Exorcising Malthusian ghosts: Vaccinating the Nexus to advance integrated water, energy and food resource resilience

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Abstract

Water-Energy-Food (WEF) Nexus interactions vary from seemingly negative and intractable wicked problems to opportunities for enhanced sustainability. The aim of this paper is to review the current state of understanding on WEF resource interactions and to provide a roadmap to enhance integrated resource management. A qualitative perspective based on expert insight and experience was supported by a more quantitative systematic analysis of the literature to define Nexus interactions, describe the nature of different challenges, and explore the factors that influence them. We found that Nexus challenges, and associated interactions (e.g. trade-offs and synergies), vary with complexity and spatial and temporal scale, and biases in research and culture act as barriers to progress. An interdisciplinary approach is needed to develop technical solutions employed through the use of orchestrated shocks (e.g. historic analogues, predictive modelling, experimentation, and scenario planning) to “Vaccinate the Nexus” and improve system resilience. To achieve this, multidisciplinary capability should be developed to solve interdisciplinary challenges, while protecting specialism. It is recognised that through embracing complexity and “Nexus (or Systems) Thinking”, future integration of resource management may be facilitated through holistic education, informed by interdisciplinary research, and ingrained in cross-sector policy and governance.

1. Introduction

When Thomas Malthus published *An Essay on the Principle of Population* (Malthus 1798) he warned that, despite technological advance leading to improved agricultural output, the “passion between the sexes” would remain constant and the resulting population growth would diminish food resources to such low levels as to cause famine and catastrophe. This process, governed by the *Iron Law of Population*, was predicted to be cyclical, with gains in quality of life repeatedly negated by the impacts of subsequent population growth; a

Malthusian Trap, in which humanity would be forever lost. Today, many (Optimists; Von Foerster et al. 1960; or Wizards, Mann 2019) argue that Malthus's predictions have been proven wrong (e.g. Shermer 2016), as evidenced by a lack of an apocalyptic human population collapse despite several fold growth since his time. However, some (Pessimists; Von Foerster et al. 1960; or Prophets, Mann 2019) suggest technological innovation has merely delayed the Malthusian trap (Smith 2015), while others provide nuance to the concept in terms of sustainability and equity of access to resources, asking whether quality of life can be sustained while improving the plight of those in need (Stokstad 2005).

Several recent predictions on global resource supply strike a distinctly Malthusian tone, highlighting unprecedented challenges in achieving sustainability, security and equity. For example, it is estimated that food production must increase by 50% (based on 2012 levels) to sustain more than 9.5 billion people in 2050 (FAO 2017), and total energy consumption will increase by 50% between 2018 and 2050 (EIA 2020), while the demand for water will rise by 55% from a 2000 baseline, assuming "business-as-usual" (Leflaive et al. 2012). Fears over how these growing demands are met have led to scenarios (e.g. Parolari et al. 2015 in relation to water) that, while not necessarily leading to global population crashes, are expected to create severe inequality (e.g. Ruel et al. 2010). It is not only the scale and implications of the challenges faced that are reminiscent of Malthus; current views of resource management also continue to focus on single isolated domains. Simplistic perspectives allow easier visualisation of complex challenges, but lead to limited appreciation of the interrelatedness of multiple sectors, such as water, energy, and food (WEF) (Rasul and Sharma 2016), and the interactions between them; the WEF Nexus.

In an attempt to embrace complexity, integrated resource management has become a central tenet of sustainability (e.g. Biggs et al. 2015; UN 2014), and the interactions between sectors is increasingly understood through adopting a Nexus based world view. For example, the food sector is estimated to account for approximately 30% of the world's total energy consumption (FAO 2011a); the generation of electricity is dependent on the abstraction of large quantities of water (IEA 2016); and water supply and treatment is a highly energy intensive process (e.g. Smith and Liu 2017). The Nexus highlights the negative impacts that the exploitation of any one resource may have on the use of others. For instance, food security is dependent on water that is essential to arable and livestock production, while irrigation represents approximately 70% of all freshwater withdrawal (UNESCO 2012; FAO 2011b). However, unsustainable abstraction reduces the integrity of other ecosystems services, such as fisheries, that if managed correctly provide a self-sustaining source of protein that may be extensively exploited by many (Baran and Borin, 2012). There is a need to better understand the often-complex relationships that govern integrated resource exploitation to identify impediments to sustainability and develop policies and practices to improve resilience.

Unfortunately, effective resource governance is rarely proactive. Historically, policies have often been created and laws enacted only after specific resources (e.g. water – Clean Water Act [US] 1972) have become so degraded as to endanger future use. Often interventions are only started once such threats become sufficiently severe as to “shock” the system (e.g. for London, UK, the Metropolis Local Management Act 1858 in response to the 'Great Stink' caused by extreme sewerage pollution, and the Clean Air Act 1956 in response to a deadly smog in 1952). However, interventions in response to such shocks may often be too late to facilitate full recovery (e.g. collapse of Newfoundland northern cod stocks despite moratorium in 1992). Nevertheless, and using the body’s immune system as an analogy, it is often only through these shocks (infections) that resource management becomes sufficiently resilient (immune), i.e. able to persist after being stressed by a perturbation (Meadows, 2009). The WEF Nexus has become an important component in policy debate because it promotes coherence in governance processes across sectors (Weitz et al. 2017) and provides a framework to understand impediments to integrated resource management. This paper: 1) highlights variation by which different WEF Nexus interactions range from seemingly intractable challenges to opportunities for sustainability; 2) considers how biases act as barriers to integrated development; 3) describes the concept of “Vaccinating the Nexus” in which orchestrated shocks may help boost system resilience; and 4) proposes a roadmap for advancing integrated resource exploitation through improved governance and interdisciplinary research and education.

2. Nexus challenges and opportunities for resource management

Resource exploitation from a single sector silo can result in unforeseen negative consequences for those operating in other domains, i.e. interactions that result in trade-offs between sectors. When considering resource management from the perspective of the Nexus, a trade-off can be defined as the balance between two desirable but incompatible ecosystem services in which there is a simultaneous reduction in one and an enhancement of another (Bennett et al., 2009; Haase et al., 2012). Trade-offs are influenced by spatial and temporal scales (Rodríguez et al., 2006) in that the effects may be felt locally or at a distant location and can take place relatively rapidly or slowly. To advance co-ordinated solutions to the challenge imposed by trade-offs, it is necessary to develop greater awareness and understanding of the broader impacts of the activities involved. Here, two examples of Nexus interactions operating over different spatial and temporal scales are provided. The first describes the contemporary challenge of local renewable energy development and the negative and potentially unseen distant consequences for water resource management. Operating at a local scale, but representing repetition of historic mistakes made elsewhere, the second considers the interaction between water and energy through the generation of hydroelectric power, and the immediate positive benefits experienced relative to the negative long-term degradation of other ecosystem services.

2.1 The disconnect between local actions and global consequences; a Nexus perspective

Several factors influence investor confidence and social acceptance of renewable energy (Sovacool and Ratan 2012). Over recent decades, government policies and associated incentives have increased local renewable energy projects (e.g. wind, solar, micro-hydropower) in rural areas (e.g. Munday et al. 2011 for the UK). For farming communities, however, onsite generation carries the risk of lost revenue due to intermittent production and potential for power outages for systems dependent on it. To balance production and consumption, energy storage can enhance security of supply. Lithium-ion battery storage is particularly attractive because the technology can be relatively small, due to a high energy density, and charged/discharged multiple times during its life, while the cost has declined substantially over recent years (Nayak et al. 2018). Those with high onsite energy usage can benefit from an increasingly decentralised system, particularly with advancing battery technology complementing solar and other forms of energy capture (KPMG 2016). When viewed from a wider perspective, such actions may aid corporate environmental responsibility agendas, e.g. by reducing carbon dioxide emissions or increasing renewables as part of a wider portfolio. Opportunities to disseminate positive messages are encouraged as part of public relations exercises; and yet there is a danger that when interactions are complex and far ranging, negative impacts remain unseen, or ignored.

The world's largest producers of lithium are Chile (Salar de Atacama) and Bolivia (Salar de Uyuni) (Gruber et al. 2011; Wanger 2011). Large transnational mining companies abstract increasing quantities to meet global demand. In the Atacama Desert, the driest place on earth, the mining projects extract the lithium from brine, and are negatively impacting ground water reserves essential for local low-income communities and high value nature conservation areas (Romero et al. 2012). These activities are having strongly intertwined impacts on the environment, biodiversity and human health as fresh water supplies to critical agricultural areas are threatened (Wanger 2011). This has created a source of environmental conflict (Oyarzún and Oyarzún 2011) and social injustice due to increasing threats imposed on the subsistence of local communities, including indigenous groups (Romero et al. 2012; Babidge 2016) whose rights are recognised by the international community, e.g. United Nations Declaration on the Rights of Indigenous Peoples (UN 2007).

This illustrates how socio-economic and environmental impacts may be experienced in one sector, in this case water, in one region of the world as a result of well-intentioned and apparently increasingly sustainable development of other resources elsewhere.

2.2 A history of repeated Nexus mistakes in hydropower.

The exploitation of water to meet relatively short-term demands to generate electricity and grow food, and thus provide jobs, represents a classic Nexus challenge. Dams have been constructed on most of the worlds' rivers for water supply and irrigation, flood management, as well as mechanical and hydroelectric power (Grill et al. 2019). The use of water to generate electricity by this tried and tested technology remains a globally important means by which to enhance quality of life while reducing dependency on hydrocarbons. Furthermore, many large-scale hydroelectric projects are closely linked with advances in food production, enabling agricultural intensification rather than land expansion. By impounding the Columbia and Snake Rivers through the construction of a cascade of dams between the 1930s and 1970s, the way was paved for Washington State to become the largest producer of hydroelectricity in the US (EIA 2019). It also enabled the realisation of the Columbia Basin Project (Bloodworth and White 2008), an irrigation network that supplied 2,700 km^2 of what was largely semi-arid Channelled Scabland desert. The hydropower and irrigation schemes, initiated partly as a mechanism to kick-start the economy by providing jobs during the Great Depression, dramatically changed the agricultural economy of the Pacific Northwest of the US by enabling places like central and eastern Washington to diversify. The downside, however, was the dramatic negative long-term impact on a previously self-sustaining source of protein, wild salmonid fisheries (Raymond 1988), which had sustained native people for millennia.

Dams damage fish populations and the fisheries they support because they fragment and degrade critical habitat and disrupt connectivity by impeding access to essential spawning and rearing grounds, alter predator-prey dynamics, and damage or kill those that enter turbines (Kemp 2015). The construction of dams for hydroelectricity, or mechanical power beforehand, has a long historical precedent going back hundreds if not thousands of years; and with it the decline and sometimes demise of populations of fish and fisheries on which they are based (Montgomery 2003). Even when environmental impact mitigation technologies and strategies, such as fish passes, screens, and dam removal, are employed, they provide at best only partial compensation (Brown et al. 2013), and in some cases can themselves be damaging (Kemp 2015).

Today, the most rapid and intense hydropower development is taking place in Asia and South America, which are experiencing unprecedented demands for electricity. For example, in South America the majority of electricity consumed in many countries is generated by hydropower (e.g. > 80% in Brazil and nearly 100% in Paraguay, IRENA 2016), with plans for further development in many areas, including the Amazon basin. In addition to immediate benefits they provide, dams can cause severe long-term damage to the freshwater fisheries on which huge numbers of people depend. In many cases, it is the small-scale artisanal inland fisheries that supplement livelihoods and provide an important source of protein for low-income communities (e.g. Béné and Friend 2011 for the Mekong basin; Novaes and Carvalho 2013 for Brazil). These fisheries are especially important for vulnerable fishing communities that inhabit landlocked regions, such as Laos in Asia, and Bolivia and Paraguay in South America, where inland fishery production is primarily for self-consumption and is critical in the diet of several indigenous groups considered most vulnerable to food insecurity (FAO 2010). These fisheries are threatened by hydropower development, the scale of which dwarf those previously experienced in Europe and North America, even those on the Columbia River, and the environmental impacts are orders of magnitude higher. For example, the Brazilian inland fisheries, that contribute around $US 250 million per year to the regional and local economy and helps secure the welfare of low-income communities, continue to decline across the country following construction of hydropower plants (Hoeinghaus et al. 2009). In Asia, the Mekong River maintains one of the world’s largest inland capture fisheries that supports millions of low-income people (60 million people in the lower Mekong basin) for their primary source of protein (Ngor et al. 2018). The Mekong River Commission (2017) predicts that the planned construction of 11 large hydropower dams on the mainstem of the lower river, and a further 120 dams on its tributaries, will result in a reduction of the total fishery biomass by 40-80% by 2040. This will have substantial economic and cultural impact on the large proportion of the population who depend on fish for their livelihoods and food.

3. Buzzwords, biases, and barriers to integrated resource management and sustainability

For some, the WEF Nexus provides a new concept to be tested (e.g. Keskinen et al. 2016); for others, it is merely a fashionable “buzzword” (Cairns and Krzywoszynska 2016) used to “rebrand” an existing field (e.g. Wichelns 2017). Indeed, the Nexus could be considered a part of “Systems Thinking”, a well-developed field in which a system is a set of elements that are interconnected in a way that achieves a function (Meadows, 2009). How systems operate have received much attention, and mechanisms such as stocks and flows, trade-offs and synergies, tipping points, feedback loops, and resilience are well described (Meadows, 2009), providing a useful conceptual framework by which to better understand the Nexus. Whether the Nexus is a novel concept, or a repackaged old one, it provides a useful framework to refocus attention on resource utilisation and management as part of a wider integrated system (Simpson and Jewitt 2019; Gondhalekar et al. 2021). For example, a Nexus based approach is recognised as a useful tool to develop integrated resource management to achieve the UN Sustainable Development Goals (SDGs) (e.g. Simpson and Jewitt 2019) that are themselves highly interlinked (Hülsmann and Ardakanian, 2018). This approach could help identify weaknesses of incoherent policies that promote sustainable development in one sector, while ignoring the negative consequences experienced elsewhere (e.g. Naidoo et al. 2021). However, even when embracing the concept, the risk of adopting biased and limited viewpoints remain. There is a need to understand strengths and weaknesses of the approach so that the framework constructed is robust. Here we summarise some of the most obvious biases identified during a quantitative assessment of the literature using a vote-counting approach.

3.1 Vote counting quantitative review

To develop insight on potential biases and gaps in understanding in the published literature on the Water-Energy-Food (WEF) Nexus, an assessment of available literature was conducted using a “rapid” vote-counting systematic review (e.g. Kemp et al., 2012) in June 2018. Available literature was collected using the bibliographic search engine “Google Scholar” by employing the search string “Water-Energy-Food-Nexus”. Articles were interrogated and key information collated in relation to ranked order of relevance (the first article on the first page retrieved was ranked 1), authors, the source (e.g. journal, book, or report), title, and year of publication. The information returned was entered into a database. A simple vote-counting methodology was used to categorise the focal topic of the article / book chapter (e.g. terrestrial, marine or freshwater ecosystem services or domains) and subject area of the source (Table 1). We were particularly interested in understanding whether there were biases in food systems (e.g. agriculture versus aquaculture or fisheries), geographic region of focus, and discipline (e.g. social sciences, engineering etc.). In-line with our aim to create a “rapid” and easy to use coarse-resolution method that others with limited resources might easily follow, we set an arbitrary cut-off at 80 returns (first 8 pages of Google scholar) based on judgements that this was sufficient to provide a general holistic impression of the biases and gaps. For other subjects, with greater depth of information, a larger number may be required.

3.2 Limitations, advantages and justifications for the approach adopted

Methods used to collate evidence from the available literature range along a continuum from inherently subjective and qualitative narrative reviews based on expert interpretation and perspective to articulate a justification for a starting position in a debate, to highly systematic quantitative meta-analyses that employ various statistical methods to integrate results (e.g. estimates of effect size) from individual studies. In the relation to the WEF Nexus, there are recent examples of the adoption of approaches at both ends of the spectrum (e.g. Simpson and Jewitt 2019 for traditional narrative review; Newell et al. 2019; Bardazzi and Bosello 2021 for meta-analyses), each of which provide valuable contributions to understanding of the subject. The use of various approaches varies with discipline, with narrative reviews being the traditional method employed in the biological and ecological sciences (Koricheva and Gurevitch 2013) and meta-analyses being commonplace in the medical and social sciences for decades (Schulze 2004). Nevertheless, today quantitative approaches are increasingly valued and more frequently adopted for a wide variety of data among multiple disciplines. There has been much debate related to the advantages and disadvantages of different approaches adopted (e.g. Combs et al. 2011 in relation to vote-counting; Kemp et al., 2016; Greco et al. 2013 in relation to meta-analyses). This has led to the development of widely applied protocols, such as PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) that is updated to take account of technological advance, e.g. in the use of natural language processing and machine learning (Page et al. 2021). We recognise the strengths and weaknesses of different approaches adopted and the need to select the one most appropriate to the aim of the study and the question posed. In this case we selected a “vote-counting” systematic review, that while more quantitative than a traditional narrative approach is considered “cruder” and coarser-resolution than the more sophisticated meta-analyses used by others (Jones et al. 1995). This was intentional; our paper provides a broad perspective on the WEF Nexus based on expert insight and experience, rather than a dedicated review alone. We employed our “scoping” analytical approach only to those sections dedicated to the discussion of biases and gaps in understanding that are evidenced by the results obtained. Importantly, we selected an approach that could be rapidly applied and easily followed and replicated by others who can readily access data that is available to most, including to those we specifically directed attention in our discussion (e.g. educators in secondary school classrooms). For example, our approach employed the widely available platform “Google Scholar”, rather than others that limit accessibility through subscription (e.g. Web of Science or Scopus), and are thus difficult to obtain outside of academic institutions or within low-income developing nations with limited resources. Likewise, we avoided the use of technical and complex statistical analysis ranging from fixed or random effects models, e.g. using general linear mixed models and Bayesian methods, to more recent approaches that often require substantial computer power, e.g. machine learning and Big Data. We do not attempt to emphasise weaknesses associated with either the alternative narrative review or more quantitative meta-analysis. Instead, our approach can be used to provide a low-cost “indication” of the current status of literature on which to base the development of further questions and hypotheses that can be rigorously tested using other more sophisticated and powerful means if necessary. Indeed, we welcome others that are starting to do so (e.g. Newell et al. 2019) to build understanding of the patterns in the WEF Nexus literature that we discuss here.

3.3 All Nexuses are equal; but are some more equal than others?

The review reinforced an intrinsic bias. By using the search string selected, we immediately ignored relevant articles published prior to an International Conference held in Germany in 2011 at which the term was first used. Furthermore, we focused only on those that relate to the WEF Nexus, ignoring elements of related and equally important, but different Nexuses (e.g. environment and health) (Wichelns 2017). Our observations support the findings of others (e.g. Simpson and Jewitt 2019) that equity, livelihoods and the environment are often excluded from WEF Nexus assessments. There is a danger that the WEF Nexus is deemed to be more important than others, and academics and practitioners are encouraged to venture towards cross-disciplinary activities, but in a narrowly defined field (e.g. focusing only on WEF); simply creating another silo that one day becomes the academic mainstream. Food, of course, is intricately linked with health; water and energy to the environment, and all to poverty and social injustice. There is a need to avoid biases to specific areas governed by the expertise available within academic think-tanks, or the perspectives of stakeholders involved in certain conflicts, and consider interactions more holistically as “Nexus Science”.

3.4 Terrestrial agriculture versus fisheries; a within sector bias

Greater consideration of terrestrial agriculture systems, with only 14% of publications providing anything more than a cursory mention of fisheries and aquaculture, reflects the majority of food systems being based on agriculture; in 2015 fisheries and aquaculture provided only 17% of animal protein consumed globally (FAO 2018). Considerations of fisheries were biased to Asia, particularly the Mekong River, while other areas, such as Africa and South America, were ignored. Concentration on Asia is logical, with 85% of the global population that engage in fisheries and aquaculture from that region (FAO 2018), while the Mekong is experiencing large-scale hydropower development (Grumbine and Xu 2011). Nevertheless, the lack of discussion of the WEF Nexus in the context of South America, where a massive hydropower sector threatens the livelihoods of people dependent on fisheries (Moran et al. 2018), remains a clear gap in the discourse. Of greatest surprise, however, is the absence of consideration of marine fisheries that represent 87.2% of the total combined (marine and inland) global catches in 2016 (FAO 2018). Perhaps this is because direct interactions with other water users are less apparent than for inland capture fisheries or terrestrial agriculture, despite interactions between marine fisheries, energy and other food systems representing often illogical resource management. More recently the interest in marine fisheries as part of an “Environment-Food-Carbon” Nexus has emerged, with evidence of synergies (when two ecosystem services are enhanced, Bennett et al., 2009) being realised through the protection of habitat (Marine Protected Areas) resulting in conserving biodiversity, increasing fisheries yield, and securing marine carbon stocks that might otherwise be disturbed by human activities (Sala et al. 2021).

If managed sustainably, fisheries could provide a natural and self-sustaining source of protein for millions of people, particularly those from low-income vulnerable communities in developing nations, with lower energy and water costs than can be achieved by terrestrial agriculture. To do so would be in-line with UN commitments to achieve sustainable fisheries for food security (FAO 2021) and to ensure access to markets for subsistence fishers, indigenous people (FAO 2015), and particularly women and girl fishers and fish workers dependent on this resource (e.g. Sruthi et al. 2016). This topic highlights an area where greater integrated resource management might provide substantial future benefits considering that our ability to increase production, in the face of consumption that is expected to continue to grow for several decades (Godfray et al. 2010), is threatened by growing competition for land, water, and energy.

3.5 Audience bias; does the WEF Nexus appeal more to specific groups?

Assessing which disciplines are more likely to adopt the WEF Nexus concept suggests a bias towards the social and environmental sciences and policy. Of the 80 sources retrieved, 57 were journal articles, four were books, ten were book chapters (of which eight were from the same book), four were reports (e.g. FAO or IUCN publications), and five provided citations only. Of the academic articles, 24 out of 57 were in journals that primarily focused on water (seven in *Water International* alone); six were published in journals related to energy (three in *Energy policy*); and only one was in a food-focused journal (*Journal of Agriculture and Food Chemistry*) (Table 1). The second largest category (16/57 journal articles) was in the field of environment and sustainability (six in *Environmental Science and Policy*) (Table 1). Two articles were published in journals that focus primarily on climate change, and one was published in a purely engineering journal (*Computers and Chemical Engineering*).

There were relatively few returns in engineering and technology (examples relate to biorefineries and drip irrigation), with the first decade of WEF Nexus development tending to concentrate on definitions, description of concepts, identification of challenges, and construction of frameworks for resource policy and management. There was less emphasis on advancing technological solutions to the problems faced; although there are many groups working on technological innovation (e.g. bioenergy), most of them, at this stage at least, have yet to identify and associate with the Nexus.

4. Understanding system shocks and improving resilience through "Vaccinating the Nexus"

Sustainability and security of WEF resources can be advanced more rapidly following systemic shocks that increase political attention through media coverage and shifts in public opinion. Nexus shocks can take many different forms. Here, shocks are defined as dramatic incidents that impact the communities, e.g. through disrupted supply of the resources affected, such as extreme weather events (e.g. flood or drought) (e.g. Elagib et al. 2021), economic disturbance (e.g. recessions / depressions) (e.g. Agri et al. 2017), health crises (e.g. pandemics) (e.g. Al-Saidia and Hussein 2021), shifts in national policy (e.g. UK exit from the EU - Brexit) (e.g. Ziv et al. 2018), political conflict (e.g. war) (Bromwich 2015), or unsustainable technological advance (Figure 1) (e.g. Thurstan et al. 2010). These shocks, although often independent, can occur in combination (e.g. Kemp et al. 2020 in relation to Brexit and Covid-19), resulting in greater impact and complexity of systemic interactions, e.g. food-health, environment, poverty and social injustice. We propose that understanding how shocks act as agents of change may enhance sustainable resource management by using immunity as an analogy and the shocks as a means to "Vaccinate" the system.

4.1 Nexus shocks

Extreme weather events provide a clear illustration, with floods and droughts disrupting and reducing the supply of water, food and energy. For example, a substantial (e.g. 1 in 100 year) drought, such as that experienced in the US and South America in 1988/ 89, reduced maize and soybean production by 12% and 8.5%, respectively, and is expected to become more frequent (e.g. 1 in 30 year by 2040) and intense as a result of climate change (Bailey et al. 2015). This could lead to instability and conflict that will have global consequences.

Engineering development can shock many ecosystem services, such as through the construction of irrigation and other networks of waterways that connect hydrologically isolated catchments. These facilitate range expansion of numerous aquatic invasive species, often at substantial economic and ecological cost. For example, golden apple snail deliberately introduced to South-east Asia from South America as a cheap and protein rich food in the 1980s have since spread widely and are a significant problem in rice production (Horgan et al. 2014). They substantially reduce yields (Schneiker et al. 2016) and prove costly to control (Nghiem et al. 2013), resulting in the development of policies and legislation aimed at mitigating negative impacts.

Impacts of economic shocks on WEF resource management are seldom straightforward. Perhaps the US experience of the Great Depression in the 1930s provides one of the best examples of how extreme events, policies, and economics interact. Encouraged by decades of federal land policies and acts (e.g. Homestead Act 1862, Kinkaid Act 1904) after the American Civil War, settlers moved westward to convert the Great Plains into arable land (Stroup 1988). As more settlers arrived, agricultural intensification increased, further escalated by an increase in the price of wheat as a result of World War I (Worster 1986; McLeman et al. 2014). By the start of the 1930s, approximately 30% of the US portion of the Great Plains had been converted (Cunfer 2005), and the stage was set for a sequence of coincidental shocks that resulted in economic, ecological and social catastrophe. The depression was made worse by a prolonged period of drought that accelerated severe wind erosion of the soil in the Southern plains (Maio et al. 2007); the Dust Bowl. The failure of the harvest for several successive years prevented the agricultural sector from driving an economic recovery, which led to the mass movement of people in search of work (Gregory 1989). Between 1929 and 1933, employment declined by 25% and productivity by 30% (Cole and Ohanian 1999), a level from which it took farming communities in the most affected regions several decades to adjust (Hornbeck 2012).

The cumulative effects of multiple interacting shocks involving the economy, policy, war, and extreme weather events, and the mismanagement of WEF resources, stimulated dramatic changes in government agricultural, land management and socio-economic policies after the dust bowl. These included the development of groundwater irrigation and large-scale water retention projects and tree planting schemes (McLeman et al. 2014). Large-scale infrastructure projects further afield, such as the Grand Coulee Dam and Columbia Basin Irrigation Project in Washington State, were partly designed to help recovery and provide jobs for a displaced workforce as part of President Roosevelt's New Deal (Pitzer 1994), although these created their own Nexus shocks. Recently, increased scholarly attention to the history of the Dust Bowl reflects a growing interest in the consequences of droughts, considering projected increases in their return frequency, and environmental change more generally (McLeman et al. 2014). This also illustrates an interest in improving system resilience in the face of future threats by learning lessons from past events; a form of Nexus vaccination.

4.2 Vaccinating the Nexus

The shift from the challenge of understanding WEF interactions, limited by data-availability and knowledge gaps in understanding, to the operationalisation of the WEF Nexus requires the development of appropriate systematic tools and software platforms (Liu et al. 2017). Advances have been made over recent years (see Endo et al. 2020; Shannak et al. 2018; Zhang et al. 2018 for reviews), and considerable effort expended in developing associated models (Table 2). However, the "Vaccinating the Nexus" concept is based on pre-emptive action to enhance WEF resilience to future shocks and requires the adoption of an alternative perspective. This approach differs from the more common reactive response to negative impacts that may also improve resilience, but over longer time-scales and at greater expense (analogous to developing innate immunity). By simulating shocks, understanding of system response and management implications will be enhanced. Vaccination may be achieved in a range of ways, many already available and actively used, such as stress testing of banks or simulation of the performance of major infrastructure under different scenarios (flood simulation, energy network modelling). The key consideration, however, is the need to adopt holistic approaches (Howarth and Monasterolo 2016) that require interdisciplinary expertise to identify the vulnerabilities of the integrated system, visualise the nature of the shocks, and understand how information received may improve resilience. Here we propose three categories of vaccination:

(i) Learning lessons from history: By reviewing and understanding past events and the lessons learnt it is possible to enhance future system resilience by identifying early signs (symptoms) of a previous shock experienced, and responding accordingly. Reviewing historic case studies provides useful analogues for current and future WEF challenges. Examples include the use of the Great Depression to learn how agriculture, climate, political and economic systems interact in a developed nation context, resulting in approaches to enhance future resilience (McLeman et al. 2014), or more recent economic recessions to re-regulate activities, abandon cost-benefit analytical tools that trivialise risk, and limit consumption (described as “benefiting from a dose of the same medicine” Klein 2009); the collapse of ancient civilisations from the perspective of renewable resource use (e.g. Janssen and Scheffer 2004); or the opportunistic exploitation of systemic shocks (e.g. reduced marine fishing pressure during war or a pandemic) to “kick-start” resource recovery (Figure 1; Kemp et al. 2020).

(ii) Future scanning through simulation, experimentation and consultation: System resilience can be improved with appropriate interdisciplinary expertise to identify where future Nexus challenges are likely to arise, e.g. by using modelling (e.g. Qian and Liang 2021; Wen et al. 2022), experimentation, “Think-Tanks”, stakeholder consultation (e.g. workshops; see Markantonis et al. 2019 for a WEF Nexus case study), and expert opinion surveys. Modelling may help predict the response of food systems to climate change, such as by the UK-US Taskforce on Extreme Weather and Global Food System Resilience (Bailey et al. 2015). Agent Based Models predict the impact of infrastructure development on fragile ecosystems

services (e.g. Guzy et al. 2008), while optimisation models help plan and regulate infrastructure networks to minimise impact and enhance sustainability (e.g. Ioannidou and O'Hanley 2016). Experimental field trials might be conducted to quantify performance of energy crops under alternative watering and fertiliser regimes (McCalmont et al. 2017); or "role-play" exercises (e.g. Trnka and Jenvald 2006), commonly employed to help disaster response teams prepare for failure of multiple integrated systems (water, sanitation, energy, food, transport, health), may be adopted. In consultation and surveys of opinion, a Nexus based approach would require participation from multiple sectors, ensuring engagement from a wider community in developing consensus or identifying differences in perspective.

(iii) Developing interdisciplinarity to integrate resource management across domains: Traditional approaches to WEF resource management are inherently weak. As government departments often operate in silos (Scott and Gong 2021) and compete for limited treasury allocation, there is a tendency to operate in a disjointed, incoherent and ineffective way, with consultation often targeting audiences aligned to traditional sectors most likely to be affected by the policy (UK Government 2018). This neglects the systems perspective that there may be far-reaching unintended Nexus impacts in other domains that thus will remain unforeseen. Likewise, silo activity predominates in both education and research. While Vaccinating the Nexus is unlikely to work using any single approach in isolation, a greater focus on enhancing capability by enabling interdisciplinarity to flourish (Howarth and Monasterolo 2016) will ultimately provide the greatest benefits over the long-term by enabling resource management to be integrated across domains.

5. Recommendations for the future: a roadmap to "Nexus Thinking" for governance, research, and education

Changes in structure and processes to enable greater interdisciplinarity are needed if the WEF Nexus is to provide a useful policy framework for coherent governance across domains

(Weitz et al. 2017). Here we are not promoting transdisciplinarity (e.g. Howarth and Monasterolo 2016) in which there is a high degree of disciplinary synthesis and interaction to achieve a unity of knowledge (and potentially new transdisciplinary subject areas, such as bioinformatics or ecohydraulics), because it is costly, difficult to achieve and hence rare. Instead, we propose that an interdisciplinary approach should be adopted based on forming and educating multidisciplinary teams consisting of specialists and generalists that cover a broader and more holistic range of expertise, while maintaining within sector experience and specialism. The creation of new generalist disciplinary silos, such as the WEF Nexus or any other Nexus-like amalgam, should be avoided in preference for more holistic "Nexus" (or Systems) "Thinking". The following recommendations are based on this ethos, and consider governance and policy, research, and education, each of which will operate over a range of temporal scales.

5.1 Governance and policy

Adopting a Nexus approach to governance and policy-making depends on understanding interactions between domains, mechanisms for collaboration and communication, and co-ordination across sectors and between levels of government (Scott 2017). A lack of understanding of the linkages and an inability of organisations to collaborate impedes integration, while political-economic factors disrupt co-ordination. While policy makers must understand where conflicts are likely to exist, the nature of trade-offs and potential for synergies, they must also appreciate the existence and influence of power dynamics across scales of governance (Newell et al. 2018). Likewise, they must also plan for the challenges to be addressed over appropriate time-scales to elicit real change and for solutions to be adopted, ensuring that the various actors (e.g. regulators, industry, consultants, community groups etc.) remain sufficiently engaged and funded accordingly.

The presumption that governance institutions value the Nexus concept and have both the capacity and inclination to manage limited resources in more sustainable and integrated ways, ignores the constraints imposed by the legacy of system structure and culture.

Aspirations of collaboration can be eroded by competition for limited resources between and within levels of government (Newell et al. 2018), creating institutional structures ill designed to accommodate cross-sector activity. Despite refocusing, restructuring, and rebranding departments or Ministries, in many nations these continue to oversee policies that independently relate to different WEF domains, often in less than coherent ways.

A Nexus approach to policy making is challenging for institutions accustomed to vertical co-ordination and management, such as the large international donor organisations and development banks, which can entrench a competitive private and market-led model (Newell et al. 2018). The challenges of managing multiple interdependent resources are magnified as trade-offs are negotiated at each level of authority; a problem referred to as the triple disconnect between global, national and local scales of governance (Newell et al. 2018). Indeed, achieving Nexus based governance, across all layers, may result in unhelpful centralisation that is impractical and costly considering the degree of complexity involved (Scott 2017). An alternative approach is to strengthen local-level government to make decisions based on appropriate cost-benefit assessments (Scott 2017). Using local knowledge within the community and making sure voices from many different perspectives are heard, there is less need for sophisticated modelling and comprehensive data analysis, enabling more pragmatic, realistic and transparent approaches to be adopted. For instance, Larcom and van Gevelt (2017) show how local-level planning decisions can successfully incorporate the interdependencies and complexities of the WEF Nexus when they follow principles of procedural justice. However, devolved local level approaches are unable to fully accommodate Nexus interactions that are global in nature (such as discussed earlier in relation to energy storage and lithium mining). In such instances, there is no escape from the need to collaborate through multi-layered structures of governing institutions that operate across national boundaries, although these are challenging in the case of trade-offs in which positive actions in one nation result in detrimental outcomes in others.

The two main impediments to a Nexus approach to governance and policy can be categorised as: (1) insufficient understanding and knowledge, and (2) impeded collaboration and communication. There is a need to develop greater understanding among decision-makers, enhance mechanisms for collaboration and advance vehicles for horizontal and vertical communication between WEF related departments and multiple scales of government, respectively. We address these briefly here:

a) *Enhancing Nexus understanding*: Identifying opportunities for greatest synergy and, where conflicts exist, understanding the nature of the trade-offs created are important first steps in decision making. To maximise involvement of stakeholder networks across policy domains and at multiple levels, a better understanding of the interactions between different units and policy areas dealing with alternative Nexus sectors is needed. Replicable methods to quantify interactions can identify potential for mutual support or conflict (Fader et al. 2018), and include traditional approaches, such as semi-structured stakeholder interviews, direct participation and observation of policy making, and discussions and personal communications with focus groups operating in different sectors (e.g. Newell et al. 2018). More recently, mixed-methods network analysis (Stein and Jaspersen 2019), quantitative modelling, and futures thinking methods (Yung et al. 2019) are used to investigate network structure and interactions.

b) *Advancing collaboration and communication:* Collaboration across government departments fosters broader understanding, helps identify linkages between sectors, and highlights drivers for prioritisation of policy, so that shared visions and common goals are developed. This might be achieved through cross-departmental and/or stakeholder “away-days” or “sandpit events”, and over a longer time-frame through interdepartmental secondments. In some cases, staff might be given a remit to address specific Nexus challenges as part of cross-department teams.

Communications and capacity building outside government can be achieved, not only through consultation, but by other mechanisms, such as “policy sabbaticals” with key stakeholder groups. Specialist public policy exchange units, such as those hosted by many universities, are able to link researchers with decision makers and promote outreach and engagement activities but remain unavailable to many stakeholders without such resources. Instead, university based policy events and cross-departmental government forums should be made accessible to wider society, such as through the internet and social media.

5.2 Research

Academics are usually trained to become specialists, having focused on specific fields, which only occasionally venture into other realms (Waldman 2013). Researchers often concentrate on a narrowly defined fundamental or applied problem and seek funding from bodies that typically represent traditional disciplines. Alternatively, funding may be acquired from industry to solve sector specific challenges, rather than across domains to benefit the wider community. There are exceptions, including cross-council funding of interdisciplinary projects, but these are less common, and suffer the weaknesses of single council co-ordination and the use of reviewers with insufficiently broad expertise to provide adequate assessments. Furthermore, the outputs are often difficult to disseminate through specialist conferences and journals, governed by unidisciplinary organising committees and editorial boards.

While many researchers agree that interdisciplinarity is positive (but see Jacobs 2014, Jacobs and Frickel 2009 for critical reviews), there remain multiple impediments at both institutional and individual levels (Waldman 2013). Universities are constrained by structural legacies of disciplinary departments and faculties centred round undergraduate and masters' levels taught programmes. Academics are recruited to teach their specialism, for which they are rewarded through promotion and tenure.

Researchers specialise early on in their careers, from graduate level dissertations to PhDs and postdoctoral positions, during which they are encouraged to develop a specialism. Networking with others with similar interests, and the need through convention to justify their work, e.g. when writing articles, presenting at conferences, and defending their theses, reinforces the strong loyalties to their chosen fields (Sutherland 2018). This can be helpful in advancing interdisciplinarity, as it provides the foundations for diverse teams (Waldman 2013), so long as there are opportunities to participate within them. However, impediments remain for those disinclined to collaborate because they are either too busy with their own focused pursuits, fail to see the academic value, or fear that departure from their traditional trajectories could be damaging to their careers. For others, the benefits of interdisciplinarity may not become apparent until later in their careers, and funding may be scarce and the formation of teams difficult, e.g. because others fear straying beyond their disciplinary boundaries. This conditioned unidisciplinary conservatism driven by the pressure to develop specialist profiles remains a strong impediment to interdisciplinary research.

There are several barriers to the dissemination of interdisciplinary research. While many journals accept some interdisciplinary submissions, at least in principle, these can cause difficulty for editors who struggle to find reviewers with appropriate expertise (Waldman 2013). Indeed, experience and confidence in handling such submissions is needed, and the editor must be able to see the value of the work, despite what may be conflicting reviews from specialists. For those less experienced, or acting on behalf of popular high impact factor journals that apply robust demand management, it is easier to employ a mechanistic approach and reject the submission in the face of one poor review, or return to the authors without review after deeming the article to be outside of the journal remit.

Perhaps counterintuitively, to promote interdisciplinarity we argue for the maintenance of disciplinary specialism. Nexus challenges will be more easily identified and solved through a combination of multi-disciplinary teams working with those that may be described as "*Big Picture Nexus Thinkers*". However, interdisciplinary research must be better promoted, and impediments that make this difficult removed. Based on the successful adoption of interdisciplinarity in some institutions (e.g. Louvel 2015), we provide the following recommendations:

(a) Funders should incentivise interdisciplinary research through specific calls that require formation of multidisciplinary teams and promote a gradual shift in priorities to Nexus related areas. Coordination by individual councils should be avoided, and independent administrative bodies set-up to do so. Variation in quality of peer review due to the shortage of expertise and experience should be accounted for, veering away from traditional mechanistic approaches that score and rank attributes of proposals submitted.

(b) Reward structures (e.g. promotion and appraisal) should shift the value towards participating in multi-disciplinary teams so that this outweighs the risks of engaging in broader activities than might otherwise be considered. With a critical mass, attitudes can be expected to shift, influencing future agendas, e.g. through dedicated conferences sessions and associated special issues. With formation of a community, members will gain positions on editorial boards and other committees where they can influence strategy and remit, ultimately garnering political and public support to influence research priorities.

(c) Interdisciplinarity at institutional levels can be achieved where proactive policies to redefine departmental boundaries are supported (Louvel 2015). These might involve establishing hubs of innovation and creativity, even if virtual, that align to some interdisciplinary “Grand Challenge” or “Goal”, such as those defined by government or intergovernmental bodies. Discretionary allocation of funds to these activities, such as studentships supervised by cross-disciplinary teams, will help promote interdisciplinarity.

5.3 Education

To promote education for sustainability (target 4.7 of the SDG 4), e.g. through challenging convention in marketing and life-styles (Purushottam et al. 2021), there is a need to integrate interdisciplinarity as part of the educational provision. Some universities promote interdisciplinarity as a means of delivering holistic learning and more adaptable students (Falcus et al. 2019; Bear and Skorton 2019). In France, pro-interdisciplinary university policies have been driven by the Ministry of Higher Education and Research (Louvel 2015), providing what some consider a useful counterbalance to excessive academism in science. However, disciplinary structures remain in place, both physically and virtually, with many universities under ever increasing pressure to market core subjects in a competitive environment. From a Nexus perspective, education should be based on strong disciplinary foundations, but also promote awareness of interrelated issues of resource management and be delivered through approaches that enhance multidisciplinary team learning. Here we provide recommendations for developing Nexus Thinking during different stages of education.

(a) Primary / elementary education: For learners between four or five and 11 or 12 years of age, primary education focuses on reading, writing and numerical skill development. In many ways, this level of education is conducive to learning about complex Nexus issues because teachers tend to be generalists and are more likely to explore topics alongside their pupils, integrating skill development within classroom activities, rather than employing a vertical "top down" one-way transfer of knowledge. As pupils have not yet experienced the silos of disciplinary learning, and continue to view the world more holistically, age-appropriate exploration of broader Nexus challenges and the complexity of trade-offs and environmental risk should be promoted as part of the curriculum.

(b) Secondary education: From the ages of 11 or 12 to around 16, learners typically experience discipline focused education, reinforced by the spatial and temporal segregation of school infrastructure (dedicated class-rooms and laboratories) and timetables. Through repeated assessment, learners become increasingly aware of their strengths and weaknesses, and are encouraged to define their interests and embark on pathways towards increased specialism. However, coherent and integrated curricula should facilitate and maintain linkages between courses to meet more holistic learning outcomes. For example, case studies (e.g. the Dust Bowl) may be used in history classes to reinforce messages provided in other subjects (e.g. geography, environmental studies, economics) to help learners develop more specialist knowledge, while developing wider understanding of

interdisciplinary issues. Furthermore, some classes may adopt an interdisciplinary remit, embracing generalism and complexity, through working as teams.

(c) Tertiary education: Tertiary education is that provided for learners above school age and includes college, university, and vocational courses. It varies between region, with some countries providing a more holistic offering (e.g. French Baccalaureate), while others focus on early specialism (e.g. UK A-Levels). In advancing capability in integrated resource management there is a trade-off between developing the breadth of understanding, knowledge acquisition, and experience needed, while learning in sufficient depth the specialist skills required by wider society to bridge gaps identified, e.g. in national industrial strategies. Historically, recruitment to degree programmes with both major and minor elements was relatively common, although the subjects tended to be closely related. Today, many programmes offer only some flexibility in accessing modules outside of the core discipline, and often provide limited experience of performing complex multi-disciplinary tasks as teams. There is a gap in the provision for cross-faculty modules designed to promote multidisciplinary working and skill development, an option likely considered attractive to employers.

Postgraduate training is an increasingly important element of many doctoral programmes, promoting development of both technical and transferable (e.g. communication and outreach) skills, sometimes by adopting cohort-based approaches. Such programmes typically focus on well-defined topic areas, sometimes delivered in partnership with industry, to produce postgraduates capable of closing skills gaps of societal relevance. Although training strategies may be diverse, those that employ peer-to-peer team learning have proven particularly successful (e.g. Lam et al. 2019) and are likely to perform well in generating Nexus related research capability. Likewise, the incorporation of “Systems Thinking” (e.g. Meadows, 2009) in modules that address issues related to integrated resource management will provide students with the conceptual framework needed to develop a greater appreciation of the Nexus.

(d) Everyday education for wider society: Education does not begin or end on entering and leaving a school or other similar institution; people learn every day, either formally (e.g. Continued Professional Development), or informally, during a process of "lifelong learning". Learning may be active or passive, driven by many factors, including a benign interest in educating the public (e.g. local historical societies); as part of a marketing strategy (e.g. for tea); to promote agendas and perspectives (e.g. conservation groups); to disseminate information (e.g. via visitor centres or engagement events); and ultimately via two-way active participation (e.g. citizen science) (Figure 2). Such efforts are funded by a variety of sources, sometimes closely aligned to vested interests, others through state sponsored campaigns (e.g. public health messages during a pandemic). We propose that wider society is not averse to receiving complex messages; life is complex in nature. But such messages may need to be delivered in ways that ensure the information gained is manageable and appropriately reinforced.

Conclusions

This paper explored the nature of Nexus interactions, such as trade-offs and synergies, and how they vary with, and are influenced by, spatial and temporal scales; how biases can impede integrated resource management; how shocks may be used to improve systems resilience, in a process we refer to as "Vaccinating the Nexus"; and how increased interdisciplinarity in governance, research and education may facilitate more holistic resource management in the future.

Nexus interactions can be complex and seemingly intractable, especially when policies and practices that appear to be both socially and environmentally beneficial are enacted, but remain unsighted of costs imposed on different sectors, potentially in different regions. Such interactions are variable, influenced by magnitude and spatial and temporal scale, and in some cases complex and nuanced, making them difficult to identify and define, while others are simple, obvious and predictable. For some, the effects are beneficial, while for others they are negative. There is a need to appreciate variability of interactions; recognise the responses observed in alternative domains; investigate mechanisms by which they operate; analyse costs and benefits holistically; identify the actors involved and stakeholder interests; and resolve challenges posed and conflicts created. Overall, the Nexus provides a framework to develop more sustainable approaches to resource development.

Although, for some, the Nexus represents a rebranding of integrated resource management as something new (Cairns and Krzywoszynska 2016), it remains a useful concept in light of the independent operation of our institutions and systems. For example, government departments invariably operate separately from others, and in many cases compete for limited budgets and time allocated; academics continue to work in the departmental silos that are long-standing and defined by their disciplines; and industry focuses on developing profits within their traditional sectoral boundaries. As greater integration of our current systems to meet more holistic goals continues to be a test to sustainable resource management, posing the challenge in Nexus terms, even by adopting a buzzword, may go some way to advance this agenda. The Nexus approach is increasingly recognised as a particularly useful way to bridge sectors and consider interrelated resources in an unbiased way to manage ecosystem services to promote sustainable development (e.g. Cansino-Loeza et al. 2021), especially given the interrelatedness of the Sustainable Development Goals (SDGs) (Hülsmann and Ardakanian, 2018).

The WEF Nexus approach may prejudice the debate towards specific domains selected, while ignoring others that are equally as important (Wichelns 2017). The bias towards water, energy and food, as opposed to the interactions between any other domain, is very real, and consideration might be better aimed at a more holistic “Nexus Science”. Nevertheless, the concentration on these resources is logical because each provides a critical foundation on which successful integrated management must be based if sustainability is to be achieved, and over which environmental, geopolitical, and socioeconomic conflict can occur.

The WEF Nexus literature is inherently biased, such as towards terrestrial agriculture rather than fisheries, and particularly lacking for the marine environment. Some disciplines and domains, such as some environmental and social sciences and the water sector, have engaged more with the concept than others. One of the dangers of creating what may at first appear to be a new discipline is that existing challenges in integrated resource management and systems thinking are redefined and frameworks reinvented, attracting researchers to participate in various Think-Tanks and discussion groups, potentially displacing already well-established entities and duplicating past efforts. There is a need to move forward and simultaneously engage a wider audience, while preserving the involvement of those already working in these areas, such as those able to develop technical solutions to the challenges faced, who as yet may not have identified the Nexus for what it is.

Shocks arise in many guises (extreme weather, infrastructure, conflict, pandemics, policy, economic) and domains, and their consideration is nothing new (e.g. for discussion in economic literature see Cole and Ohanian 1999). Multiple Nexus shocks (e.g. the Covid-19 pandemic and Brexit, Kemp et al. 2020) may interact across several sectors and over a range of spatial and temporal scales, and greater interdisciplinary expertise is needed to fully understand them. Shocks can be considered useful when employed proactively to stimulate cross-sector thinking needed to improve the resilience of our systems (Vaccinating the Nexus), e.g. by using historic analogues from which to learn; predicting future responses through simulation, experimentation and consultation; and building interdisciplinary capability. They can also provide opportunities, such as the initiation of policies to be better manage resources in the future (e.g. Kemp et al. 2020).

Purpose, as opposed to profit-led, business strategies that include sustainability at their core are becoming an increasingly common component of industry governance. Whether this is driven by the consumer or government, or vice versa, is open to debate, but it provides a pathway for increased Nexus Thinking and more holistic and sustainable resource exploitation in the future. However, due to the complexity of many systems-based sustainability challenges, government policy must focus on incentivising increased interdisciplinary in research and education. This should be achieved while maintaining strong foundations in the core disciplines, and instead promoting enhanced multi-disciplinary team formation and collaborative working. Understanding of more holistic perspectives of global challenges associated with resource development and use should be facilitated through early-stage educational curricula and maintained throughout life-long learning and employment. Failure to achieve this will risk continued threats to water, energy and food resources, and as shocks in supply are exacerbated by shifts in climate the threats of conflict will increase, possibly presenting a societal apparition of Malthus's ideas.

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Data availability

Data supporting this study are openly available from the University of Southampton repository at http://doi.org/10.5258/SOTON/D2048

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Tables and figures

Table 1. Number of journal articles returned during an assessment of the literature related to "Water-Energy-Food Nexus" using the search engine, Google Scholar. Of 80 sources received, 57 were scientific journal articles. The percentages relate to number of journal articles, not the total numbers of sources retrieved (all categories).

Subject area and journal title	Number of returns	Percentage returns
Water		
Water International	7	12
Water	5	9
Water Alternatives	4	7
Journal of Hydrology	3	5
International Journal of Water Resource Development	3	5
Water Policy	1	2
Ground Water	1	2
	24	**42**
Energy		
Energy policy	3	5
Energies	1	2
Energy Science and Engineering	1	2
Journal of Energy Resources Technology	1	2
	6	**11**
Food		
Journal of Agriculture and Food Chemistry	1	2
	1	**2**
Environment and Sustainability		
Environmental Science and Policy	6	11
Current Opinion in Environmental Sustainability	3	5
Frontiers of Environmental Science and Engineering	2	4
Ecology and Society	1	2
Environmental Research Letters	1	2
Journal of Environmental Management	1	2
Journal of Environmental Studies and Sciences	1	2
Science of the Total Environment	1	2
	16	**28**

Table 2. Some examples of models tools developed to operationalise the WEF Nexus.

Tool	Function	Scale	Citation
Integrated model including system dynamics-based model	Quantify WEF demand and generated waste, explore impact of change in user behaviour, income and seasonality, and future scenarios.	Household	Hussein et al. 2017
Simultaneous equations model	Evaluate intensities and direction of interactions between WEF related factors related to supply, consumption and waste disposal processes.	Local to regional (data from 30 Chinese provinces)	Huang et al. 2020
Integrative analytical model - Analytic Hierarchy Process (AHP)	The model provides evidence for policy and is a decision support tool that highlights priority areas for intervention.	National (South Africa)	Nhamo et al. 2020
Data Envelopment Analysis (DEA) Model and Malmquist index	Using the Chinese input output index system to evaluate the WEF input-output efficiency. Indicates regional consumption of WEF resources and facilitates decision making.	City – regional. scale (data from 30 Chinese Provinces)	Li et al. 2016
Integrated model (AWEFSM) based on multi-objective programming, nonlinear programming, and intuitionisitic fuzzy numbers	Enhance the sustainable management of WEF resource in an agricultural system. Identifies trade-offs and helps develop policies and strategies with uncertainty	Regional	Li et al. 2019
Coupled hierarchical indicator framework, synergy assessment, and synergy optimization assessment model	Quantitatively analyses WEF synergies and identify steady states of WEF systems. Provides information for decision making	City-regional scale (China)	Zhang et al. 2020
Multi-objective optimization model (coupled well established water and power system models)	Spatially explicit framework for decision support in hydropower. Objectives: minimise power deficit and maximise export, water for irrigation, reduce flooding, and environmental flows.	Nepal (Local)	Dhaubanjar et al. 2017

The Q-Nexus Model	Mathematically-based quantitative WEF nexus assessment tool / platform to quantify, simulate and optimize water, energy and food as interconnected systems of resources.	Multi	Karnib 2018
Interpretive structural modeling (ISM) method based on factor analysis	Identify different factors operating in the REF Nexus and create a hierarchy to understand relative importance.	City level - Multi	Li et al. 2019

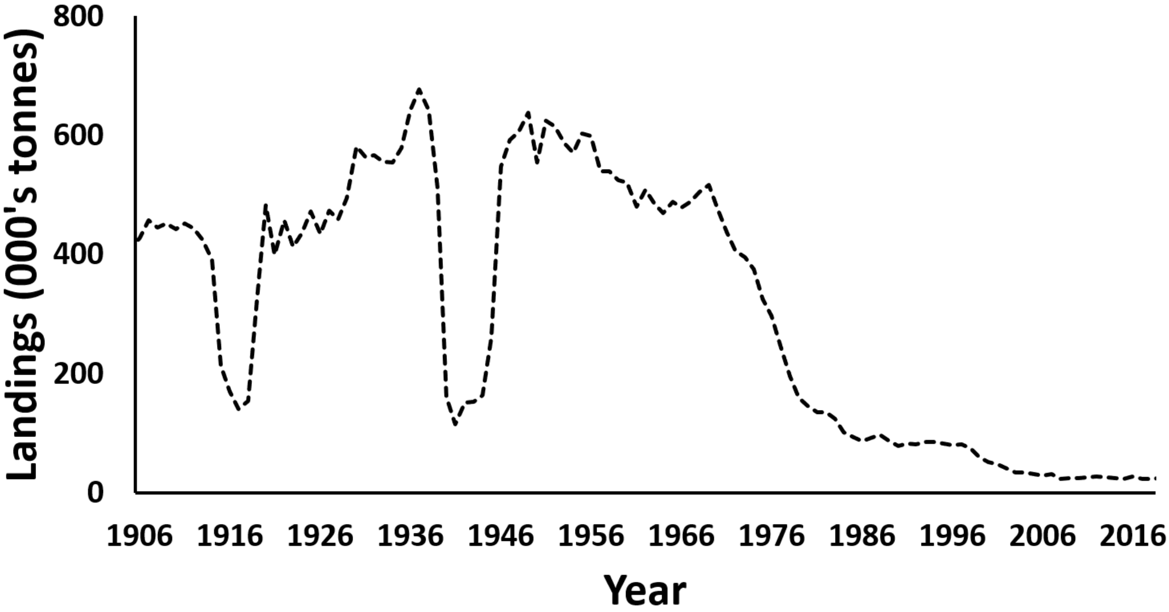

Figure 1. Total annual landings of demersal fish by the home fleet into English and Welsh ports between 1906 and 2019. Marine fisheries are socio-ecological systems and two distinct systemic shocks to the fishing industry in World Wars I and II are clearly apparent, with a rapid return to “business as usual” thereafter as fishers benefitted from greater catches due to a recovery of stock after fishing pressure was reduced. A more insidious long-term shock to the ecological system is apparent due to overfishing after World War II, as the fleet converts to diesel engines and fishing power increases drammatically during the 1960s to peak in 1972 (Thurstan et al. 2010). Today total landings are lower than they were during the two World Wars.

Figure 2. Methods of “everyday education” that range from passive assimilation of information to active search for knowledge in areas that are intrinsically interdisciplinary (in this case focusing on fisheries and infrastructure related issues). Top left: public information

plaque explaining history of Grand Coulee Dam construction in the US; top right: collectable education cards purchased with tea and introducing the public to fish identification; middle left: bill board providing a conservation message in downtown Seattle, US; middle right: visitor centre informing the public of fish passage issues in Seattle, US; bottom left: public engagement event to explain hazards associated with river infrastructure as part of “Fish Migration Day”, UK; bottom right: increasing public awareness of river fragmentation due to infrastructure through citizen science projects, Europe.