying sufficient freshwater for multiple purposes, and could lead to problems with wastewater treatment capacity, even in the short term. As energy is consumed to produce synthetic fertilisers, it would not be inconceivable that prolonged power reductions could lead to reduced output of synthetic fertilisers, leading to knock-on impacts on food yields. On the food side, major changes in crops grown for biofuels production could lead to impacts on biofuels availability, especially in nations that rely heavily on biofuels (Nass et al. 2009; Antunes et al. 2019) or biomass for energy generation, potentially impacting on energy accessibility/security. Yet significant shifts towards bioenergy crops can impact national food security ambitions. The mismatch in spatial and temporal scales between resources availability and demand makes matters more complicated (resources may not be where they are needed or when they are needed in sufficient quantity and/or quality and/or price; Geijzendorffer et al. 2015; González-García et al. 2020; Zhang et al. 2021).

These examples and Fig. 1 serve to demonstrate that the WEF nexus forms a mutually self-supporting system, in which the security and sustainable functioning of each sector depends explicitly on the functioning, availability, quality of, access to, and supply of resources and outputs from the other sectors. This idea of a mutual self-supporting system represents fundamental tenets of the WEF nexus (Hoff 2011): that WEF sectors are reliant on each other; that changes/shocks to one impacts all others and; that the system is greater than the sum of its parts due to complexity and feedbacks. Quantification and assessment of WEF nexus behaviour under various scenarios (e.g. hypothetical development scenarios, implementation of plausible development policies) at a range of scales have been widely published in the literature (Hussein et al. 2017; Bakhshianlamouki et al. 2020; Nhamo et al. 2020; Sridharan et al. 2020; Sušnik et al. 2021; Yates et al. 2021; Brouwer 2022; Zeng et al. 2022; Wang et al. 2023; Mirindi et al. 2024). Many studies however, while using climate change and socio-economic pathways as scenarios, rarely examine the wider implications of nexus resource use on ecosystems or other sectors, and rarely discuss the importance of ecosystems or societal development in a nexus context. This is where this paper makes its major contribution.

If any WEF sector or their underlying resources, supplied by ecosystems, that fuel outputs on which society is dependent were to collapse or fail, it could mean a cascade failure, with catastrophic societal and ecosystems consequences. This wider systems idea is conceptualised in Fig. 2 in the new framework, whereby the WEF nexus sectors are shown to be mutually interacting with each other and with ecosystem and societal systems. Figure 2 shows that ecosystems supply resources to the WEF sectors and that society places demands on the WEF sectors, exploiting and degrading underlying resources. This demand can threaten WEF sector security and ecosystems functioning, which in turn hampers ecosystems' ability to supply resources to the WEF sectors, further threatening WEF security and impacting societal development—a detrimental positive feedback loop. Climate change impacts the supply of resources that ecosystems provide, whereas societal behaviours and consumption patterns driven by socio-economic worldviews, political agendas and conflicts impact on resource demand.

Recent work has highlighted the important role of ecosystems and ecosystems services and functioning as supporting the provisioning of WEF resources and the security of the WEF sectors (e.g. De Groot et al. 2010; Hülsmann et al. 2019; van den Heuvel et al. 2020; Mooren et al. 2024), and the WEF nexus plays an often-overlooked role in low flows, or environmental flows, supporting such services (LeRoy

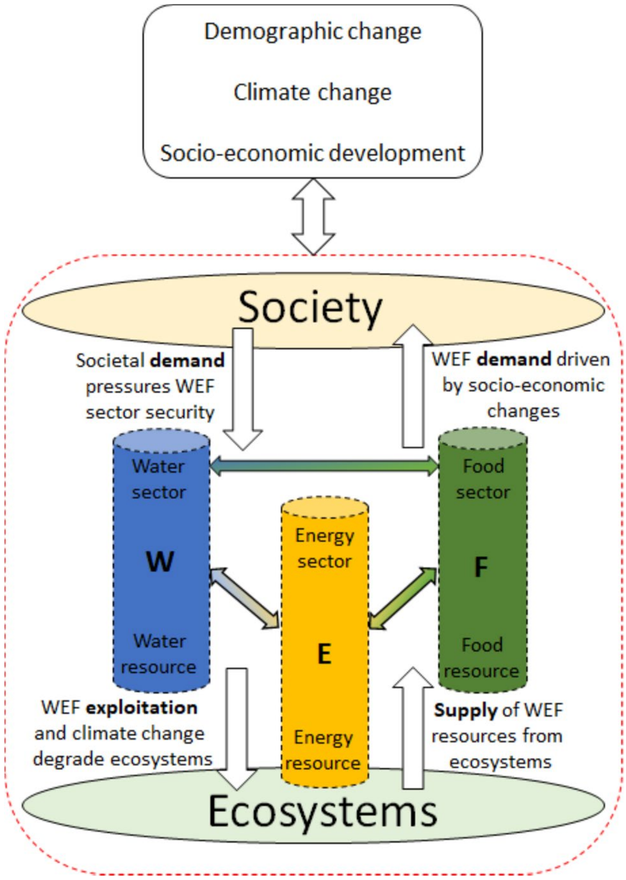

Fig. 2 Conceptualisation of the WEF nexus set within the wider spheres of ecosystems and their services, and society. The WEF nexus is supported by, and supports, these wider spheres. Ecosystems ensure the supply of resources to the WEF sectors maintaining their functioning and security, from which resources are demanded by society (e.g. water, food products, electricity). The WEF sectors depend intrinsically on each other for their own functioning and security (denoted by the dashed black lines around the WEF 'columns'; e.g. the energy sector is dependent on both the water and food sectors to enable energy provision to society). Societal demand pressures lead to challenges regarding WEF sector security through resources overexploitation and degradation. WEF exploitation and climate change impacts on ecosystems. This entire system, bounded by the dashed red box, is pressured by demographic changes, climatic changes, and socio-economic development, which themselves are mediated to some extent by the WEF-ecosystem-society system

Poff and Matthews 2013; Acreman et al. 2014). Further examples of the services that ecosystems provide include, but are not limited to: enabling water cycling, including water purification, which contributes towards freshwater provisioning and pollution reduction and control; maintaining the health of landscapes and soils, contributing towards crop growth for food provision and energy crops; biodiversity provision, pollinating insects for crop growth and yield and forest and floodplain ecosystems provide biomass that act as a global carbon sink and oxygen supply (Bell et al. 2016; Martinez-Hernandez et al. 2017) as well as a fuel source and building material but also for hunting and gathering of food stuff for people around the world. The importance of ecosystems services in urban settings can be significant, and should not be overlooked (Ding et al. 2023), though are often not considered fully.

This dependency of the WEF sectors upon ecosystems, and their integrity and ability to provide the requisite services and functions for WEF resources provisioning to society is conceptualised in Fig. 2, with 'ecosystems' positioned at the bottom of the WEF nexus (green circle, Fig. 2), supporting and underpinning WEF functioning by providing resources to the WEF sectors. In this anthropogenic view, if ecosystems were removed, or if their functioning should significantly differ or diminish, it is possible that the subsequent availability of WEF resources could be compromised, with global consequences. It is essential to maintain ecosystems integrity (Shepherd et al. 2016). Lucca et al. (2025) show that Water-Energy-Food-Ecosystem nexus conceptualizations need to move beyond an anthropocentric view towards a holistic perspective where 'nature' is allowed to exist in its own right without being valued or used for human purposes and needs. This is particularly important as humanity has overstepped many planetary boundaries, and is close to overstepping others, especially some very relevant in a WEF nexus context such as nitrogen and phosphorus flows, freshwater changes, and land system changes (Steffen et al. 2015a; Richardson et al. 2023; Fletcher et al. 2024).

WEF resources demand (utilisation, quality, spatial distribution, etc.) also feedback to impact upon ecosystems via the WEF sectors, forming another mutually dependent link (Fig. 2). For example, degradation of forest lands by converting forests to (monocultured) agricultural land in an effort to secure a WEF-related resource (food), could have a detrimental impact on the corresponding supporting ecosystem(s), potentially impacting on biodiversity, soil quality and soil erosion, water quality, carbon sequestration potential, local near-surface air temperature, etc. Indeed, tropical forests were the primary source for new agricultural lands through the 1980s and 1990s (Gibbs et al. 2010). Such ecosystems changes could influence the viability of agricultural activities in that region, due to, for example, lower water availability, lower quality soils, and lower insect diversity, leading to lower crop yields (Bindraban et al. 2012). Further, it has been suggested that deforestation in the Amazon is so great that the basin is now a net carbon source, with planet-wide implications (Gatti et al. 2021). It is suggested that global warming could lead to constraints on crop yields of maize, rice, and soybean (Wang et al. 2020), another indication of how reliant the WEF sectors, humanity, and their underlying resources are on a well-functioning ecosystems base. Global soil erosion due to land use changes is significant (Borelli et al. 2017), with impacts directly on crop yields, demonstrating how ecosystems support food production via maintenance of soils quality (a resource), but also how massive changes to land use impact on the underlying ecosystem base, negatively affecting that food production.

At the top of Fig. 2 (beige circle), being supported by both ecosystems and by WEF security, sustainability, provisioning, quality, quantity, is 'society' or societal functioning (similar to ecosystems, the term is used here in a broad sense to include, for example, health, development, economic activity). Society conditions demand for WEF resources and ecosystems services. The implication is that the inability to secure and distribute sufficient WEF resources for a multitude of societal purposes at the required time and space, in the required quantity and at the required quality, could hinder societal development and functioning or, at worst, jeopardize WEF security for people in a certain region. As an example, it is shown that access to water services directly and significantly contributes to enabling human development gains (Amorocho-Daza et al. 2023). By altering the availability of freshwater resources and their access, and/or by impacting the underlying ecosystem services supporting water resources availability, this important societal benefit diminishes, impacting on the livelihoods of millions of people globally. Food production and availability is another supporting link from the WEF nexus and the concomitant supporting ecosystem services to the enabling of societal functioning and human development (Oliver and Gregory 2014; Crist et al. 2017). Insufficient food has detrimental impacts on human health and development, but loss of soil integrity (an ecosystems-provided resource to the food sector) leads to reductions in crop yields and productivity as well as grain quality and thus quality of food intake, with far-reaching consequences. Energy, and energy access, have likewise been shown to have significant societal benefit, contributing to human development, especially in lesser-developed parts of the world (Smith et al. 2013; Acheampong et al. 2021). However, it is shown by Smith et al. (2013) that all energy sources entail human health risks to some degree, especially solid fuels, coal, and biomass. Therefore, it is not just energy quantity and access that count, energy 'quality' should also be considered (cf. ESMAP 2015). Of concern related to energy is depletion of raw resources, especially in the case of fossil-based energy sources, but also for biomass sources. Depletion of these sources, without substitution for renewable sources not relying on a finite source, may lead to energy sector insecurity and potential energy blackouts, leading to knock-on impacts for human and societal well-being and development. While the abundance, security, and quality of WEF resources act to support and enhance societal development, socio-economic development acts to drive WEF demand, with many studies suggesting a strong positive correlation between (economic) development and resources demand extraction (Krausmann et al. 2009; Steffen et al. 2015b; Wiedenhofer et al. 2020). It is critical to keep this demand under check because society depends on the availability on those very resources and on the underlying ecosystems base (Fig. 2).

Finally, the new framework (Fig. 2) suggests that the WEF-ecosystems-society system is itself driven by, and affects, demographic change, climate change, and socio-economic development. Such a coupling between societal and economic development has been widely suggested in the literature (Krausmann et al. 2009; Smil 2019; Wiedenhofer et al. 2020). Of particular concern is to 'decouple' (economic) growth from resource demands, insofar that (economic) growth may continue without a concomitant increase in resources demand (Wiedenhofer et al. 2020). There have been studies suggesting a potential decoupling between GDP and water demand for the very richest nations (Duarte et al. 2013; Katz 2015), where water demand does not increase with GDP gains due to population stabilisation or decline and/or rapid efficiency gains in supply infrastructure and water-using appliances. Such decoupling is particularly important regarding energy consumption, especially when fossil-fuel derived. Despite this necessity and some optimism, others have suggested that decoupling economic growth from environmental impact is not possible (Ward et al. 2016). This is important. If natural resources do continue to be exploited and depleted at increasing rates (e.g. Richardson et al. 2023; www.footprintnetwork.org), then the ecosystems supplying resource will be put under severe pressure and could collapse.

WEF resources quantity, quality, availability, accessibility, etc., act to mediate demographic change, climate change, and socio-economic development. For example, changes in the abundance, quality, and security of WEF resources may result in demographic changes (e.g. Meadows et al. 1972; Anderies 2003). Likewise, as postulated by Sušnik (2018), the bi-directional relationship between economic growth and electricity consumption (does economic growth 'cause' changes in electricity consumption, or vice-versa?) is so tight that a dominant causal direction in this relationship is all but impossible to determine. As such, it is possible that reductions in the energy security of a nation/region could lead to detrimental economic consequences, hampering overall societal development, which then may feedback to influence (energy) demand. Furthermore, an additional complication is brought about by temporal dynamics, particularly of the natural system. These relationships are highly variable in both space and time. For example, during drought increased energy may be needed to pump additional water for irrigation to supply food while water availability in the situation/

system is lower due to the drought. During a drought, hydropower is heavily impacted, leading to a reduction in energy production as water is retained in dams to save and rationalise water use for the duration of the drought.

The picture emerging from this discussion is that the WEF nexus, while complex in itself, sits within a much wider, much more complex context (Fig. 2), with multiple connections and feedbacks, many of which are indirect and/or poorly understood. One important outcome of this is that policy should improve in coherence across sectors and scales such that goals, objectives, and implementation related to one sector do not impinge on the goals, objectives, and implementation of policies in other sectors. Governance arrangements should be adapted to promote policy coherence by enabling cross-sectoral and cross-scale collaboration. This collaboration should focus on managing trade-offs and leverage synergies among policy goals, with provisions in place (financial and human resources) for implementation. Such a need for policy coherence and nexus-oriented governance arrangements has been alluded to by John et al. (2023), Suda et al. (2024), and Pahl-Wostl et al. (2018).

Considering the mutually interacting nature of this complex system, the fact that resources are already shown to be overexploited (cf. Richardson et al. 2023), and that change appears to be small-scale, slow, and/or incremental, leads to the assertion that nothing short of a global societal shift in thinking is required. It is suggested that it is human behaviour itself (economic growth focus, marketing, pronatalism; Merz et al. 2023) that has resulted in the overshoot of natural resources extraction. A number of recent studies have started to quantify the extent to which the planetary boundaries have been transgressed, or the extent to which humanity is on its way to approaching the boundaries (Rockström et al. 2024; Schlesier et al. 2024; Tian et al. 2024), while others have focused on quantifying whether or if humanity, at current population and levels of resource demand, can stay within certain boundaries and what it would take to bring resources utilisation back within proposed boundaries to preserve ecosystem integrity and support a just future for all (Gupta et al. 2024). This demand increase, coupled with climate related changes in resources supply, mean that gaps between WEF supply and demand are increasing, putting ever-greater pressure on resources, threating ecosystems integrity, thereby compromising WEF sector security.

This demand–supply dichotomy is at the centre of the sustainable development debate. On the one hand is the supply of resources from ecosystems to support the functioning and security of the WEF sectors on which society depends for the provision of WEF resources. Climate change and demands from society degrade the resources and ecosystems, threatening resource supply and WEF sector security with societal implications. Demand for resources outstrips supply, that is the 'carrying capacity' (Monte-Luna et al. 2004) is exceeded, leading to the transgression of planetary boundaries. To make matters worse, it is recently suggested the SDGs are not providing the environmental or social benefits intended (Fairbrass et al. 2024). As population continues to increase, and as socio-economic conditions generally improve, resource demand is expected to increase. At the same time, resources supply is threatened by both climate change impacts and ongoing ecosystems degradation, hence planetary boundary transgression and living 'outside the doughnut' (see Raworth 2018 for an explanation of the resources doughnut concept). These competing facets threaten WEF security. It is suggested that humanity can live 'within the doughnut', but will require a significant societal shift. Schlesier et al. (2024) show that 8 billion and 10.4 billion people can live within planetary boundaries with 81% and 73% probability respectively, though to do so would mean fossil-free energy generation, a near-vegan diet, and no additional cropland conversion, 'prices' that many may not be willing to pay. In all this, there is talk of 'optimising' the nexus (e.g. Namany et al. 2019; Ogbolumani and Nwulu 2021). Yet a question arises: to what extent can the nexus be 'optimised'? Given supply constraints and demand increases, to what extent can the planets' ability to support humanity be stretched? What is the 'carrying capacity' of the WEF nexus – where lies WEF security? These questions echo those posed by Meadows et al. (1972), but do not address equality or equity issues on resources access and availability for all, especially over long timescales. Related unresolved questions include what further insights can be drawn about potential futures about how to make the nexus sectors and their interrelations 'resilient'? What may future populations have to accept as reasonable demand expectations to be able to live within planetary boundaries (leading to questions of intergenerational environmental justice; Hiskes 2006)? These are tough questions, some relating to the issue of the 'tragedy of the horizon' in which current generations have little incentive to deal with the cost of climate impacts, a cost therefore imposed on future generations (BoE 2015; Espinoza et al. 2020), which future research should urgently seek to address.

New economic models such as doughnut economics (Raworth 2018; Schlesier et al. 2024), together with integrated policy and governance (John et al. 2023; Suda et al. 2024), increased cooperation between all levels of stakeholders, and a move towards a fully systems-thinking mentality (Capra and Luisi 2014) are required to prevent further ecological and environmental deterioration and to ensure society develops and thrives in a sustainable and equitable manner for all. This may be somewhat idealistic, as recent work has suggested that even with changes to food production techniques, reductions in waste, lower consumption of meat products, and improved yields, some planetary boundaries will still be exceeded by 2050 (Conijn et al. 2018; Ridoutt et al. 2021). Such a shift will require globally led coordination and financing, but with local-level actions and initiatives, which must work together such that local actions do not clash with higher levels of coordination (cf. the Latin American context; Cisneros et al. 2024). Such a drastic cultural and societal paradigm shift to prevent ecological catastrophe and the corresponding viability of the WEF sectors on which we depend has been recently called for by Fletcher et al. (2024).

While there is little contestation that the WEF nexus should be seen as an integrated whole, that ecosystems form an integral part in supporting WEF sectors integrity, and recognising that the ideas presented here are not necessarily new per-se, the novel contribution here is in bringing everything together and extending previous ideas into one framework where no single sector is given primacy, where the contribution of ecosystems is explicitly elaborated, and where the demands from, and effects of, society are accounted for. The WEF nexus is underpinned by ecosystems from which resources are demanded and (over-) exploited to meet societal needs, which in turn degrades ecosystems and the WEF resources base. This extension of current thinking is demonstrated through studies and assessments of the WEF nexus that tend to overlook, either explicitly or implicitly, the role of ecosystems in the support of WEF resources provision and security and/or the role of society in degrading both (Conway et al. 2015; Al-Saidi and Elagib 2017; D'Odorico et al. 2018; Zhang et al. 2018; Simpson and Jewitt 2019b; Avellan and Roidt 2022; Mpandeli et al. 2022; Simonovic and Breach 2023; Brouwer et al. 2024). This study thus brings together much recent research and thinking to place explicit emphasis on the need for a systems view of the WEF nexus (Capra and Luisi 2014), ecosystems, and society (cf. Lovelock 1972).

Conclusion

The water-energy-food (WEF) nexus is a complex system whose parts are mutually interacting, causing actions and shocks in one sector to have an impact on the availability, quality of resources, and security of the others. This paper shows that each WEF sector relies strongly on the others for its own security and sustainability, and that the ability to provide outputs (resources) from the respective sectors would be greatly diminished if the functioning of the other sectors was compromised. There is no 'centrality' to the nexus: all sectors stand on an equal footing, though in practice this may not be attainable due to socio-economic or geopolitical drivers. In these situations, the nexus concept may help minimize the negative impacts or help highlight new opportunities to leverage change. Should any sector fail or collapse, there would be a risk of the entire system failing, with societal-wide consequences. The WEF nexus is further conceptualised as a complex system within a much wider system. It is supported by the integrity of ecosystems and their services, and their ability to sustain the provision of safe, plentiful, timely water, energy, and food resources to enable WEF sector security. Ecosystems, forming the 'base' of the WEF nexus, are affected by exploitation of WEF resources, with potentially detrimental impacts to biodiversity, soil integrity, and water purification functions. Nature and ecosystems have a right to exist on their own unharmed from human interventions and without needing to service human needs or being commodified. Humanity has already overstepped many planetary boundaries, and change appears to be incremental and slow. Societal development (population, health, economic activity, development) is supported and dependent on the seamless functioning of the WEF nexus. Society depends on secure WEF resources in adequate quantity, quality, and at the appropriate time in the appropriate place. WEF sector insecurity could have detrimental impacts on human health and wider societal development gains. Yet society places demand on WEF resources. Remaining within planetary boundaries is essential to our collective wellbeing and functioning, and is morally indisputable. The entire WEF-ecosystems-society system is pressured by but also affects demographic change, climate change, and wider socio-economic development. The WEF nexus, while not the widest-scale, or broadest system, is integral to supporting good functioning of ecosystems and society, and is itself mediated by the proper functioning of those larger system elements. The WEF nexus should be seen for what it has for a long time been conceptualised as: a mutually self-supporting resources system that is greater than the sum of its parts that demands good functioning of each of the sectors to be sustainable. No sector or resource holds centre-stage. The resources supply–demand dichotomy needs urgently addressing to secure WEF resources for all, now and in the future, in an equitable manner. Nothing short of a wholesale, drastic shift in societal thinking about resources use, abstraction, exploitation, and the link to economic development is proposed, and that a systems-thinking mentality is central to such a change in global natural resources management. Future resource should seek to better quantify these interactions, and determine, perhaps per-nation, where national resources boundaries and societal limits lie.

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Declarations

Conflict of interest The authors declare no conflicts of interests or competing interests relating to the work presented in this paper.

References

Acheampong AO, Erdiaw-Kwasie MO, Abunyewah M (2021) Does energy accessibility improve human health development? Evidence from energy-poor regions. Energy Econ 96:105165. https://doi.org/10.1016/j.eneco.2021.105165

Acreman M, Arthington AH, Colloff MJ, Couch C, Crossman ND, Dyer F, Overton I, Pollino CA, Stewardson MJ, Young W (2014) Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. Front Ecol Environ 12:466–473. https://doi.org/10.1890/130134

Ahmadi MS, Sušnik J, Veerbeek W, Zevenbergen C (2020) Towards a global day zero? Assessment of current and future water supply and demand in 12 rapidly developing megacities. Sustain Cities Soc 61:102295. https://doi.org/10.1016/j.scs.2020.102295

Albrecht TR, Crootof A, Scott CA (2018) The water-energy-food nexus: a systematic review of methods for nexus assessment. Environ Res Lett 13:043002. https://doi.org/10.1088/1748-9326/aaa9c6

Alexander P, Rounsevell MDA, Dislich C, Dodson JR, Engstroem K, Moran D (2015) Drivers for global agricultural land use change: the nexus of diet, population, yield and bioenergy. Glob Environ Change 35:138–147. https://doi.org/10.1016/j.gloenvcha.2015.08.011

Allen T (1993) Fortunately there are substitutes for water: otherwise our hydropolitical futures would be impossible. 13–26. In: Proceedings of the Conference on Priorities for Water Resources Allocation and Management. Overseas Development Administration, London, UK. ISBN: 090 2500 49X. Available at: https://www.ircwash.org/sites/default/files/210-93PR-11967.pdf#page=18

Al-Saidi M, Elagib NA (2017) Towards understanding the integrative approach of the water, energy and food nexus. Sci Total Environ 574:1131–1139. https://doi.org/10.1016/j.scitotenv.2016.09.046

Amorocho-Daza H, van der Zaag P, Sušnik J (2023) Access to water related services strongly modulates human development. Earths Future 11:e2022EF003364

Anderies JM (2003) Economic development, demographics, and renewable resources: a dynamical systems approach. Environ Dev Econ 8:219–246. https://doi.org/10.1017/S1355770X0300123

Antunes FAF, Chandel AK, Teran-Hilares R, Milessi TSS, Travalia BM, Ferrari FA, Hernandez-Perez AF, Ramos L, Marcelino PF, Brumano LP, Silva GM, Forte MBS, Santos JC, Felipe MGA, da Silva SS (2019) Biofuel production from sugarcane in Brazil. In: Khan M, Khan I (eds) Sugarcane biofuels. Springer, pp 91–121. https://doi.org/10.1007/978-3-030-18597-8_5

Avellan T, Roidt M (2022)The nexus: concepts and frameworks. pp. 16–35. In: Brouwer F (ed) 2022. Handbook on the water-energy-food nexus. Edward Elgar Publishing, Cheltenham, pp 448. https://doi.org/10.4337/9781839100550 (**ISBN: 9781839100543**)

Bakhshianlamouki E, Masia S, Karimi P, van der Zaag P, Sušnik J (2020) A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia Lake Basin, Iran. Sci Total Environ 708:134874. https://doi.org/10.1016/j.scitotenv.2019.134874

Bekhet HA, Azlina A (2010) Energy use in agriculture: input-output analysis. Int Bus Res 3:111–121

Bell A, Matthews N, Zhang W (2016) Opportunities for improved promotion of ecosystem services in agriculture under the water-energy-food nexus. J Environ Stud Sci 6:183–191. https://doi.org/10.1007/s13412-016-0366-9

Bennetzen EH, Smith P, Porter JR (2015) Decoupling of greenhouse gas emissions from global agricultural production: 1970-2050. Glob Change Biol 22:763–781. https://doi.org/10.1111/gcb.13120

Bennetzen EH, Smith P, Porter JR (2016) Agricultural production and greenhouse gas emissions from world regions—the major trends over 40 years. Glob Environ Chang 37:43–55. https://doi.org/10.1016/j.gloenvcha.2015.12.004

Beswick RR, Oliveira AM, Yan Y (2021) Does the green hydrogen economy have a water problem? ACS Energy Lett 6:3167–3169. https://doi.org/10.1021/acsenergylett.1c01375

Bhaduri A, Bogardi J, Siddiqi A, Voigt H, Vörösmarty C, Pahl-Wostl C, Bunn SE, Schrivastava P, Lawford R, Foster S, Kremer H, Renaud FG, Bruns A, Osuna VR (2016) Achieving sustainable development goals from a water perspective. Front Environ Sci 4:64. https://doi.org/10.3389/fenvs.2016.00064

Biggs EM, Bruce E, Boruff B, Duncan JMA, Horsley J, Pauli N, McNeill K, Neef A, Van Ogtrop F, Curnow J, Haworth B, Duce S, Imanari Y (2015) Sustainable development and the water-energy-food nexus: a perspective on livelihoods. Environ Sci Policy 54:389–397. https://doi.org/10.1016/j.envsci.2015.08.002

Bijl DL, Bogaart PW, Kram T, de Vries BJM, van Vuuren DP (2016) Long term water demand for electricity, industry, and households. Environ Sci Policy 55:75–86. https://doi.org/10.1016/j.envsci.2015.09.005

Bindraban PS, van der Velde M, Ye L, van den Berg M, Materechera S, Kiba DI, Tamene L, Ragnarsdottir KV, Jongschaap R, Hoogmoed M, Hoogmoed W, van Beek C, van Lynden G (2012) Assessing the impact of soil degradation on food production. Curr Opin Environ Sustain 4:478–488. https://doi.org/10.1016/j.cosust.2012.09.015

BoE (2015) Breaking the tragedy of the horizon—climate change and financial stability. Speech given by Mark Carney, Governor of the Bank of England (BoE) to Lloyd's of London, UK, 29 September. Video available at: http://bit.ly/2aaFiXV

Borelli P, Robinson DA, Fleischer LR, Lugato E, Ballabio C, Alewell C, Meusburger K, Modugno S, Schutt B, Ferro V, Bagarello V, Van Oost K, Montanarella L, Panagos P (2017) An assessment of

the global impact of 21st century land use change on soil erosion. Nat Commun. https://doi.org/10.1038/s41467-017-02142-7
Brouwer F (2022) Handbook on the water-energy-food nexus. Edward Elgar Publishing, Cheltenham, p 448. https://doi.org/10.4337/9781839100550 (**ISBN: 978 1 83910 054 3**)
Brouwer F, Caucci S, Karthe D, Kirschke S, Madani K, Mueller A, Zhang L, Guenther E (2024) Advancing the resource nexus concept for research and practice. Sustain Nexus Forum. https://doi.org/10.1007/s00550-024-00533-1
Cai X, Zhang X, Wang D (2011) Land availability for biofuel production. Environ Sci Technol 45:334–339. https://doi.org/10.1021/es103338e
Cann KF, Thomas DR, Salmon RL, Wyn-Jones AP, Kay D (2013) Extreme water-related weather events and waterborne disease. Epidemiol Infect 141:671–686. https://doi.org/10.1017/S0950268812001653
Canning P, Charles A, Huang S, Polenske K, Waters A (2010) Energy use in the US food system. United States Department of Agriculture. Econ Res Serv.
Capra F, Luisi PL (2014) The systems view of life: a unifying vision. Cambridge University Press, Cambridge, p 510
Chen B, Han MY, Peng K, Zhou SL, Shao L, Wu XF, Wei WD, Liu SY, Li Z, Li JS, Chen GQ (2018) Global land-water nexus: agricultural land and freshwater use embodied in worldwide supply chains. Sci Total Environ 613–614:931–943. https://doi.org/10.1016/j.scitotenv.2017.09.138.
Cisneros P, Solorio I, Trimble M (2024) Thinking climate action from Latin America: a perspective from the local. NPJ Clim Action 3:5. https://doi.org/10.1038/s44168-023-00081-2
Clasen AP, Agostinho F, Teodosiu C, Almeida CMVB, Giannetti BF (2022) Shaping cities: a proposal for an integrative FEW nexus model. Environ Sci Policy 136:326–336. https://doi.org/10.1016/j.envsci.2022.06.013
Conijn JG, Bindraban PS, Schröder JJ, Jongschaap REE (2018) Can our global food system meet food demand within planetary boundaries? Agr Ecosyst Environ 251:244–256. https://doi.org/10.1016/j.agee.2017.06.001
Conway D, van Garderen EA, Deryng D, Dorling S, Krueger T, Landman W, Lankford B, Lebek K, Osborn T, Thurlow J, Zhu T, Dalin C (2015) Climate and southern Africa's water-energy-food nexus. Nat Clim Chang 5:837–846. https://doi.org/10.1038/NCLIMATE2735
Crist E, Mora C, Engelman R (2017) The interaction of human population, food production, and biodiversity protection. Science 356:260–264. https://doi.org/10.1126/science.aal2011
Dale J, Zou CB, Andrews WJ, Long JM, Liang Y, Qiao L (2015) Climate, water use, and land surface transformation in an irrigation intensive watershed—streamflow responses from 1950 through 2010. Agric Water Manag 160:144–152. https://doi.org/10.1016/j.agwat.2015.07.007.
Daramola DA, Hatzell MC (2023) Energy demand of nitrogen and phosphorus based fertilizers and approaches to circularity. ACS Energy Lett 8:1493–1501. https://doi.org/10.1021/acsenergylett.2c02627
de Fraiture C, Giordano M, Liao Y (2008) Biofuels and implications for agricultural water use: blue impacts of green energy. Water Policy 10:67–81. https://doi.org/10.2166/wp.2008.054
de Fraiture C, Wichlens D, Rockstrom J, Kemp-Benedict E, Eriyagama N, Gordon LJ, Hanjra MA, Hoogeveen J, Huber-Lee A, Karlberg L (2018) Looking ahead to 2050: scenarios of alternative investment approaches. Irrig Drain Syst 22:127
De Groot RS, Alkemade R, Braat L, Hein L, Willemen L (2010) Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol Complex 7:260–272. https://doi.org/10.1016/j.ecocom.2009.10.006.
Deng X, Shi Q, Zhang Q, Shi C, Yin F (2015) Impacts of land use and land cover changes on surface energy and water balance in the Heihe River Basin of China, 2000–2010. Phys Chem Earth Parts a/b/c 79:2–10. https://doi.org/10.1016/j.pce.2015.01.002
Ding N, Liu J, Yang J, Lu B (2018) Water footprints of energy sources in China: exploring options to improve water efficiency. J Clean Prod 174:1021–1031. https://doi.org/10.1016/j.jclepro.2017.10.273.
Ding T, Chen J, Fang L, Ji J, Fang Z (2023) Urban ecosystem services supply-demand assessment from the perspective of the water-energy-food nexus. Sustain Cities Soc 90:104401. https://doi.org/10.1016/j.scs.2023.104401
Dodds F, Higham A, Sherman R (eds) (2009) Climate Change and energy insecurity: the challenge for peace, security, and development. Routledge Earthscan, New York, p 352 (**ISBN: 978-1-84407-855-4**)
D'Odorico P, Davis KF, Rosa L, Carr JA, Chiarelli D, Dell'Angelo J, Gephart J, MacDonald GK, Seekell DA, Suweis S, Rulli MC (2018) The global food-energy-water nexus. Rev Geophys 56:456–531. https://doi.org/10.1029/2017RG000591
Duarte R, Pinilla V, Serrano A (2013) Is there an environmental Kuznets curve for water use? A panel smooth transition regression approach. Econ Model 31:518–527. https://doi.org/10.1016/j.econmod.2012.12.010.
Dupraz C (2023) Assessment of the ground coverage ratio of agrivoltaic systems as a proxy for potential crop productivity. Agroforest Syst. https://doi.org/10.1007/s10457-023-00906-3
Dupraz C, Marrou H, Talbot G, Dufour L, Nogier A, Ferard Y (2011) Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes. Renew Energy 36:2725–2732. https://doi.org/10.1016/j.renene.2011.03.005
ESMAP (2015) Beyond connections. Energy Access Redefined. Available at: openknowledge.worldbank.org/server/api/core/bitstreams/248a7205-e926-5946-9025-605b8035ad95/content
Espinoza D, Morris J, Baroud H, Bisogno M, Cifeuntes A, Gentzoglanis A, Luccioni L, Rojo J, Vahedifard F (2020) The role of traditional discounted cash flows in the tragedy of the horizon: another inconvenient truth. Mitig Adapt Strateg Glob Change 25:643–660. https://doi.org/10.1007/s11027-019-09884-3
Fairbrass AJ, O'Sullivan A, Campbell J, Ekins P (2024) The SDGs provide limited evidence that environmental policies are delivering multiple ecological and social benefits. Earths Future 12:e2024EF004451. https://doi.org/10.1029/2024EF004451
Falkenmark M, Rockström J (2006) The new blue and green water paradigm: breaking new ground for water resources planning and management. J Water Resour Plann Manage 132:129–208. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129)
FAO (1995) Future energy requirements for Africa's agriculture. Pp. FAO, Rome, Italy. Available at: https://www.fao.org/3/v9766E/v9766e00.htm#Contents
FAO (2017) Energy: energy used in agriculture and forestry—agriculture and forestry energy use as a % of total energy use. Dataset. Available at: https://ourworldindata.org/grapher/share-of-total-energy-used-in-agriculture-and-forestry
Farthing A, Rosenlieb E, Steward D, Reber T, Njobvu C, Moyo C (2023) Quantifying agricultural productive use of energy load in Sub-Saharan Africa and its impact on microgrid configurations and costs. Appl Energy 343:121131. https://doi.org/10.1016/j.apenergy.2023.121131
Feng K, Hubacek K, Ling Siu Y, Li X (2014) The energy and water nexus in Chinese electricity production: a hybrid life cycle analysis. Renew Sustain Energy Rev 39:342–355. https://doi.org/10.1016/j.rser.2014.07.080.
Fletcher C, Ripple WJ, Newsome T, Barnard P, Beamer K, Belh A, Bowen J, Cooney M, Crist E, Field C, Hiser K, Karl DM, King DA, Mann ME, McGregor DP, Mora C, Oreskes N, Wilson M

(2024) Earth at risk: an urgent call to end the age of destruction and forge a just and sustainable future. PNAS Nexus 3:1–20. https://doi.org/10.1093/pnasnexus/pgae106

Flörke M, Schneider C, McDonald RI (2018) Water competition between cities and agriculture driven by climate change and urban growth. Nat Sustain 1:51–58. https://doi.org/10.1028/s41893-017-0006-8

Gatti LV, Basso LS, Miller JB, Gloor M, Domingues LG, Cassol HLG, Tejada G, Aragao LEOC, Nobre C, Peters W, Marani L, Arai E, Sanches AH, Correa SM, Anderson L, Von Randow C, Correira CSC, Crispim SP, Neves RAL (2021) Amazonia as a carbon source linked to deforestation and climate change. Nature 595:388–393 https://doi.org/10.1038/s41586-021-03629-6

Geijzendorffer IR, Martin-Lopez B, Roche PK (2015) Improving the identification of mismatches in ecosystem services assessments. Ecol Indic 52:320–331. https://doi.org/10.1016/j.ecolind.2014.12.016

Gerbens-Leenes PW, Xu L, de Vries GJ, Hoekstra AJ (2014) The blue water footprint and land use of biofuels from algae. Water Resour Res 50:8549–8563. https://doi.org/10.1002/2014WR015710

Gibbs HK, Ruesch AS, Achard F, Clayton MK, Holmgren P, Ramankutty N, Foley JA (2010) Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proc Natl Acad Sci U S A 107:16732–16737. https://doi.org/10.1073/pnas.0910275107

Gleick PH (1994) Water and energy. Annu Rev Energy Environ 19:267–299. https://doi.org/10.1146/annurev.eg.19.110194.001411

Gleick PH (2011) The world's water volume 7. The biennial report on freshwater resources. Island Press, Washington, p 424. https://doi.org/10.1007/978-1-59726-228-6

Gołaszewski J, de Visser C, Brodziński Z, Myhan R, Olba-Zięty E, Stolarski M, de Buisonjé F, Ellen H, Stanghellini C, van der Voort M, Baptista F, Leopoldo Silva L, Murcho D, Meyer-Aurich A, Ziegler T, Ahokas J, Jokiniemi T, Mikkola H, Rajaniemi M, Balafoutis A, Briassoulis D, Mistriotis A, Panagakis P, Papadakis G (2012) State of the art on energy efficiency in agriculture: country data on energy consumption in different agro-production sectors in the European Countries. agree Deliverable 2.1. 70pp. Available at: www.acrres.nl/wp-content/uploads/2018/05/AGREE_2.1-State-of-the-Art-of-EE-in-Agr.pdf

González-García A, Palomo I, Gonzalez JA, Lopez CA, Montes C (2020) Quantifying spatial mismatches in ecosystem services provides insights for land-use planning. Land Use Policy 94:104493. https://doi.org/10.1016/j.landusepol.2020.104493

Gragg RS, Anandhi A, Jiru M, Usher KM (2018) A conceptualization of the urban food-energy-water nexus sustainability paradigm: modeling from theory to practice. Front Environ Sci 6:133. https://doi.org/10.3389/fenvs.2018.00133

Graham NT, Hejazi MI, Chen M, Davies EGR, Edmonds JA, Kim SH, Turner SWD, Li X, Vernon CR, Calvin K, Miralles-Wilhelm F, Clarke L, Kyle P, Link R, Patel P, Snyder AC, Wise MA (2020) Humans drive future water scarcity changes across all Shared Socioeconomic Pathways. Environ Res Lett 15:014007. https://doi.org/10.1088/1748-9326/ab639b

Guo M, Song W, Buhain J (2015) Bioenergy and biofuels: history, status, and perspective. Renew Sustain Energy Rev 42:712–725. https://doi.org/10.1016/j.rser.2014.10.013

Gupta J, Bai X, Liverman DM, Rockström J, Qin D, Stewart-Koster B, Rocha JC, Jacobson L, Abrams JF, Andersen LS, McKay DIA, Bala G, Bunn SE, Ciobanu D, DeClerck F, Ebi KL, Gifford L, Gordon C, Hasan S, Kanie N, Lenton TM, Loriani S, Mohamed A, Nakicenovic N, Obura D, Ospina D, Prodani K, Rammelt C, Sakschewski B, Scholtens J, Tharammal T, van Vuuren D, Verburg PH, Winkelmann R, Zimm C, Bennett E, Bjorn A, Bringezu S, Broadgate WJ, Bulkeley H, Crona B, Green PA, Hoff H, Huang L, Hurlbert M, Inoue CYA, Kilkis S, Lade SJ, Liu J, Nadeem I, Ndehedehe C, Okereke C, Otto IM, Pedde S, Pereirra L, Schulte-Uebbing L, Tabara JD, de Vries W, Whiteman G, Xiao C, Xu X, Zafra-Calvo N, Zhang X, Fezzigna P, Gentile G (2024) A just world on a safe planet: a lancet planetary health-earth commission report on earth-system boundaries, translations, and transformations. Lancet Planet Health 8:E813–E873. https://doi.org/10.1016/S2542-5196(24)00042-1

Hanjra MA, Qureshi ME (2010) Global water crisis and future food security in an era of climate change. Food Policy 35:365–377

Hardin G (1968) The tragedy of the commons. Science 162:1243–1248. https://doi.org/10.1126/science.162.3859.1243

Hiskes RP (2006) Environmental human rights and intergenerational justice. Hum Rights Rev 7:81–95. https://doi.org/10.1007/s12142-006-1023-6

Hoekstra AJ, Chapagain AK, Aldaya MM, Mekonnen MM (2009) Water footprint manual: state of the art 2009. 131pp. Water Footprint Network. Available at: www.waterfootprint.org

Hoff H (2011) Understanding the nexus: background paper for the Bonn 2011 Nexus Conference. 51pp. Available at www.sei-international.org/publications?pid=1977

Hostettler S, Gadgil A, Hazboun E (eds) (2015) Sustainable access to energy in the global south: essential technologies and implementation approaches. Springer, p 254. https://doi.org/10.1007/978-3-319-20209-9

Hülsmann S, Sušnik J, Rinke K, Langan S, van Wijk D, Janssen ABG, Mooij WM (2019) Integrated modelling of water resources: the ecosystem perspective on the nexus approach. Curr Opin Environ Sustain 40:14–20. https://doi.org/10.1016/j.cosust.2019.07.003

Huntington HP, Schmidt JI, Loring PA, Whitney E, Aggarwal S, Byrd AG, Dev S, Dotson AD, Huang D, Johnson B, Karenzi J, Penn HJF, Salmon AA, Sambor DJ, Schnabel WE, Wies Jr Jr., Wilber M (2021) Applying the food-energy-water concept at the local scale. Nat Sustain 4:672–679. https://doi.org/10.1038/s41893-021-00719-1

Hussein WA, Memon FA, Savić DA (2017) An integrated model to evaluate water-energy-food nexus at a household scale. Environ Model Softw 93:366–380

International Energy Agency (2016) World energy outlook 2016. 684pp. Available at: www.iea.org

Jewitt G, Kunz R (2011) The impact of biofuel feedstock production on water resources: a developing country perspective. Biofuels Bioprod Biorefin 5:387–398. https://doi.org/10.1002/bbb.314

Jin G, Wang P, Zhao T, Bai Y, Zhao C, Chen D (2015) Reviews on land use change induced effects on regional hydrological ecosystem services for integrated water resources management. Phys Chem Earth Parts a/b/c 89:33–39. https://doi.org/10.1016/j.pce.2015.10.011

John TW, Sušnik J, Masia S, Jewitt G (2023) Towards realization of nexus-doing at the grassroots level: water-energy-food governance assessment in the Songwe River Basin (Tanzania and Malawi). Environ Sci Policy 150:103596. https://doi.org/10.1016/j.envsci.2023.103596

JRC (2022) Crop monitoring in Europe June 2022. JRC MARS Bull 30(6):57. https://doi.org/10.2760/81945. Available at https://ec.europa.eu/jrc/en/mars/bulletins (accessed Sep 2022).

Kanagawa M, Nakata T (2008) Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. Energy Policy 36:2016–2029

Katz D (2015) Water use and economic growth: reconsidering the environmental Kuznets curve relationship. J Clean Prod 88:205–213. https://doi.org/10.1016/j.jclepro.2014.08.017

Kebede E, Kogochi J, Jolly CM (2010) Energy consumption and economic development in Sub-Saharan Africa. Energy Econ 32:532–537. https://doi.org/10.1016/j.eneco.2010.02.003

Kocar G, Civas N (2013) An overview of biofuels from energy crops: current status and future prospects. Renew Sustain Energy Rev 28:900–916. https://doi.org/10.1016/j.rser.2013.08.022
Krausmann F, Gingrich S, Eisenmenger N, Erb K-H, Haberl H, Fischer-Kowalski M (2009) Growth in global materials use, GDP and population during the 20th century. Ecol Econ 68:2696–2705. https://doi.org/10.1016/j.ecolecon.2009.05.007
La Jeunesse I, Quevauviller P (2016) Changement climatique et cycle de l'eau. Impacts, adaptation, législation et avancées scientifiques. Lavoisier Tec & Doc, Paris, France, pp 325 (**ISBN: 978-2743020842**)
Lalawmpuii PKR (2023) Role of water-energy-food nexus in environmental management and climate action. Energy Nexus 11:100230. https://doi.org/10.1016/j.nexus.2023.100230
Lee J, Perera D, Glickman T, Taing L (2020) Water-related disasters and their health impacts: a global review. Prog Disaster Sci 8:100123. https://doi.org/10.1016/j.pdisas.2020.100123
LeRoy Poff N, Matthews JH (2013) Environmental flows in the Anthropocene: past progress and future prospects. Curr Opin Environ Sustain 5:667–675. https://doi.org/10.1016/j.cosust.2013.11.006
Liang Y, Li Y, Liang S, Feng C, Xu L, Qi J, Yang X, Wang Y, Zhang C, Li K, Li H, Yang Z (2020) Quantifying direct and indirect spatial food-energy-water (FEW) nexus in China. Environ Sci Technol 54:9791–9803. https://doi.org/10.1021/acs.est.9b06548
Liu Y, Hejazi M, Kyle P, Kim SH, Davies E, Miralles DG, Teuling AJ, He Y, Niyogi D (2016) Global and regional evaluation of energy for water. Environ Sci Technol 50:9736–9745. https://doi.org/10.1021/acs.est.6b01065
Liu Y, Tang H, Muhammad A, Huang G (2019) Emission mechanism and reduction countermeasures of agricultural greenhouse gases – a review. Greenhouse Gases 9:160–174. https://doi.org/10.1002/ghg.1848
Lovelock JE (1972) Gaia as seen through the atmosphere. Atmos Environ 6:579–580. https://doi.org/10.1016/0004-6981(72)90076-5
Lu C, Tian H (2017) Global nitrogen and phosphorus fertiliser use for agriculture production in the past half century: shifted hotspots and nutrient imbalance. Earth Syst Sci Data 9:181–192. https://doi.org/10.5194/essd-9-181-2017
Lucca E, Kofinas D, Avellán T, Kleemann J, Mooren CE, Blicharska M, Teutschbein C, Sperotto A, Sušnik J, Milliken S, Dašić T, Vasilić V, Dordevic D, Fader M, Taiwo B, Baubekova A, Pineda-Martos R, Baganz GFM, Spyropoulou A, el Jeitany J, Oral HV, Sambo B, Merheb M, Pagano A, Castelli G, Arnold M, Suškevičs M, Masia S, Psomas A, Radenović T, La Jeunesse I, Amorocho-Daza H, Bresci E, Das SS, Munaretto S, Brouwer F, Laspidou C (2025) Incorporating ecosystems in the water-energy-food nexus: current perspectives and future directions. Sci Total Environ 966:178600. https://doi.org/10.1016/j.scitotenv.2025.178600
Macknick J, Newmark R, Heath G, Hallett KC (2012) Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ Res Lett 7:045802. https://doi.org/10.1088/1748-9326/7/4/045802
Malin SA, Ryder S, Lyra MG (2019) Environmental justice and environmental resource extraction: intersections of power, equity and access. Environ Sociol 5:109–116. https://doi.org/10.1080/23251042.2019.1608420
Martinez-Hernandez E, Leach M, Yang A (2017) Understanding water-energy-food and ecosystem interactions using the nexus simulation tool NexSym. Appl Energy 206:1009–1021. https://doi.org/10.1016/j.apenergy.2017.09.022
Meadows DH, Meadows DL, Randers J, Behrens WW (1972) The limits to growth. Universal Books
Merz JJ, Barnard P, Rees WE, Smith D, Maroni M, Rhodes CJ, Dederer JH, Bajaj N, Joy MK, Wiedmann, Sutherland R (2023) World scientists' warning: the behavioural crisis driving ecological overshoot. Sci Progress 106:1–22. https://doi.org/10.1177/00368504231201372
Mirindi D, Sušnik J, Masia S, Jewitt G (2024) A system dynamics modelling assessment of water-energy-food resource demand futures at the city scale: Goma, Democratic Republic of Congo. World Dev Sustain 5:100159. https://doi.org/10.1016/j.wds.2024.100159
Monte-Luna PD, Brook BW, Zetina-Rejon MJ, Cruz-Escalona VH (2004) The carrying capacity of ecosystems. Glob Ecol Biogeogr 13:485–495. https://doi.org/10.1111/j.1466-822X.2004.00131.x
Mooren CE, Munaretto S, Hegger DLT, Driessen PPJ, La Jeunesse I (2024) Towards transboundary Water-Energy-Food-Ecosystem Nexus governance: a comparative governance assessment of the Lielupe and Mesta-Nestos river basins. J Environ Planning Policy Manage 26:623–642. https://doi.org/10.1080/1523908X.2024.2384582
Mpandeli S, Nhamo L, Senzanje A, Jewitt G, Modi A, Massawe F, Mabhaudi T (2022) The watereenergyefood nexus: its transition into a transformative approach. In: Mabhaudi T, Senzanje A, Modi A, Jewitt G, Massawe F (eds) 2022. Water–Energy–Food nexus narratives and resource securities: a global south perspective. Elsevier, Amsterdam, p 332. https://doi.org/10.1016/B978-0-323-91223-5.00004-6
Namany S, Al-Ansari T, Govindan R (2019) Optimisation of the energy, water, and food nexus for food security scenarios. Comput Chem Eng 129:106513. https://doi.org/10.1016/j.compchemeng.2019.106513
Nass LL, Pereira PAA, Ellis D (2009) Biofuels in Brazil: an overview. Crop Sci 47:2228–2237. https://doi.org/10.2135/cropsci2007.03.0166
Nassrullah H, Anis SF, Hasaikeh R, Hilal N (2020) Energy for desalination: a state-of-the-art review. Desalination 491:114569. https://doi.org/10.1016/j.desal.2020.114569
Newborough M, Cooley G (2021) Green hydrogen: water use implications and opportunities. Fuel Cells Bull 12:12–15. https://doi.org/10.1016/S1464-2859(21)00658-1
Nhamo L, Mabhaudi T, Mpandeli S, Dickens C, Nhemachena C, Senzanje A, Naidoo D, Liphadzi S, Modi AT (2020) An integrative analytical model for the water-energy-food nexus:outh Africa case study. Environ Sci Policy 109:15–24
Odo DB, Yang IA, Knibbs LD (2021) A systematic review and appraisal of epidemiological studies on household fuel use and its health effects using demographic and health surveys. Int J Environ Res Public Health 18:1411. https://doi.org/10.3390/ijerph18041411
Ogbolumani OA, Nwulu NI (2021) Multi-objective optimisation of constrained food-energy-water-nexus systems for sustainable resource allocation. Sustain Energy Technol Assess 44:100967. https://doi.org/10.1016/j.seta.2020.100967
Oliver MA, Gregory PJ (2014) Soil, food security and human health: a review. Eur J Soil Sci 66:257–276. https://doi.org/10.1111/ejss.12216
Olsson G (2021) Water and energy: threats and opportunities. IWA, London, p 294
O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, Levy M, Solecki W (2015) The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob Environ Chang. https://doi.org/10.1016/j.gloenvcha.2015.01.004
Ostrom E (1998) Scales, polycentricity and incentives: designing complexity to govern complexity. In: Lakshman DG, McNeely JA (eds) Protection of global biodiversity: converging strategies. Duke University Press, Durham, pp 440. https://hdl.handle.net/2027/mdp.39015047081172. **(ISBN: 978-0-8223-2188-0)**

Pahl-Wostl C (2007) Transitions towards adaptive management of water facing climate and global change. Water Resour Manage 21:49–62. https://doi.org/10.1007/s11269-006-9040-4

Pahl-Wostl C, Bhaduri A, Bruns A (2018) Editorial special issue: the nexus of water, energy and food–an environmental governance perspective. Environ Sci Policy 90:161–163

Paris B, Vandorou F, Balafoutis AT, Vaiopoulos K, Kyriakarakos G, Manolakos D, Papadakis G (2022) Energy use in open-field agriculture in the EU: a critical review recommending energy efficiency measures and renewable energy sources adoption. Renew Sustain Energy Rev 158:112098. https://doi.org/10.1016/j.rser.2022.112098

Pham-Truffert M, Metz F, Fischer M, Rueff H, Messerli P (2020) Interactions among the sustainable development goals: knowledge for identifying multipliers and virtuous cycles. Sustain Dev 28:1236–1250. https://doi.org/10.1002/sd.2073.

Phoumin H, Kimura F (2019) The impacts of energy insecurity on household welfare in Cambodia: empirical evidence and policy implications. Econ Model 82:35–41. https://doi.org/10.1016/j.econmod.2019.09.024

Plappally AK, Leinhard JH (2012) Energy requirements for water production, treatment, end use, reclamation, and disposal. Renew Sustain Energy Rev 16:4818–4848. https://doi.org/10.1016/j.rser.2012.05.022

Quaranta E, Georgakaki A, Letout S, Kuokkanen A, Mountraki A, Grabowska M, Gea Bermudez J, Tattini J (2023) Clean energy technology observatory: hydropower and pumped hydropower storage in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets. Publications Office of the European Union, Luxembourg, 2023. https://doi.org/10.2760/841176 (**JRC134918**)

Raworth K (2018) Doughnut economics. Random House, p 288 (**ISBN: 9781847941398**)

Richardson K, Steffen W, Lucht W, Bendtsen J, Cornell SE, Donges JF, Drüke M, Fetzer I, Bala G, von Bloh W, Feulner G, Fiedler S, Gerten D, Gleeson T, Hofmann M, Huiskamp W, Kummu M, Mohan C, Nogués-Bravo D, Petri S, Porkka M, Rahmstorf S, Schaphoff S, Thonicke K, Tobian A, Virkki V, Wang-Erlandsson L, Weber L, Rockström J (2023) Earth beyond six of nine planetary boundaries. Sci Adv 9:eadh2458. https://doi.org/10.1126/sciadv.adh2458

Ridoutt BG, Baird D, Hendrie GA (2021) Diets within planetary boundaries: what is the potential of dietary change alone? Sustain Prod Consum 28:802–810. https://doi.org/10.1016/j.spc.2021.07.009

Rockström J, Steffen W, Noone K, Persson A, Stuart Chapin F III, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Constanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley JA (2009) A safe operating space for humanity. Nature 461:472–475. https://doi.org/10.1038/461472a

Rockström J, Donges JF, Fetzer I, Martin MA, Wang-Erlandsson L, Richardson K (2024) Planetary boundaries guide humanity's future on Earth. Nat Rev Earth Environ 5:773–788. https://doi.org/10.1038/s43017-024-00597-z

Rogers P, Hall AW (2003) Effective Water Governance. Global Water Partnership Technical Committee (TEC). TEC Background Papers No. 7, pp 48. Available at: https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/07-effective-water-governance-2003-english.pdf

Roidt M, Avellán T (2019) Learning from integrated management approaches to implement the nexus. J Environ Manage 237:609–616. https://doi.org/10.1016/j.jenvman.2019.02.106

Rulli MC, Bellomi D, Cazzoli A, De Carolis G, D'Odorico P (2016) The water-land-food nexus of first-generation biofuels. Sci Rep 6:22521. https://doi.org/10.1038/srep22521

Sachs JD (2015) The age of sustainable development. Columbia University Press, p 544 (**ISBN: 9780231173155**)

Salem HS, Pudza MY, Yihdego Y (2022) Water strategies and water–food nexus: challenges and opportunities towards sustainable development in various regions of the World. Sustain Water Resour Manage 8:1–54. https://doi.org/10.1007/s40899-022-00676-3

Sanders KT, Webber ME (2012) Evaluating the energy consumed for water use in the United States. Environ Res Lett 7:034034. https://doi.org/10.1088/1748-9326/7/3/034034

Scherer L, Pfister S (2016) Global water footprint assessment of hydropower. Renew Energy 99:711–720. https://doi.org/10.1016/j.renene.2016.07.021

Schlesier H, Schäfer M, Desing H (2024) Measuring the doughnut: a good life for all is possible within planetary boundaries. J Clean Prod 448:141447. https://doi.org/10.1016/j.jclepro.2024.141447

Shepherd E, Milner-Gulland EJ, Knight AT, Ling MA, Darrah S, van Soesbergen A, Burgess ND (2016) Status and trends in global ecosystem services and natural capital: assessing progress towards Aichi Biodiversity Target 14. Conserv Lett 9:429–437. https://doi.org/10.1111/conl.12320

Simonovic SP, Breach PA (2023) System context: global change and the food-energy-water nexus. J Water Resour Plann Manage 149:04023064. https://doi.org/10.1061/JWRMD5.WRENG-6076

Simpson GB, Jewitt GPW (2019a) The water-energy-food nexus in the anthropocene: moving from 'nexus thinking' to 'nexus action.' Curr Opin Environ Sustain 40:117–123. https://doi.org/10.1016/j.cosust.2019.10.007

Simpson GB, Jewitt GPW (2019b) The development of the water-energy-food nexus as a framework for achieving resource security: a review. Front Environ Sci 7:8. https://doi.org/10.3389/fenvs.2019.00008

Simpson GB, Jewitt GPW, Mabhaudhi T, Taguta C, Badenhorst J (2023) An African perspective on the water-energy-food nexus. Sci Rep 13:16842. https://doi.org/10.1038/s41598-023-43606-9

Smil V (2018) Energy and civilisation: a history. MIT Press, p 568

Smil V (2019) Growth: from microorganisms to megacities. MIT Press, p 634

Smith KR, Frumkin H, Balakrishnan K, Butler CD, Chafe ZA, Fairlie I, Kinney P, Kjellstrom T, Mauzerall DL, McKone TE, McMichael AJ, Schneider M (2013) Energy and human health. Annu Rev Public Health 34:159–188. https://doi.org/10.1146/annurev-publhealth-031912-114404

Sola P, Ochieng C, Yila J, Iiyama M (2016) Links between energy access and food security in sub Saharan Africa: an exploratory review. Food Secur 8:635–642. https://doi.org/10.1007/s12571-016-0570-1

Sridharan V, Shivakumar A, Niet T, Ramos EP, Howells M (2020) Land, energy and water resource management and its impact on GHG emissions, electricity supply and food production – insights from a Ugandan case study. Environ Res Commun 2:085003. https://doi.org/10.1088/2515-7620/abaf38

Steffen W, Richardson K, Rockstrom J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, Folke C, Gerten D, Heinke J, Mace GM, Persson LM, Ramanathan V, Reyers B, Sorlin S (2015a) Planetary boundaries: guiding human development on a changing planet. Science 347:1259855. https://doi.org/10.1126/science.1259855

Steffen W, Broadgate W, Deutsch L, Gaffney O, Lugwig C (2015b) The trajectory of the Anthropocene: the great acceleration. Anthropocene Rev 2:81–98. https://doi.org/10.1177/2053019614564785

Stoner O, Lewis J, Martinez IL, Gumy S, Economou T, Adair-Rohani H (2021) Household cooking fuel estimates at global and country

level for 1990 to 2030. Nat Commun 12:5793. https://doi.org/10.1038/s41467-021-26036-x
Suda AO, Sušnik J, Masia S, Jewitt G (2024) Policy coherence assessment of water, energy, and food resources policies in the Tana River Basin, Kenya. Environ Sci Policy 159:103816. https://doi.org/10.1016/j.envsci.2024.103816
Sušnik J (2018) Data-driven quantification of the global water-energy-food system. Resour Conserv Recycl 133:179–190. https://doi.org/10.1016/j.resconrec.2018.02.023
Sušnik J, Masia S, Indriksone D, Brēmere I, Vamvakeridou-Lyroudia LS (2021) System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate nexus in Latvia. Sci Total Environ 775:145827. https://doi.org/10.1016/j.scitotenv.2021.145827
Sušnik J, Masia S, Teutschbein C (2023) Water as a key enabler of nexus systems (water-energy-food). Cambridge Prisms Water 1:1–11. https://doi.org/10.1017/wat.2023.1
Tian P, Zhong H, Chen X, Feng K, Sun L, Zhang N, Shao X, Liu Y, Hubacek K (2024) Keeping the global consumption within the planetary boundaries. Nature. https://doi.org/10.1038/s41586-024-08154-w
Timilsina GR (2014) Biofuels in the long-run global energy supply mix for transportation. Philos Trans R Soc Lond A Math Phys Eng Sci. https://doi.org/10.1098/rsta.2012.0323
Toreti A, Masante D, Acosta Navarro J, Bavera D, Cammalleri C, De Felice M, de Jager A, Di Colli C, Hrast Essenfelder A, Maetens W, Magni D, Spinoni J (2022). Drought in Europe July 2022. EUR 31147 EN. Luxembourg: Publications Office of the European Union. https://doi.org/10.2760/014884
Tripathy KP, Mishra AK (2023) How unusual is the 2022 European compound drought and heatwave event? Geophys Res Lett 50:e2023GL105453. https://doi.org/10.1029/2023GL105453
UN DESA (Department of Economic and Social Affairs) (2019) World urbanisation prospects: the 2018 revision. 126pp. New York: United Nations. ISBN: 978-92-1-148319-2. Available at: https://population.un.org/wup/Publications/
United Nations World Water Assessment Programme (WWAP) (2014) The United Nations World Water Development Report 2014: Water and Energy. Paris: UNESCO. United Nations World. Available at: www.unwater.org/publications/un-world-water-development-report-2014
United Nations World Water Assessment Programme (WWAP) (2019) The United Nations World Water Development Report 2019: Leaving no One behind. Paris: UNESCO. Available at: www.unesco.org/en/wwap/wwdr/2019
van den Heuvel L, Blicharska M, Masia S, Sušnik J, Teutschbein C (2020) Ecosystem services in the Swedish water-energy-food-land-climate nexus: anthropogenic pressures and physical interactions. Ecosystem Serv 44:101141. https://doi.org/10.1016/j.ecoser.2020.101141
Wang Z-H, Li S-X (2019) Chapter Three—Nitrate N loss by leaching and surface runoff in agricultural land: a global issue (review). Adv Agron 156:159–217. https://doi.org/10.1016/bs.agron.2019.01.007
Wang S, Cao T, Chen B (2017) Urban energy–water nexus based on modified input–output analysis. Appl Energy 196:208–217. https://doi.org/10.1016/j.apenergy.2017.02.011
Wang X, Zhao C, Muller C, Wang C, Ciais P, Janssens I, Penuelas J, Asseng S, Li T, Elliott J, Huang Y, Li L, Piao S (2020) Emergent constraint on crop yield response to warmer temperature from field experiments. Nat Sustain 3:908–916. https://doi.org/10.1038/s41893-020-0569-7
Wang X, Dong Z, Sušnik J (2023) System dynamics modelling to simulate regional water-energy-food nexus combined with the society-economy-environment system in Hunan Province, China. Sci Total Environ 863:160993. https://doi.org/10.1016/j.scitotenv.2022.160993
Ward JD, Sutton PC, Werner AD, Constanza R, Mohr SH, Simmons CT (2016) Is decoupling GDP growth from environmental impact possible? PLoS ONE 11:e0164733. https://doi.org/10.1371/journal.pone.0164733
Wiedenhofer D, Virag D, Kalt G, Plank B, Streeck J, Pichler M, Mayer A, Krausmann F, Brockway P, Schaffartzik A (2020) A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping. Environ Res Lett 15:063002. https://doi.org/10.1088/1748-9326/ab8429
Yates D, Mehta VK, Huber-Lee A, McCluskey A, Purkey D (2021) Exploring the water-energy nexus in California via an integrative modeling approach. J Water Resour Plann Manage 147:04021084. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001431
Zakari A, Toplak J, Tomažič L (2022) Exploring the relationship between energy and food security in Africa with instrumental variables analysis. Energies 15:5473. https://doi.org/10.3390/en15155473
Zeng Y, Liu D, Guo S, Xiong L, Liu P, Yin J, Wu Z (2022) A system dynamic model to quantify the impacts of water resources allocation on water-energy-food-society (WEFS) nexus. Hydrol Earth Syst Sci 26:3965–3988. https://doi.org/10.5194/hess-26-3965-2022
Zhang C, Chen X, Li Y, Ding W, Fu G (2018) Water-energy-food nexus: concepts, questions and methodologies. J Clean Prod 195:625–639. https://doi.org/10.1016/j.jclepro.2018.05.194
Zhang P, Zhang L, Chang Y, Xu M, Hao Y, Liang S, Liu G, Yang Z, Wang C (2019) Food-energy-water (FEW) nexus for urban sustainability: a comprehensive review. Resour Conserv Recycl 142:215–224. https://doi.org/10.1016/j.resconrec.2018.11.018
Zhang S, Hu W, Li M, Guo Z, Wang L, Wu L (2021) Multiscale research on spatial supply-demand mismatches and synergic strategies of multifunctional cultivated land. J Environ Manage 299:113605. https://doi.org/10.1016/j.jenvman.2021.113605