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Groundwater Protection and the Food–Water–Energy Nexus: A Conspectus

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ABSTRACT

There are critical opportunities and profound challenges at the food–water–energy nexus. Crucial to the global nexus is the role of groundwater. Groundwaters provide 99% of the world's useable freshwater supplies. Irrigation is required for much of the world's food production, as 40% of the food grown globally uses irrigation. Yet some 10% of today's irrigation water is "stolen" from tomorrow, as it relies on today's use of non-renewable groundwater. With "business-as-usual," it is predicted we will reach "peak groundwater" around 2050. We review groundwater-protection measures under two contrasting food-production systems: viticulture in temperate New Zealand, and halophyte production for food, fibre, and fuel in the hyper-arid United Arab Emirates (UAE). Some 75% of New Zealand's wine is produced in the Marlborough region, and the vines generally require irrigation using groundwater. Our *in-situ* measurements of drainage and leaching show that there is net drainage-recharge of groundwater, and that the nitrate concentrations in the leachates are less than the drinking water standard. Groundwater is being protected though a net aquifer recharge of about 100 $mm·a^{-1}$. Our work in the UAE focussed on groundwater protection under the production of the obligate halophyte *Salicornia* using irrigation with the reject brine from a desalination unit. A leaching-fraction is needed to despatch the residual salts out of the rootzone back to groundwater. Our heuristic modelling predicts a hyperbolic rise in aquifer salinity. From an initial salt concentration of 18.8 $kg·m^{-3}$ the concentration of salt would be predicted to reach about 100 $kg·m^{-3}$ in just 40 years. Solutions to extend the life of these groundwaters could involve the use of zero-liquid-discharge desalination, or the conjunctive use of alternative waters, either directly, or indirectly via managed aquifer recharge. There are opportunities and challenges at the nexus. Solutions will rely on engineering science and technology.

1. The nexus

Globally, there is a challenging nexus between our need for food security, and our ability to maintain energy supplies, whilst protecting our water resources, especially those underground in our aquifers. This challenge is heightened through a rapidly rising population, declining water resources, both in terms of quantity and quality, plus the need to maintain energy supplies. We need of course to supply these growing populations with affordable and healthy diets.

There is a range of upstream drivers that affect the dynamics of the nexus (Fig. 1). These include our natural capital stocks of waters, soils, biota and climate, as well as built-capital infrastructures and financial–capital reserves. Policy instruments, global trading patterns and pacts, plus new technologies will drive change at the nexus. From these drivers there will be downstream responses emanating from the nexus. These responses will include growth or diminution in the inventory of our natural capital stocks, such as changing groundwater reserves. There can be environmental impacts, both beneficial or deleterious, and these can affect rural

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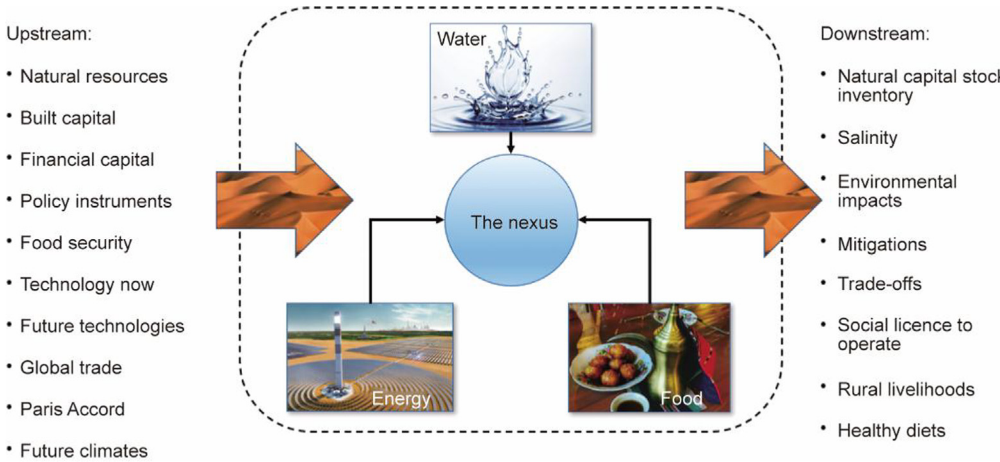

Fig. 1. The food–water–energy nexus (center) is influenced by a range of upstream drivers (left), and there are downstream responses (right).

livelihoods and the diets of all. Responses to changes at the nexus will require mitigations and assessments of options and trade-offs when making resource-use decisions. The framework of the food–water–energy nexus provides an integrated approach to considering these options, synergies, and trade-offs for decision-making in relation to resource use. The nexus highlights that a single "optimum" outcome does not exist. Rather choosing a "best" outcome depends simply on the objective function used. Is maximum food production sought? Or is minimization of water-use the prime criterion? Or is energy supply limited? The connections at the nexus enable relative assessments of the options and trade-offs when using such a range of objective functions.

Here in this conspectus, we begin by considering current knowledge of the nexus and extant gaps in our understanding of nexus functioning. We next discuss current challenges along each of the three axes of the nexus and then we review two contrasting case studies where food–water concerns are linked link to impacts in relation to irrigation practices for food production, energy considerations in relation to pumping and desalination technologies.

2. Current knowledge and extant gaps

In a recent review of the food–water–energy nexus, Mahbhaudhi et al. [1] found that 50% of studies were sectorally unbalanced and had a focus on one, or more, resource apices. They determined that water and energy were the key nexus modes in most frameworks. Rhouma et al. [2] and Mai et al. [3] provided bibliometric analyses which showed no publications before 2008. There were only one, or two, publications per year until 2015, but followed by a sudden rise in research publication, with nearly 90% of all articles being published between 2018 and 2023. Rhouma et al. [2] found that the agricultural sector was notably underdeveloped in nexus studies with few studies at the science–policy–society interface. The analysis by Mai et al. [3] focussed on the food–water–energy nexus in agriculture, and they discerned an emerging trend of policy, environment, and energy concerns in agricultural nexus research. They found that implementation of nexus knowledge was highly dependent on institutional stability and technical expertise, and they concluded that it is "... critical to develop effective context-specific solutions."

Li et al. [4] proposed that in order to develop these specific solutions it is necessary to connect the food-water-energy nexus with natural capital accounting and the delivery of ecosystem services. This they showed would help identify synergies and determine critical impacts for the sustainable and coordinated growth of regional resources and ecosystems. Both Ghosh et al. [5] and Drobinski et al. [6] showed that research across the interconnected tripartite axes of the nexus enables the fostering of synergies and the quantification of the impacts and trade-offs through governance and management actions. An area of nescience identified by Khan et al. [7] was the lack of transfer of scientific concepts into real-world applications, decision making and stakeholder practices.

Later in this conspectus we present two contrasting case studies of irrigation using groundwater for food production, and both involve differing energy considerations. We show how these highlight various trade-offs and impacts that can be both controlled by governance through regulation, and be managed by growers' practices in the field. Borgoemeo et al. [8] addressed the food imperative, and they called for a rethinking of irrigation in an increasingly water-scarce world. Roy et al. [9] developed an integrated sustainability assessment of food–water–energy nexus indicators, and they concluded there is a need to develop tailored strategies to enhance water utilization and ensure robust agricultural productivity. Our case studies highlight these imperatives in contrasting ways.

3. Contemporary challenges at the nexus

Water is the world's critical natural–capital stock. Yet 99% of the water on Earth is not immediately usable by humans, as it is either in the ocean, or locked-up in glaciers or ice caps. Of the 1% of the world's water that is usable, over 99% resides underground as groundwater. Lakes and rivers comprise just under 1% of the usable freshwater reserves [10].

Food production through the growing of crops and the raising of animals consumes water through plant evapotranspiration [11]. This plant water-use is either sustained naturally by rainfall, or it is supplemented by irrigation. Global freshwater use has increased six-fold since 1900. Now over 70% of freshwater withdrawals are for agriculture [12]. Some 17% of agricultural lands are irrigated, and thankfully these irrigated fields provide 40% of the world's food [13]. Irrigation is focused in the arid and semi-arid regions of the world, which cover 41% of the Earth's surface. These arid lands are home to 2.5 billion people and produce 44% of the world's food [14]. Yet, the World Resources Institute (WRI 2019) has predicted a 56% "food-gap" between the baseline production year of 2010 and 2050. The gap is of the order of 7000 trillion kilocalories per year.

Wada et al. [15] quantified the three proportions of irrigated food-crop water-use that derive from rainfall, sustainable groundwater extraction, plus the use of groundwater that is not renewably recharged. They found that globally some 10% of contemporary groundwater extractions to irrigate crops for today's food is non-renewable. So, in essence, we are "stealing" tomorrow's water to feed ourselves today. This axis of the food-water nexus is not sustainable. Scanlon et al. [16] reviewed data from the Gravity Recovery and Climate Experiment (GRACE) satellite and found globally varying patterns of total water-storage in aquifers. Climate variability accounts for some storage changes, but human intervention, notably irrigation, is a major driver of decline. They called for diversified water management strategies to protect groundwater resources, including 'grey' solutions using desalination and waste-water reuse. Niazi et al. [17] used an integrated model of the coupled human-earth system to simulate groundwater withdrawals across 235 water basins of 900 future scenarios of global change. They found a distinct peak-and-decline signature in groundwater withdrawals. For many catchments they predicted that peak groundwater-extraction would occur mid-century and then decline towards 2100. Niazi et al. [17] concluded that this will have important consequences for global agricultural food production and trade, with groundwater being unable to meet agricultural water-demands. Not only is the quantity of global freshwater reserves under threat, so is the quality of our water resources, notable through rises in salinity. Kaushal et al. [18] identified a rising concern they labelled the "freshwater salinization syndrome." They found that this salinization had expanded beyond arid and semi-arid zone and was now becoming more widespread even in humid regions. Salinity is predicted to affect some 50% of the world's arable soils by 2050 [14].

The third pole of the nexus is that of energy. Energy demand is projected to rise by 50% between 2006 and 2030 [19]. Currently the global agri-food system is responsible for 15% of all fossil-fuel emissions [20]. The energy sector currently uses 10% of world's water, and this is projected to rise by 60% by 2030 [21]. Given the burgeoning global demand for water, and the growing freshwater salinization syndrome, there has been a dramatic rise in the use of desalination technologies to produce freshwater from sea water, brackish rivers and lakes, and saline groundwaters (Dhakal et al. [22]). It is projected that total energy use in the Middle East for desalination will rise from today's 5% to 15% by 2040 [23]. There is an increasing use of stand-alone desalination units on farms in arid and semi-arid regions to 'freshen' saline groundwaters, so that they can be used to irrigate high-value crops. Renewable energy sources can be used to power these desalination units [24].

There is an emerging engineering technology of osmotic-power generation on this third pole, which could also connect through the nexus to both water resources and food production. Electricity can be produced by forward osmosis using a saline feedstock. Through osmosis there is an increase in pressure on the salty side of a membrane due to the influx of freshwater, and this pressure can then be used to drive a turbine generator [25]. The world's second osmotic-power generation facility has just been commissioned in Japan [26]. The brine from desalination units can also be used as the feedstock, as this increases the difference in the salt concentrations and this produces more energy. This emerging technology potentially connects all axes of the nexus.

Energy is used to treat wastewaters around the world prior to discharge, often either to land or receiving waters. Increasingly, however, treated wastewater (TW) is being used as an alternative to groundwater for irrigation, not only of amenity vegetation [27], but also for food crops [28]. Reuse of TW is currently around 15% in the Middle East, North Africa, and Europe, whereas globally it is just under 6% [29]. As well, produced-water (PW) is a waste-stream product from oil and gas extraction. Blending PW with other waters can be used to irrigate food and oil–seed crops [30] Although the cost of managing PW for irrigation can be 2.5 times higher than simply disposing of it, this practice could become competitive with the rising value of cropping in drylands. In these cases of TW and PW, energy is traded off to produce alternative waters to support food production. There are future opportunities to increase further the use of alternative water sources for food production.

4. Future imperatives

Beddington [31] wrote that there was a perfect storm of global events brewing at the nexus between food, water, energy, and climate. Given the food-gap, increased demands for water and rising requirements of energy, he pondered how can we:

(1) Feed 9 billion people healthily, equitably and sustainably using our available soil resources?
(2) Cope with future demands for water, given that it is a finite resource?
(3) Provide enough energy from multiple sources to meet the requirements of the growing population?
(4) Do all these things at the same time around the world, whilst mitigating and adapting to climate change?

These are the contemporary challenges at the global food–water–energy nexus [32]. These issues will need to be addressed using sustainable land-and-water management practices that are guided by good environmental policies and constrained by equitable resource regulations that are underpinning by scientific evidence. Moreover, overcoming these exigencies will require implementation of innovative engineering solutions.

5. Conspectus objectives

In this review of groundwater protection and food–water–energy nexus, we have three objectives:

(1) To identify how measurements and quantification of the soil–water balance in the rootzone of food crops can be used to provide metrics of the sustainability of irrigation water-use to protect of groundwater quantity and quality;
(2) To demonstrate through heuristic modelling the challenges posed to groundwater quantity and quality through the use of saline waters, including the reject brine from desalination units, for irrigation of halophytic crops that can be used for food, forage and biofuel production;
(3) To detail engineering opportunities to protect groundwater and to overcome water-quantity and water-quality challenges at the food–water–energy nexus, especially in arid regions.
(4) For the first objective, we use results from our 5 year study of water-use by grapevines in the Mediterranean climate of Marlborough, New Zealand. For the second two objectives, we use results obtained over 5 years of study on the irrigation with saline waters of the obligate halophyte in the United Arab Emirates. Both studies used passive-tension drainage fluxmeters (DFM) to measure groundwater recharge by drainage from the rootzone through the vadose zone to the water table, and to monitor leachate loadings on the underlying aquifer.

6. Measuring groundwater recharge and leachate loadings on aquifers

It is a challenge to make direct measurements of recharge of groundwater by drainage through the vadose zone, and to quantify the leachate loadings on aquifers. Lysimeters, both weighing and non-weighing, can be used to measure directly drainage and leaching [33]. However, they are expensive and cannot easily be replicated. Passive-tension drainage fluxmeters (DFM) can inexpensively mimic the unsaturated capillary conditions in soil, and they enable direct measurements of drainage and leaching [34]. Although DFMs provide only point-based measurements, their low-cost and simplicity means that replication is easily possible in order to provide a really averaged results and indicators of spatial variation. These DFMs therefore provide a trade-off between the complexity and cost of lysimeters, with the ease of use, replication, and the simple mimicking of the capillary conditions that control drainage and leaching [35].

The type of DFM we have used in our work here is represented in Fig. 2. The DFM assembly is lowered into a pre-formed hole so that the top of the convergence ring is at the required depth in, or just below, the rootzone. The soil is carefully repacked back into the hole above the DFM so that it is buried with as little disturbance as possible. A fibreglass capillary-wick of length 600 mm draws water by unsaturated flow from the soil in the convergence ring, and then the free-water drainage from its distal end fills the reservoir underneath. After rainfall, or irrigation events, a pump is used to extract water from the reservoir. The volume of drainage can be recorded, and the water samples analyzed for solute concentrations to compute the leaching loads.

We next describe the use of these DFMs to quantify groundwater recharge and leaching loads under irrigated vineyards in New Zealand, and the cropping of a halophyte irrigated with saline waters in the hyper-arid desert of the United Arab Emirates. These studies show how groundwater protection measures can be developed at the food–water–energy nexus.

7. Groundwater protection under vineyards in a Mediterranean climate

The alluvial soils and Mediterranean climate of New Zealand's Marlborough region provide a valuable terroir for growing *Sauvignon blanc* grapes. Invariably, the vines are irrigated, predominantly using groundwater. Wine exports from New Zealand are worth 2.1 billion NZD, and 82% of New Zealand wine exported comes from Marlborough. Over 98% of New Zealand vineyards are registered to sustainable winegrowing New Zealand, an eco-credentialled sustainability programme. The Wairau aquifer which underlies Marlborough vineyard's is "... arguably the region's most valuable natural resource" [36]. The environment plan of the local regulatory agency, the Marlborough District Council, seeks to ensure that "... the management applied to the taking and use of water is appropriate to the hydrological and environmental circumstances" [37]. Groundwater protection is therefore critical, not only for the eco-credentialling of Marlborough's *Sauvignon blanc* wine, but also to sustain the natural capital stocks of the region.

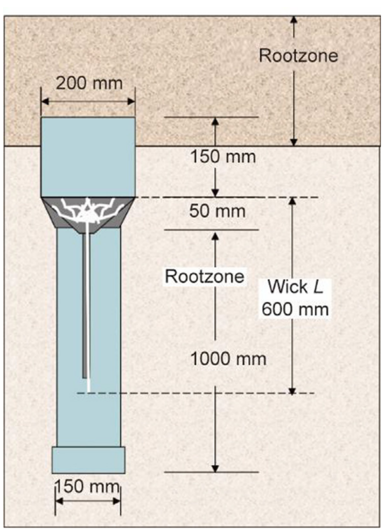

Fig. 2. Passive-wick tension DFM are devices that can be used to measure *in situ* the unsaturated drainage of water through rootzone soil into the vadose zone below and towards groundwater. As well, water samples can be recovered from the reservoir in the DFM for solute analyses to infer the leachate loads. A 200 mm diameter convergence-ring atop the DFM constrains the flow vertically into the device, and a capillary wick of length *L* establishes a passive tension to mimic the unsaturated capillary conditions in the soil of the rootzone.

We carried out a 5 year programme of research which sought, *inter alia*, to determine whether the taking of groundwater from the Wairau aquifer for irrigation was "appropriate for the hydrological settings" of the vineyards.

As part of this programme, we installed drainage fluxmeters in two vineyards close to each other in the Fairhall region of Marlborough. They were coded 21-SBC and 23-SBF. In early November 2015, 12 DFMs were installed in each vineyard, with an array of three DFMs at four locations within the vineyard. For each array, two DFMs were in the row of the vines and one in the inter-row. Following rainfall events, the DFMs were pumped dry and the volume of drainage recorded, and the nitrate-N concentration in the drainage water measured. The cumulative drainage values and nitrate-N loading losses are presented for the years 2015–2019 in Fig. 3.

There was variation in the annual totals between years, but there is a general degree of similarity in the annual values between the two vineyards, as they were located near to each other. The annual values for drainage and nitrate-N losses, along with grape yields and irrigation totals are presented in Table 1.

The annual rainfall totals between July and June recorded at the nearby airport of Woodbourne were 320, 555, 645, and 495 mm respectively for the years 2016, 2017, 2018, and 2019. Grape yields ranged between 16 and 26 $t{\cdot}ha^{-1}$ for vineyard 21-SBC, and 10–17 $t{\cdot}ha^{-1}$ for 23-SBF. Irrigation varied between years and sites. For vineyard 21-SBC there was a relationship between irrigation and yield, but not for 23-SBF. The response to irrigation for 21-SBC of 44 $kg{\cdot}ha^{-1}{\cdot}mm^{-1}$ was due to better water management within and between years. The average total water applied annually by 21-SBC was 97 mm, but only 63 mm for SBC, and the irrigation tactics adopted by 21-SBC were better tailored to the ephemeral periods of drought. This disparity shows that the value from irrigation only accrues if the scheduling is well managed. Drainage for both vineyards was predominantly in winter and spring, with annual totals between about 100 and 240 mm, being about one third of rainfall. Net groundwater recharge, the difference between drainage minus irrigation abstraction, varied from −40 $mm{\cdot}a^{-1}$, through to nearly 200 $mm{\cdot}a^{-1}$. Not surprisingly, the lowest recharge values were in the driest years of 2016 and 2019. On grand average across both sites and four years, there was 105 $mm{\cdot}a^{-1}$ of groundwater recharge, being about 20% of the average rainfall. Groundwater quantity is therefore being protected through viticultural practices here.

Cumulative nitrate losses were low, being less than 8 kilogram NO_3-N per hectare per year (kg NO_3-$N{\cdot}ha^{-1}{\cdot}a^{-1}$; 1 ha = 10 000 m^2). Furthermore, leachate NO_3 concentrations in the drainage despatched to groundwater were invariably lower than the New Zealand drinking water standard. This is important, as in Marlborough the Wairau aquifer is the primary source of potable water. Indeed, across New Zealand groundwater is the source for 40% of the country's potable water.

These data are useful in terms of validating metrics used to eco-credential the water footprint of food production, and here our focus is on the groundwater footprint. The amount of water transpired by the vines, the so-called green-water, is large. Both Herath

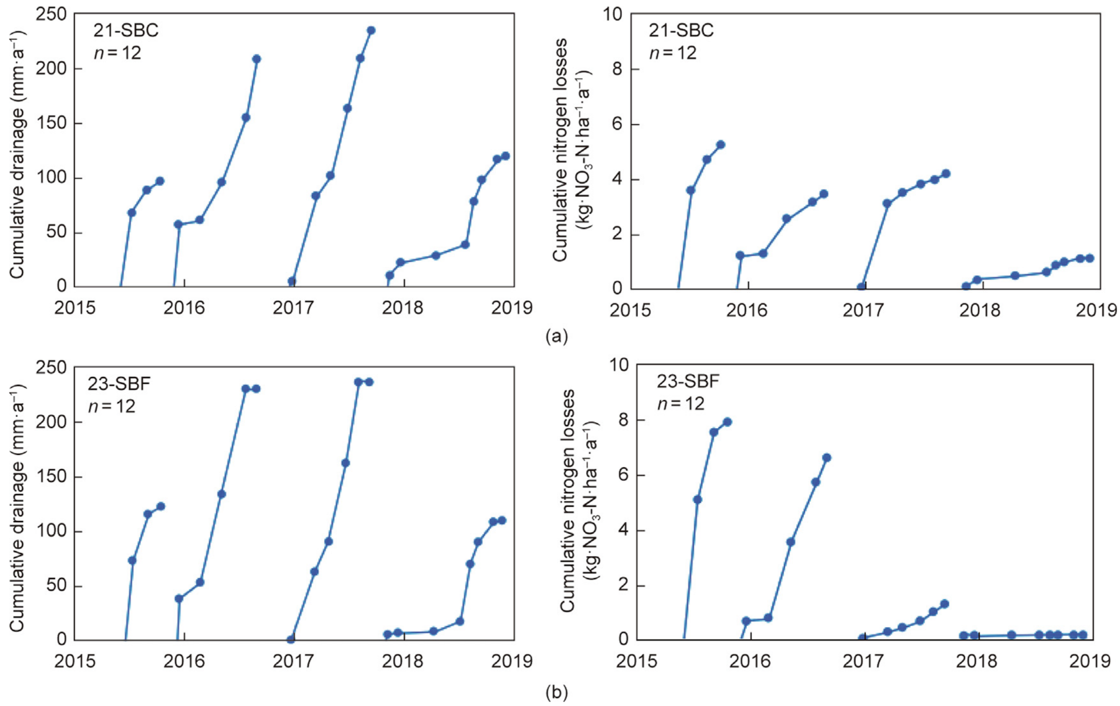

Fig. 3. Cumulative drainage and cumulative leaching of nitrate-N measured by DFM over the four years 2015–2019 for two *Sauvignon blanc* vineyards in the Fairhall sub-region of Marlborough, New Zealand. Both vineyards were on loamy soils and located less than 10 km apart. (a) Vineyard 21-SBC and (b) vineyard 23-SBF for cumulative drainage ($mm{\cdot}a^{-1}$) and cumulative nitrate-N loss ($kg\ NO_3\text{-}N{\cdot}ha^{-1}{\cdot}a^{-1}$), respectively. There was an array of 12 DFMs within each vineyard arranged across 4 locations, each comprising 3 DFMs, with 2 along the vine-row, and 1 in the inter-row.

Table 1
The grape yield, vineyard water-balance measurements and N-leaching loads over 4 years from two *Sauvignon blanc* vineyards in Marlborough, New Zealand. The difference between irrigation and drainage was used to calculate the annual net recharge to groundwater.

Vineyard	Year	Grape yield ($t{\cdot}ha^{-1}$)	Irrigation ($mm{\cdot}a^{-1}$)	Drainage ($mm{\cdot}a^{-1}$)	Net groundwater recharge ($mm{\cdot}a^{-1}$)	Cumulative N leaching ($kg\ NO_3\text{-}N{\cdot}ha^{-1}{\cdot}a^{-1}$)
21-SBC	2016	26.3	136	96	-40	4.7
	2017	19.2	61	208	147	3.4
	2018	16.5	47	234	187	6.4
	2019	20.9	100	119	19	3.4
23-SBF	2016	16.7	19	124	105	7.7
	2017	10.3	83	232	149	6.4
	2018	12.8	42	238	196	1.2
	2019	11.3	34	111	77	0.1

et al. [38] and Bonamente et al. [39] found that the green-water footprint of wine was of the order of 600 L per 750 mL bottle. However, the amount of water transpired by the vines says very little about the hydrological impact of irrigation in vineyards, and it says absolutely nothing about the hydrologically critical role of groundwater recharge. Here we find that the use of irrigation, or the so-called blue-water, is on average about 40 L per bottle, assuming that 1 kg of grapes is used to produce one 750 mL bottle of wine [38]. The hydrologically important environmental metric is, however, the amount of groundwater recharge per bottle of wine. For vineyard 21-SBC, there was 46 L of aquifer recharge per bottle, and a contribution of 107 L to groundwater per bottle for vineyard 23-SBF.

Direct measurements using passive-tension DFM show that groundwater is not being over-exploited, either in terms of quantity or quality, through the use of irrigation to produce grapes for wine in Marlborough. These measurements and analyses highlight the sustainable connections along the food–water axis of the nexus for this viticultural land-use in this region. Nonetheless, it is acknowledged that the dominant supply of water to the Wairau aquifer is through unconfined exfiltration from the Wairau River which flows along the northern periphery of the aquifer. A total mass-balance of all inflows and total extractions would reveal the degree to which the aquifer's total water use is sustainable.

8. Groundwater challenges irrigating halophytic crops with saline waters

In the hyper-arid United Arab Emirates, the government has aspirational policy goals on all three axes of the nexus. Sheikh Mohamed Al Nayan, the ruler of the UAE, declared 2023 as the "Year of Sustainability" under the theme of "Today for Tomorrow." In its National Food Security Strategy 2051 (The Official Portal of the UAE Government) the UAE seeks to be the top country in the Global Food Security Index by 2051. It was number 9 in 2021. Meanwhile, the Government's Water Security Strategy 2036 seeks to reduce water supply to agriculture from 8.2 to 7.1 million cubic meters per day ($Mm^3{\cdot}d^{-1}$). The UAE currently has the lowest energy-grid emission factor in the Middle East and Asia, of 0.56 kg $CO_2eq{\cdot}(kW{\cdot}h)^{-1}$, and it seeks to halve that by 2030 through trebling the capacity of renewable-energy production. By 2050, the UAE seeks to achieve net carbon-zero in both the energy and water sectors (UAE Energy Strategy 2050; The Official Portal of the UAE Government).

Here we review our recent work at the food–water–energy nexus in the UAE and consider future options that seek to protect better groundwater quantity and quality. Irrigation of agricultural plants and amenity vegetation consumes about 80% of the UAE's groundwater use.

Al Yamani et al. [26] highlighted the value of using energy to treat wastewater so that it could be used to irrigate amenity plantings and arid forests and thereby obviate the need to use groundwater for irrigation.

Al Muaini et al. [40] revealed the impact of groundwater salinity on the production of dates. Irrigation of dates accounts for about 30% of groundwater usage. Al Muaini et al. [40] calculated a benefit-cost ratio of 1.4 through the operation of a desalination unit to "freshen-up" groundwater from 15 to 5 $dS{\cdot}m^{-1}$ for the irrigation of high-value dates. Not surprisingly, there are now over 2000 stand-alone desalination units, many solar powered, on Emirati farms [24,41]. Lyra et al. [42,43] described an integrated aqua-agriculture system (IAAS) that uses the reject brine from these desalination units for land-based aquaculture of Tilapia fish (*Oreochromis niloticus*), and then subsequent use of the effluent from the fish-tanks to irrigate the halophytic food–forage–biofuel crop *Salicornia*. *Salicornia* is also known as glasswort, marsh samphire, sea asparagus, or sea bean (Fig. 4 [42,43]).

The experimental set-up of Al Tamimi et al. [44] near Dubai comprised nine plots each 8 m by 8 m. Three types of saline water were used for irrigation of the *Salicornia*: aquabrine from the fish tanks, and reject brine from a desalination unit, both at about 40 $dS{\cdot}m^{-1}$, plus saline groundwater at about 25 $dS{\cdot}m^{-1}$. Three types of irrigation emitters were used: pressure-compensated drip emitters, bubblers and subsurface irrigation. Each of the nine plots was divided in four 2 m × 2 m quadrants with a DFM located in each quadrant, such that there were 36 DFMs in total, with four per treatment. Full details are given in Al Tamimi et al. [44,45]. For simplicity in this review to highlight the key findings, we will simply use the global means from across all nine plots. Irrigation (I, $mm{\cdot}d^{-1}$) was applied, more or less consistently, every day throughout the growing season of 2023, at an average rate of about 13 $mm{\cdot}d^{-1}$ to ensure a sufficient salt-leaching fraction (LF).

The seasonal pattern in the crop water-use (ET_c) by the *Salicornia* in 2023 was modelled using an FAO-56 crop-factor approach [46], and the predicted pattern in ET_c ($mm{\cdot}d^{-1}$) is shown in Fig. 5 [45,47]. Drainage (D) through the rootzone can simply be predicted as $D = I - ET_c$. The drainage water will carry with it the excess salts left after the *Salicornia* osmotically extracts freshwater to maintain the crop's ET_c. Ayers and Westcott [47] defined the leaching fraction (LF) as:

$$\mathrm{LF} = \frac{\text{Depth of water drained below the rootzone}, D = (I - \mathrm{ET_c})}{\text{Depth of water applied as irrigation}, I}.$$

Ayers and Westcott [47] showed that by using simple, mass-balance calculations they could predict the ratio of the salt concentration in the effluent leachate (C_{out}, $dS{\cdot}m^{-1}$) relative to that in the influent irrigation water (C_{in}, $dS{\cdot}m^{-1}$) as:

$$\frac{C_{out}}{C_{in}} = \mathrm{LF}^{-1} = \frac{I}{(I - \mathrm{ET_c})}.$$

The predicted relative salt-concentration in the leachate over the 2023 season under the *Salicornia* is shown in Fig. 5. The irrigation was essentially constant over the season, thus as the crop grew and the ET_c increases and consumes more of the irrigation water, the predicted $\frac{C_{out}}{C_{in}}$ of the residual salts in the leachate is simply expected to rise up to nearly fourfold, before declining as the *Salicornia* senesces and eventually dies.

From our measurements, the seasonal track in the global average of the monitored $\frac{C_{out}}{C_{in}}$ from the 36 DFMs is shown in Fig. 6 [45]. The coefficient of variation (n = 36) was 11%. Freshened water at 10 $dS{\cdot}m^{-1}$ was used to ensure germination of the *Salicornia* seeds. Irrigation with the saline waters began on 23 February 2023. The depth of soil above the DFM is about 500 mm, including the convergence ring, and with a volumetric water content of 0.4, one pore-volume would be 200 mm of water. With saline irrigation at 13 $mm{\cdot}d^{-1}$ this would take about 16 days to flush through the one pore-volume of the low salinity water initially resident in the soil above the DFM. It can be seen in Fig. 6 that the relative concentration took until about mid-March for the effluent concentration to reach that of the influent concentration. Thereafter the measured relative concentration rose as increasing crop water-use concentrated that salt in the rootzone that became leached out by the subsequent irrigation. The seasonal trend and the peak in the measured $\frac{C_{out}}{C_{in}}$ (Fig. 6) are similar in seasonal trend and shape to those predicted simply from mass-balance considerations (Fig. 5).

Here we have both predicted and measured the rising concentration of salts in the leachates under a halophyte crop irrigated with saline waters. In an analogous closed water-basin context, albeit at a catchment-scale, Pauloo et al. [48] termed this process of increasing salinization "evapo-concentration," since the salt always remains whilst water is continuously lost from the system by evapotranspiration from the vegetation.

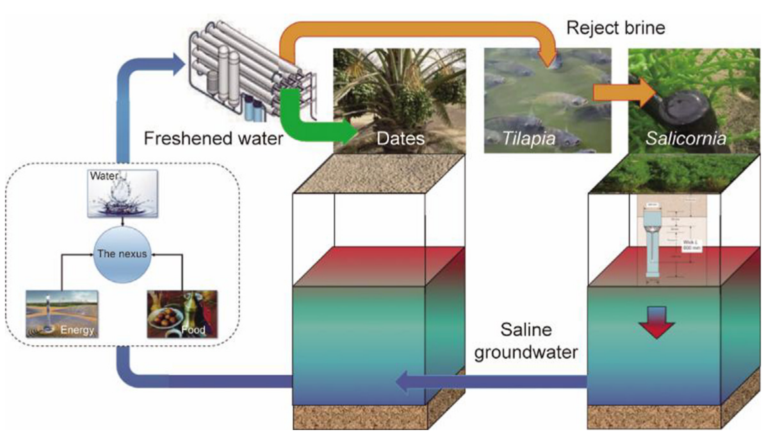

Fig. 4. A food–water–energy nexus representation of the Integrated Agri-Aquaculture System (IAAS) developed by Lyra et al. [42,43] where desalinated saline groundwater is used to grow high-value crops such as dates, with the reject brine from the desalination unit then used for land-based aquaculture, and the effluent from the fish-tanks subsequently used to irrigate a halophyte such as *Salicornia*. Passive-tension drainage fluxmeters (DFM, Fig. 2) were used to measure groundwater recharge and salt leaching under the *Salicornia* crop (right).

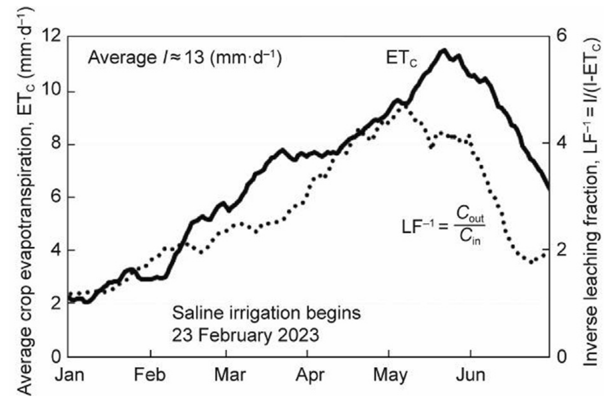

Fig. 5. Average modelled crop–water use (ET_c mm·d^{-1}, solid line) by the halophyte *Salicornia* adapted from Al Tamimi et al. [45], along with the measured average rate of daily irrigation applied (I, mm·d^{-1}). The averages relate to the global means across all nine treatment plots from Ref. [45]. The inverse leaching fraction, LF^{-1}, of the daily depth of irrigation applied, I, divided by the daily depth of water leached, $I - ET_c$, is given as the dotted line. Ayers and Westcott [47] used mass-balance arithmetic to show that LF^{-1} would be the ratio of the salt concentration leaching to groundwater (C_{out}, kg·m^{-3}) to that applied in the irrigation water C_{in}.

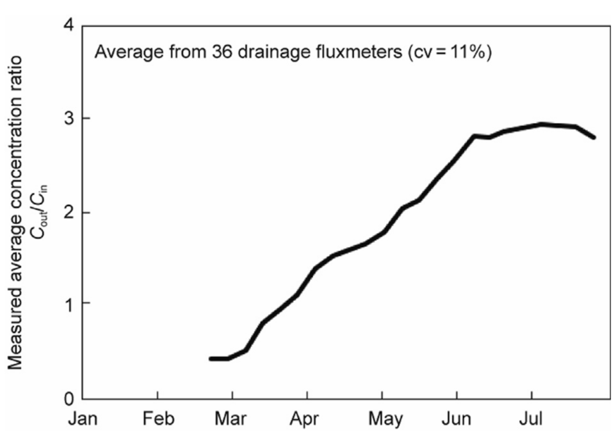

Fig. 6. The ratio of the measured electrical-conductivity in the drainage water (C_{out}, kg·m^{-3}) measured by 36 DFM across the 9 plots of Al Tamimi et al. [45] to the electrical conductivity in the irrigation water (C_{in}, kg·m^{-3}) applied to the crop of *Salicornia* in 2023. The average coefficient of variation in the measured ratio was 11%. Saline irrigation began on 23 February 2023. The one pore-volume of "fresh water" residing in the 500 mm above the DFM would be predicted to be flushed through by 11 March 2023. cv: coefficient of variation.

This rise in the concentration of salts in the leachate under a halophytic crop irrigated with saline groundwater potentially poses a threat to groundwater. To assess this, Al Tamimi et al. [45] developed a heuristic model to predict the impacts and trade-offs. Their mass-balance model for an endorheic basin predicts a linear decline in groundwater quantity with irrigation use, as in this desert-setting the recharge rates are very slow compared to the rates of groundwater extraction for irrigation [49,50]. Al Tamimi et al. [45] found that in this hyper-arid context the rise in salinity in the underlying groundwater would be analytically in the form of a hyperbola and driven primarily by the rate at which the crop transpires water (ET_c). In this closed-basin hydrological loop, drainage water ($I - ET_c$) is returned to the groundwater, albeit with a higher concentration of salts than that in the water taken up for irrigation.

We now apply the heuristic model of Al Tamimi et al. [45] to simulate the groundwater futures that might apply to agricultural region around Remah, near Al Ain. Here about half the total land area (T) is irrigated (A), and the initial depth of the groundwater can be taken to be about 120 m. Crop transpiration is taken to be 1.6 m·a^{-1} from the FAO-56 modelling of ET_c by Al Tamimi et al. [46], and so with $\frac{A}{T} = \frac{1}{2}$, the predicted decline in the groundwater level is shown in Fig. 7 to be about 2 m·a^{-1}. This is of a similar order to the 50 m drop recorded by EAD [50] between 1998 and 2017. The predicted rise in salinity is shown in Fig. 7. After a slow increase, the salinity rises rapidly as the residual salts are concentrated in the declining volume of groundwater. The prediction here is that the salt concentration rises from about 20 kg·m^{-3} to about 50 kg·m^{-3} after the first 30 years. It was reported by Ministry of Environment and Water (MOEW) (2014) [49] that near Remah the salinity rose by about 10 kg·m^{-3} between 1969 and 2009. This heuristic model could be adapted to include dilution by any natural rate of recharge.

Our measurements and heuristic modelling highlight imperatives for groundwater protection when using saline groundwaters for irrigation. There are challenges at the food–water–energy nexus here. Solutions through innovative engineering processes are needed not only here, but also in other arid and semi-arid regions around the world.

9. Engineering opportunities to protect groundwater under food-production systems in arid regions

The rise in stand-alone desalination units in the United Arab Emirates is supported through the use of renewable energy supplies by wind or solar power-generation. A new mode of renewable power generation using osmotic energy production is emerging [25]. Osmotic power-plants use the difference in salt concentration between saline and fresh water to drive a turbine resulting from the increased pressure as forward osmosis increases the quantity of water on the saline side of the membrane due to the influx of fresh water. There are already two osmotic power plants in operation, one in Norway and the other in Japan. Using the reject brine from a desalination unit as a feedstock will increase the difference in salt concentration, thereby increasing the energy available for power generation. This process could tighten the links at the nexus between using desalination units to generate freshened water for food production and the requirement for power to desalinate saline waters. Although this would entail some re-use of the reject brine, there would remain quantities of reject brine still requiring disposal.

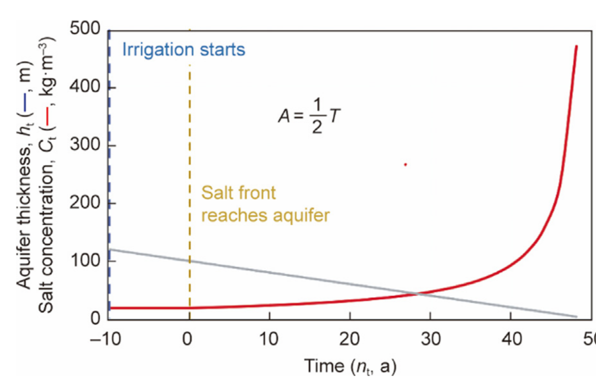

Fig. 7. Predictions of the temporal decline (n_t, a) in groundwater thickness (h_t, m) and the time-rise in groundwater salt-concentration (C_t, kg·m^{-3}, dotted line) using the heuristic model of Al Tamimi et al. [45]. Crop water-use ET_c is taken to be 1.6 m·a^{-1}. The irrigated area A above the total areal extent of the aquifer T is taken to be $\frac{1}{2}$. The initial groundwater depth is taken to be 120 m, and it takes 10 years of saline irrigation for the salt front to reach the groundwater table, by which time the thickness of the aquifer is 100 m. The initial salt concentration of the groundwater is taken to be 18.8 kg·m^{-3}, or about 30 dS·m^{-1}.

The imperative is to avoid the application of reject brines onto land, where the salt can eventually find its way down to groundwater.

An emerging technology that eliminates the production of reject brine involves using more energy to drive desalination further such that there is Zero Liquid Discharge (ZLD) [51]. This ZLD obviates the need either for land-based discharge, or even the growing of halophytic crops with reject brines. The ZLD process uses a trade-off with greater energy use to produce more freshwater such that the brine is taken right through to salt crystallization. Groundwater is protected through the increased use of energy in the desalination process.

To avoid using saline groundwater alternative water sources could be used. These would provide new opportunities at the food-water-energy nexus, although technical and social challenges remain. Produced water (PW) from industrial and mining activities can be treated so that it can be used alone, or blended with fresh water, for irrigation of food crops [30]. Tertiary TW can safely be used to irrigate amenity plantings and food crops, although assurances of quality will be needed to overcome societal concerns about waste-stream re-use for edible crops [29].

10. Prospects

Given the declining quantity and quality of global groundwater reserves, there are many exigencies at the food-water-energy nexus that are in need of practical solutions, either through apt regulations or by sustainable management options. Mai et al. [3] have commented on the emergence of governance and management challenges at the food–water–energy nexus, and they called for the development of context-specific solutions. There are emerging engineering science and technology innovations that will enable solutions to local problems found at the nexus. If we can develop better ways to protect our critical reserves of groundwater from the over-consumption and degradation resulting from activities at the nexus, it has been shown that slow recovery in aquifer reserves is possible [52]. Jasechko [53] outlined 16 interventions of three types that would facilitate groundwater recovery either through policy and market actions, or alternative water-supply considerations, plus artificial-recharge initiatives.

In this conspectus we have highlighted two contrasting case studies of the manifold challenges at the nexus. We have identified that distinct options are available. In temperate New Zealand, better hydrological measurements have been shown to quantify the sustainability of groundwater usage for irrigating grapes, which are of high value, and yet parsimonious users of water. In the hyper-arid United Arab Emirates, the spectre of salt at the nexus requires addressing trade-offs between food security, energy usage, and groundwater degradation.

Engineering science and technology offers innovative options and trade-offs at the nexus to ensure that local solutions can be found for the governance and management of food-production systems, groundwater resources, and energy supplies.

CRediT authorship contribution statement

Brent Clothier: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Steve Green:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Victoria Raw:** Writing – review & editing, Project administration, Methodology, Investigation, Conceptualization. **Roberta Gentile:** Writing – review & editing, Project administration, Methodology, Investigation, Conceptualization. **Mansoor Al-Tamimi:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Wasel Abou Dahr:** Writing – review & editing, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ahmed Al-Muaini:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Lesley Kennedy:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Khalil Ammar:** Writing – review & editing, Resources, Methodology, Conceptualization. **Dionysia Lyra:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Mohamed Dawoud:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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