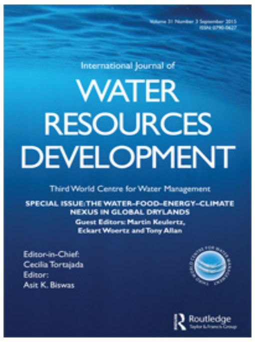

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Rapid assessment of the water–energy–food–climate nexus in six selected basins of North Africa and West Asia undergoing transitions and scarcity threats

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Existing strategies for management of water scarcity in the Middle East and North Africa negotiate a complex system of trade-offs between water, energy, and food production. The effects of rural households' green water management practices on basin-level water, energy, food and carbon stocks and flows are sketched qualitatively in six basin agro-ecosystems. The case for increased strategic support for green agricultural water management practices appears stronger when weighed from the nexus perspective, rather than purely from the point of view of water balance and food production. Trade-offs under critical transitions affecting agricultural water use are explored, and the scope for quantitative monitoring is discussed.

Keywords: water-energy-food-climate nexus; North Africa; West Asia; scarcity; water balance; ecosystem accounting

Introduction

The water–energy–food–climate nexus approach highlights the synergies in human life-support systems between these essential types of ecosystem stocks and flows (Hoff, 2011). In the drylands, a growing population will need to be nourished while balancing competing demands for all sectors of the economy with less dependable water availability in future (Falkenmark & Molden, 2008; IPCC, 2014). Energy use for pumping and treating water can boost water supplies, but increasing emissions further exacerbates climate change and threatens resource-dependent populations (WWDR, 2014). The nexus approach invites water managers to reconsider the inevitability of a bloated blue water and emissions footprint for agriculture by maximizing green agricultural water uses (Herren, 2011; IAASTD, 2009; Keys, Barron, & Lannerstad, 2012) and re-evaluating the integration of water, geochemical and energy cycles in agriculture together with the other sectors (UN, 2014; WEF, 2014).

Implementing the nexus approach requires integrated scientific re-assessment of resource-use efficiencies in relation to the interlinked water, energy and food agendas to better inform national economic development strategies and more sustainable business models (WEF, 2014). Environmental and social impact assessment of existing strategies offers a key tool for retrospective identification and weighing of observed trade-offs. *Ex ante* impact assessment using scenarios and cost–benefit assessment of options enables

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the exploration of improved strategies for the future to secure win-win trade-offs maximizing benefits across all sectors. Policy design, implementation and monitoring are social learning processes that require a strong experimental design, inclusive stakeholder participation and adaptive management (Gallopín, 2006). Marginalized and low-income populations are critical stakeholders in policy making at the water–energy–food–climate nexus in the drylands due to their resource dependence, knowledge and stewardship practices (Safriel et al., 2005).

A solid consensus on shared objectives and measures of collective progress towards them is critical to unite and motivate all stakeholders in the policy process, including resource-dependent populations. This article explores the application of the water–energy–food–climate nexus frame (Hoff, 2011) as a means to weigh the trade-offs associated with selected green water management practices in six water basin systems across North Africa and West Asia (see Figure A1 in the online supplemental data at http://dx.doi.org/10.1080/07900627.2015.1026436). A three-dimensional hydro-agro-ecological assessment of current effects of rural households' green water management practices on the basin-level water–energy–food balance is presented. Discussion of anticipated future evolution of these balances under ongoing climatic changes introduces a fourth dimension to the assessment. The approach is used to locate and qualitatively weigh the trade-offs between agro-ecosystem inputs and products under different land management practices in search of scope for strategic intervention to increase cross-sectorial efficiencies.

The objectives of the article are:

1. to broaden decision frames from available basin-level water-balance analyses of 'blue water' versus the efficient 'green' use of soil moisture to consider stocks and flows of geochemicals and energy
2. to uncover and characterize the synergistic balances of energy and nutrients inherent in the available water-balance scenarios with and without green water management practices from localized action research findings and available decision-support tools applied in six water-scarce basins
3. to make recommendations for adaptive management strategies to monitor, adapt and maximize synergies using measurements to assign values to the units of water, energy and food stocks and flows.

Assessing the benefits of green agricultural water management practices in agro-ecosystems

Blue water flow is the total runoff, including the sum of surface runoff (produced from the partitioning of rainfall at the land surface) and groundwater recharge (produced from the partitioning of soil water in the soil profile) (Rockström, 1999). Green water is the return flow of water to the atmosphere as evapotranspiration, which includes a productive part as transpiration and a non-productive part as direct evaporation from the soil, lakes, and ponded areas, and from water intercepted by canopy surfaces. Farmers' green water management practices focus on ensuring that there is sufficient water within the soil profile to support crop productivity, adding irrigation where needed to supplement soil water (IAASTD, 2009).

Although resource users' primary objective in green water management is usually the maximization of crop productivity and income, it has been observed that other ecosystem benefits may also result from conserving evapotranspiration, net primary production and resilience in dryland ecosystems (Rockström & Gordon, 2001; Rockström et al., 2010).

Assessments of ecosystem services or multifunctional benefits associated with 'green' or 'sustainable' agriculture have gained increasing attention (IAASTD, 2009; Pretty, 2003; Pretty et al., 2006). In addition to maximizing the availability of rainwater for use, 'green' agriculture usually has low demands for energy and other inputs, and can encourage carbon sequestration (Hoff, 2011). It can also enhance (blue) groundwater recharge (Keys et al., 2012).

The identification of trade-offs within ecosystems requires understanding of the system function, processes and qualities of the stocks and flows of resources that move within them (Ash et al., 2010; Watson & Zakri, 2005). The water–food–energy–climate nexus targets three essential types of resource flows and assets: hydrological, geochemical and energy. At the policy level, through national strategies for water, agriculture and energy, these are usually considered on a sectorial basis, whereas national climate adaptation and mitigation strategies take a cross-sectorial view. Although national strategies do not correspond to the scale of basin systems (which are often either sub-national or international), they are sometimes able to incorporate the findings of basin-level studies (Falkenmark & Molden, 2008), where these are available to decision makers.

Methodology

Six basins were selected for discussion as case studies in this article (Table 1). This selection targets research and pilot-testing sites in rainfed and irrigated agro-ecosystems integrating livestock production and household water supplies maintained by National Agricultural Research and Extension System staff members taking part in the Water and Livelihoods Initiative of the International Center for Agricultural Research in the Dry Areas (ICARDA) (WLI, 2014).

Based on information available as of the end of 2013, a rapid review of rural communities' household budgeting of the selected green water productivity-enhancing practices was made to identify what is known or can be inferred about effects on water availability and consumption, energy and geochemical processes, and food production.

Table 1. Selected basins in the Middle East and North Africa (partially based on UNDP, 2013).

Agro-ecosystem	Basin	Countries	Basin size (1000 km^2)
Rainfed with supplemental irrigation from groundwater	Abyan	Yemen	0.536
Rangeland in urbanizing water basin under population pressure and water scarcity	Zeuss Koutine	Tunisia	1.305
Rangeland in urbanizing water basin under population pressure and water scarcity	Jordan River	Lebanon, Syria, Israel, Jordan, Palestine	19.839
Rainfed with supplemental irrigation from groundwater	Orontes	Lebanon, Syria, Turkey	37.900
Irrigated from large river system under increasing water scarcity	Tigris-Euphrates	Iraq, Syria, Turkey, Jordan, Saudi Arabia, Iran	793.314 (combined)
Irrigated from large river system under increasing water scarcity	Nile	11 countries	3173

This review included consideration of previously published research on the water–energy–food–climate nexus in each of the selected basins.

The benefits of resource consumption under different management practices were weighed qualitatively as positive and negative factors. This was based on the use of a simplified resource-accounting approach (UN, 2014) to either quantitatively or qualitatively characterize the opening balance, inflows, storage, products, and outflows of water, energy and geochemicals associated with each land management alternative, based on the information available. Geochemical inputs produce two closing balances: food, and by-products that include waste and pollution hazards.

For presentation and discussion of the case-study results, the available mix of quantitative and qualitative information on water, energy and geochemical stocks and flows in the selected basins is tabulated in a binary representation. This approach is similar to those used in the future scenarios of the millennium ecosystem assessment (Carpenter, Pingali, Bennett, & Zurek, 2005) and popular assessments of sustainable land management strategies (WOCAT, 2013). This presentation provides a simple indication of the direction of change in each closing balance of each natural capital stock as either positive or negative.

Rapid nexus assessment of agricultural water management practices in six catchments in transition

Transitions from rainfed to groundwater-irrigated agro-ecosystems: horticultural production in the Abyan Delta and the Orontes Basin

In the Abyan Delta and the Orontes Basin, as in much of the region, a transition has taken place from reliance on periodic rainfall events to use of groundwater for irrigation. This reduces present climate-driven uncertainty, but increases energy use, emissions and future water scarcity by lowering the water table. Increased certainty enables higher input agriculture, including horticultural production. This requires and rewards the increased use of agrochemicals, which can affect the environment. Export horticulture also requires long-distance transportation and other water- and energy-intensive processing.

The Abyan Delta basin (Figure A2 in the supplemental online data) covers 53,000 ha. It receives less than 100 mm average annual rainfall in the lower reaches but often considerably more in the upper reaches. Irrigation is traditionally achieved through a system whereby seasonal floodwater travelling through usually dry ephemeral river systems (known as *wadis*) is conveyed to irrigable fields. This is known as spate irrigation because the floodwater flow pattern is characterized by discrete events, which last for only a few hours. These create water discharges and recession flows, usually lasting only one to a few days. The flow is diverted from the *wadi* channels into typically short steep canals that convey the water to bunded basins, which can be inundated to depths of 0.2–2 m (Mehari, Van Steenbergen, & Schultz, 2011).

In Abyan, horticultural production has expanded in recent years. This is generating high-value crops, and can therefore be considered by the farmers who are growing them to have a positive effect on productivity (Table 2). Horticultural crops such as bananas require continuously available water to be pumped from the ground, as well as inputs of agrochemicals, which are believed to have affected biodiversity and reduced honey production in the delta (ICARDA, 2013). The human time and energy required for management of the spate irrigation system is reduced when groundwater pumping systems are installed. But the use of fuel for energy and the resulting carbon emissions are increased. Rich farmers who can dig wells and invest in inputs benefit from the transition,

Table 2. Transition from spate water to groundwater use in the Abyan Delta basin agro-ecosystem.

	Balance of ecosystem stocks and flows
Water	↓
Food and income	↑
Natural cycling and storage of geochemicals	↓
Carbon sequestration and emissions reduction	↓

but the free supply of water and good soil conditions that the spate systems used to provide to poor farmers are degraded.

The total renewable annual water supply to the spate irrigation system through the four main *wadis* in the Abyan Delta has been affected by changes in the climate, in addition to the anthropogenic changes associated with the expansion of horticultural production (Atroosh & Moustafa, 2012; RoY, 2013). The total volume of water available in the Abyan Delta basin has been calculated at 156 MCM (million cubic metres) per year. This is supplemented by increasing volumes of groundwater use, currently estimated at 112 MCM/y, of which only 84 MCM/y is recharged (Atroosh, 2013). Although there is scope for improvement of the water accounting, it is already evident that the groundwater table is falling and that saline intrusion is occurring in coastal areas (UNDP, 2013).

The transition from spate water to groundwater use may have a positive effect on food and income production for some farmers, but the negative effects on water availability in the spate system, the underlying aquifer and the soil profile will have negative effects on others. The natural cycling and storage of geochemicals, carbon sequestration and emissions reductions are also negatively affected by the altered cultivation pattern (Table 2).

Good agricultural practices, including the use of agroforestry to create favourable microclimates, selection of drought-resistant varieties, maintenance of local biodiversity, integrated pest management, reduced application of agrochemicals, and water harvesting can save on input costs, reduce environmental pollution, improve soil quality and sequester carbon (IAASTD, 2009; Massaad & Jomaa, 2013; MoE, 2012). As illustrated above, large-scale horticulture production, particularly for export, can discourage these traditional green water management practices developed by generations of land and water users in the drylands. However, market incentives can also reward and reinforce them, e.g. by enabling access to organic and other certification- and labelling-dependent markets (WLI, 2014).

The total area of the Orontes Basin is 37,900 km^2, including parts of Lebanon, Syria and Turkey (Figure A3 in the supplemental online data). Lebanon's Beka'aa Valley covers 17,000 ha at the upstream end of the basin, and receives average annual rainfall of 150 mm (total volume: 25 MCM/y). In the Beka'aa, imported commercial varieties of grapes (Superior table grape), and soft fruits, are increasingly cultivated in expanding orchard plantations, using groundwater for irrigation.

Changes in land and water use in the Beka'aa have been captured through studies of the variations in summer agricultural vegetative cover over the last decade (Jaafar, 2015). Overall, the agricultural land cover visible in summertime has expanded by more than 20% on average since the beginning of the century, mainly in areas not served by the existing open-channel irrigation scheme. The water required for these lands emanates from the groundwater of the Orontes Basin.

Retaining rainfed cultivation of the drought-resistant local fruit-tree varieties, harvesting rainwater in *negarims* around the bases of the trees and using integrated pest management practices increases resilience to drought, pests and disease, conserves a diversity of fruit tastes, and maximizes the productive use of available rainwater (IAASTD, 2009; Massaad & Jomaa, 2013). Farmers' use of good practices can lead to beneficial effects on stocks and flows of water and food, natural cycling and storage of geochemicals, carbon sequestration and emissions reductions (Table 3). However, it is difficult to assess whether these are enough to counter the effects of the increasing use of energy to pump groundwater for irrigation over the increasing cultivated land area.

The second national communication of Lebanon to the United Nations Framework Convention on Climate Change (UNFCCC) identifies emissions from agriculture, including those associated with enteric fermentation, manure management, soils and field burning of crop wastes, but not water pumping or treatment (MoE, 2011). The water resources and irrigation sector does not have a separate emissions inventory. Vulnerability and adaptation assessments are presented for the water sector and the agricultural sector, but not for the energy sector. It is not possible to know the volume of emissions, nor how much water is being pumped, nor what volumes of agricultural chemicals are being applied.

The total volume of flow through the Orontes Basin from springs and runoff water amounts to around 400 MCM/y (Comair, McKinney, Scoullos, Flinker, & Espinoza, 2013). International agreements give Lebanon the right to use 80 MCM/y of surface water and 16 MCM/y of groundwater for irrigation in the Beka'aa. This was calculated to allow use of an estimated 7000 m^3 of irrigation water per hectare per year, for 7000 ha. Presently, only 50 MCM/y is believed to be in use to support cultivation on 5000 ha of land, 4600 of which are irrigated (Comair et al., 2013). Springs are recharged annually by the rainwater, including flows through the *wadi* beds, but spring water also includes the natural discharge of stored reserves of palaeowater (Al-Bakri, Suleiman, Abdulla, & Ayad, 2011; Al-Charideh, 2013).

Whether the increase in groundwater extraction will be sustained in the near future has yet to be determined, given unofficial reports of declining groundwater levels in the upstream part of the basin (Jaafar, 2015). Although available studies suggest that there is not an overall deficit in the water balance in the basin, climatic changes are already affecting crop and livestock production in the Beka'aa, and further effects are predicted in future due to both climate change (MoE, 2011) and demographic pressures.

Precision irrigation and water reuse for economic water-use efficiency in the irrigated agro-ecosystems of the Nile Delta and the Mesopotamian Plain

Agro-ecological green water management strategies in irrigated areas of the Nile Delta, Mesopotamian Plain, Abyan Delta, Orontes Basin and across the region continue to focus more tightly on aligning water supply to economically productive crop-water needs and

Table 3. Potential effects of reinforcing good agricultural practices on balance of stocks and flows in horticulture production systems, Beka'aa, Lebanon.

	Without good practices	With good practices
Water	↓	↑
Food and income	↑	↑
Natural cycling and storage of geochemicals	↓	↑
Carbon sequestration and emissions reduction	↓	↑

increasing the use of marginal-quality water in agriculture. Regulation of irrigation volumes and timing to avoid over-irrigation can improve the quality of crop production, including for high-value horticultural crops (FAO, 2012). But reducing water application will also reduce downward percolation to recharge reusable shallow groundwater.

Aligning fertigation and nutrient requirements to plant requirements helps further increase the volume and quality of production achievable per unit of water (FAO, 2012). In systems where water application is reduced, high-quality water is needed, to avoid salinity build-up due to lack of soil flushing. Organic matter renewal, soil water holding capacity and carbon sequestration may also be reduced.

Increasing control of water application through pressurized sprinkler or drip systems requires more energy (El-Qousy, Mohamed, Aboamera, & Kheira, 2006; García, Díaz, Poyato, Montesinos, & Berbel, 2014) (Table 4). Ensuring sufficient water for salt-sensitive horticultural produce such as citrus can involve further energy costs to pump or treat water. Deficit irrigation requires compelling demonstration of plants' responses to water stress and identification of cost savings, improved qualities (e.g. higher sugar in citrus) and increased value of produce to convince and motivate farmers to use these techniques (FAO, 2012).

Many farmers across the region use shallow drainage water and groundwater to reduce their vulnerability to water shortage and increase productivity, because these sources are available at any time on demand, avoiding the uncertainty and variability of irrigation volumes and timing delivered through public or collectively managed systems. These practices have an energy cost, which can range across several orders of magnitude, depending on whether and how the water is treated (UNDP, 2013). Using or reusing saline and marginal-quality water to produce fodder for livestock avoids costs for treatment (although it may still include costs for pumping), adds value to a resource that might otherwise go to waste (Saleh, Ibrahim, Dhehibi, & Hassan, 2013), and enables saving higher-quality water for other uses.

The Euphrates runs through Turkey, Syria and Iraq (Figure A4 in the supplemental online data). In the Iraqi stretch of the river, the Abu Ghraib irrigation system covers around 272,000 ha in the Mesopotamian Plain between the Euphrates and Tigris Rivers. Average annual rainfall is about 123 mm (Al-Falahi, 2014). Due to reductions anticipated in precipitation over the basin (J. P. Evans, 2009), the decrease in annual discharge simulated for the Turkish portion of the Euphrates has been projected to reach 30–70% at the end of the twenty-first century. There is no climate change adaptation strategy for the Euphrates. Iraq has not published a national communication to the UNFCCC, nor any sectorial climate change strategy for water, agriculture or energy. Turkey has prepared strategies to adapt to the anticipated reductions in rainfall and surface water flows in the Turkish portion of the Euphrates (TR, 2011).

Flows into Iraq through the Euphrates have decreased from around 29 km^3 of water per year during 1932–1974 to around 21 km^3/y during 1975–2003 due to upstream

Table 4. Effects of precision irrigation and water reuse on balance of ecosystem stocks and flows in the Nile Delta and the Mesopotamian Plain.

	Precision irrigation	Water reuse
Water	↑	↑
Food and income	↑	↑
Natural cycling and storage of geochemicals	↓ ?	↓ ?
Carbon sequestration and emissions reduction	↓ ?	↓ ?

developments as well as climatic changes (J. P. Evans, 2009). Additional flow from the Tigris is estimated at around 50 km^3/y, resulting in a total of 70 km^3/y entering Iraq at the first entry point on the Iraqi–Syrian border. According to the records kept by the Office of Irrigation of the Ministry of Water Resources (MoWR), the total volume of water flowing into the Abu Ghraib canal entry point is 622 MCM/y. The total water requirement for agriculture has been estimated at somewhere close to 700 MCM/y, and the outflow at around 150 MCM/y (Al-Falahi, 2013, 2014).

The sources and volumes of water used in irrigation at Abu Ghraib have been estimated as follows: irrigation network sourced from the Abu Ghraib Canal, 80% (622 MCM/y according to MoWR); groundwater, 17% (132 MCM/y); drainage water, 3% (23 MCM/y) (Al-Falahi, 2013, 2014). Recent studies appear to show a lowering of the groundwater table at Abu Ghraib, suggesting an imbalance between extraction and recharge (Voss et al., 2013). At the same time, salinity problems are exacerbated (Evans, Soppe, Barrett-Lennard, & Saliem, 2012). Although techniques for water saving and reuse offer a means to cope with some of these problems (Hussien, Aoda, & Alfalahi, 2014; Neama, Al-Falahi, & Hamoudi, 2014; WLI, 2014), the implications concerning associated uses of chemicals and energy in agriculture are difficult to assess with any accuracy, and no policy framework is in place through which this could be done systematically.

The Nile Delta extends over around 2,500,000 ha, with maximum annual rainfall of around 200 mm at the coast, and less inland. The cultivated area of the delta is supplemented by ongoing land reclamation. The annual volume of surface water inflow at the High Aswan Dam is 55.5 km^3/y, and annual outflow to the sea, 12.2 km^3/y (MWRI, 2010). Present and anticipated future water balance and food production have been intensively studied. Present and potential future uses of precision irrigation and water reuse technologies have also received significant attention (Attaher & Medany, 2008; Nour El-Din, 2013).

Under climate change and upstream development the volume of water reaching the Nile Delta from the Nile Basin (Figure A5 in the supplemental online data) will be reduced. Water demand for drinking in Egypt is 1.8 km^3/y, while industry requires 1.4 billion cubic metres. The amount of water used by the agricultural sector in 2010 is about 67 km^3/y, including leaching requirements and deep percolation to shallow groundwater. To achieve this, and also support other sectors, other water sources are used besides surface water. These include groundwater and drainage water.

Egypt has prepared two national communications to the UNFCCC (EEAA, 2010b), a National Environmental, Economic and Development Study for Climate Change (EEAA, 2010a), an assessment of potential impacts of climate change on the Egyptian economy and a draft adaptation strategy for the Ministry of Water Resources and Irrigation (Nour El-Din, 2013). The national communication includes assessments of national water resources and the energy and agricultural sectors – these are the two sectors with the highest emissions in the national greenhouse gas emissions inventory.

The water resources and irrigation sector does not have a separate emissions inventory, but basic methods for estimating the energy used to pump the water used in agriculture are available (Attia et al., 2005; Fraenkel, 1986). Vulnerability and adaptation assessments are presented in the national communication for the water and agricultural sectors but not for the energy sector. The balance of effects on stocks of water and food that will be achieved with ongoing technological shifts in irrigation management and water reuse can be expected to be positive. However, there remains a need to better understand the accompanying effects of these transitions on the natural cycling and storage of geochemicals, carbon sequestration and emissions reductions (Table 4).

Increasing urban water and food demands: water harvesting in the Jordan River Basin and the Zeuss Koutine Watershed

Increasing water scarcity, constrained access to pasture resources, decreasing returns from agriculture, and more attractive livelihood opportunities promised by other sectors have led to depopulation of the rural areas, neglect of traditional cultivation practices, increasing reliance on imports of food and animal feed, and out-migration to cities (Sghaier, 2009). As a result, the energy demands of cities to pump and treat water are growing, as are their demands for food imports.

Water harvesting is widely recommended as a solution to support rural communities and sustainable food production in dry areas (Jaafar, 2014; WOCAT, 2013). This practice is recognized to save water, increase productivity, and improve soil and carbon sequestration (Table 5). Where rainwater captured in the soil profile exceeds the water holding capacity, it can percolate downwards to recharge groundwater reserves. Increasing groundwater recharge could help in avoiding the need for the construction of more water treatment plants and slow the increasing energy demands for pumping groundwater from a falling water table in the urban areas. However, because water harvesting is labour-intensive, rural communities often do not anticipate sufficient benefits from investing in it.

Wadi Oum Zessar (surface area: 33,600 ha) is one of several ephemeral rivers feeding the Zeuss Koutine Aquifer in the Koutine Watershed, Tunisia (Figure A6 in the supplemental online data). Traditionally, in the upper reaches of the Koutine Watershed, rainfall and water-harvesting structures (known as *jessour*) support agroforestry, intercropping of barley and natural vegetation for grazing by livestock. Further down, in the plain, water-harvesting structures are known as *tabia*. Harvesting rainwater to support trees and fodder for livestock can simultaneously increase the recharge of groundwater (Ouessar et al., 2009, 2004). Where rainwater captured in the soil profile exceeds the water holding capacity, it will percolate downwards and recharge the groundwater reserves flowing through the Zeuss Koutine Aquifer, serving the downstream urban population in the cities of Medenine, Tataouine, Jarzis, Jerba and Benguerdene.

Maintenance of the water-harvesting systems is labour-intensive and not particularly profitable for private farmers. The Tunisian government has invested directly in increasing recharge to the aquifer through the construction and maintenance of artificial recharge structures in the upper part of the watershed (Hadded et al., 2013). The only direct incentive the rural population has for providing this recharge service is the 10% of groundwater recharge that they extract again at their own cost for local use (WLI, 2013). Economic incentives for smallholders to undertake and maintain water-harvesting systems require attention (Table 5).

The water, energy and food balances in the Oum Zessar Watershed have been relatively well-studied. The total area of the aquifer is 1305 km^2 (Hadded et al., 2013). Average annual rainfall (209 mm) is split into evapotranspiration (72%), transmission loss (3%), percolation (19%) and outflow (6%) (Ouessar et al., 2009). Across most of the region, the recharge rate

Table 5. Water harvesting in the Zeuss Koutine Watershed and the Jordan River basin.

	Balance of ecosystem stocks and flows
Water	↑
Food and income	?
Natural cycling and storage of geochemicals	↑
Carbon sequestration and emissions reduction	↑

is 2.42% of rainfall (Hadded, 2008). But in the *wadis*, the rate of infiltration to groundwater recharge has been estimated at 70% of the total volume (10.230 MCM/y), due to the installation of the artificial recharge structures (Hadded et al., 2013).

The average energy consumption for urban water abstraction is estimated at 0.834 kWh/m^3 (Hadded et al., 2013). Since demand exceeds supply, part of the shortfall is made up by two desalination plants that have already been constructed to treat seawater, and further water treatment facilities are considered likely to be needed in future. These will use additional energy, and may emit waste-products.

Tunisia's second national communication to the UNFCCC (Tunisia, 2014) builds on the national adaptation strategy for agriculture (MARH, & GTZ, 2007) and those of other sectors. Scenarios for agricultural emissions, water supplies and productivity have all been developed, and action research to identify the effects of water harvesting and recharge practices is well integrated and supported through the National Agricultural Research and Extension System (WLI, 2013; WOCAT, 2013). Although the Tunisian policies, and particularly the proactive water-conservation and groundwater-recharge interventions implemented in Southern Tunisia, can be seen as relatively exemplary for the region, the national communication itself still explicitly underlines the need for further mainstreaming and integration amongst the sectorial agendas.

The Jordan River basin includes parts of Lebanon, Syria, Jordan, Palestine and Israel (Figure A3 in the supplemental online data). This includes the catchments of the West Bank that feed the mountain aquifer which is shared by Palestine and Israel (Chenoweth, 2011; Comair, Gupta, Ingenloff, Shin, & Mckinney, 2013; Hoff, Bonzi, Joyce, & Tielbörger, 2011; Mansour, Peach, Hughes, & Robins, 2012). In the West Bank, many people depend on livestock production for their living, but natural vegetation provides only 15% of livestock food needs, and only during winter and spring (Sholi, 2013). The remaining feed requirements for livestock and food for humans is met through crop production, which is mainly rainfed due to restrictions on groundwater extraction for irrigation. Transporting water and feedstuffs or moving animals from overgrazed areas to less degraded lands requires fuel and vehicles, in addition to other transaction costs. Where sufficient feedstuffs cannot be grown locally, they have to be imported at high cost from Israel to Palestine.

Constructing and maintaining water-harvesting structures requires the use of vehicles and fuel as well as labour (Sholi, 2013). Harvesting rainwater can make the difference between failure and success for rainfed barley production, avoid the need for irrigation of crops, and reserve scarce water supplies for other local uses by households or downstream flows. However, farmers in the West Bank are not necessarily willing to invest their time, land and labour in this practice unless they can see a clear economic case for doing so. They do not anticipate benefits from increased groundwater recharge, because they are not permitted to construct wells (Sholi, 2013).

Palestine has a Climate Change Adaptation Strategy and Programme of Action which have identified sectorial vulnerabilities, including those in the agricultural and energy sectors, as well as water security challenges (UNDP, 2011; UNDP/PAPP, 2009). The strategy and programme have underlined the untapped potential for energy measures to simultaneously deliver climate mitigation and adaptation benefits, particularly in situations of increased water scarcity as a result of climate change.

There is no joint climate adaptation strategy for the Jordan River basin countries, nor any framework for water and carbon emission accounting. However, Jordan's second national communication to the UNFCCC draws on available water-balance studies for portions of the basin in Jordan, including one for the Amman Zarqa Basin (GoJ, 2009).

At this level, recognition of the scope for investigation of the water–energy–food and climate trade-offs associated with groundwater recharge in water-harvesting systems is just beginning (WLI, 2014). However, the potential scope for policies enabling payment or other incentives for these watershed services is already attracting attention.

Discussion

Although in all six systems explored in this article rural communities have been practising agricultural water management strategies with potential to maximize benefits to water, food and energy resource management under climate change, the available evidence concerning the merits of these practices has rarely been sufficient to convince policy makers that they provide solutions worth investing in. Instead, decision makers are opting to pay rising costs for wastewater treatment and desalination. The overviews of water-balance studies presented in this article demonstrate the uneven current state of knowledge in the selected basins and sub-basin catchments, despite the availability of promising tools as demonstrated by Hadded et al. (2013) and Hoff et al. (2011). How then can implementation of the nexus approach be connected to the proposed four-dimensional assessment framework?

The qualitative approach taken in this article, integrating consideration of the water balance with inputs and outputs of energy and geochemicals through the water basin systems, advocates and invites further refinement of the approximated ratios of positive and negative factors presented so far. This would be compatible with emerging approaches to ecosystem accounting (UN, 2012, 2014; WAVES, 2014), as well as ongoing water resource accounting efforts (Karimi, Bastiaanssen, & Molden, 2013; Molden & Sakthivadivel, 1999). Resource accounting would enable more precise and effective weighing of the comparative values of benefits and trade-offs in the nexus by quantifying the stocks and flows of water, energy and geochemicals through the systems.

Using three or more different metrics for quantifying the effects of strategies and practices complicates quantification and weighing of trade-offs between sectorial objectives. The simple binary weighting and ratios used in this article give equal weight to stocks and flows of widely different magnitudes. This severely limits the effective weighing of trade-offs. Economic cost–benefit assessment is more convenient for informing decision makers because it translates the varying quantities of each of the inputs and outputs or benefits into monetary units that are directly comparable (TEEB, 2011; Pascual & Muradian, 2010). This presents a foregone conclusion regarding the optimal strategy, avoiding the burden of subjective decision making. However, economic assessments are only as good as the underlying data-sets quantifying the stocks and flows of each commodity.

The disaggregated four-dimensional approach is more intelligible for consideration and discussion by stakeholders than an aggregated value may be, and avoids other widely observed drawbacks inherent in economic assessment approaches. These include failure to take into account environmental externalities including pollution and resource degradation, failure to assign sufficient value to ecosystem function and services, use of discount rates that favour short-term gains over long-term sustainability (see further discussion in Chambwera et al., 2014; Pascual & Muradian, 2010) and general unintelligibility of the economic ‘black box’ amongst concerned stakeholders.

None of the countries where the case studies are located has yet adopted ecosystem accounting methods wholesale at the national scale, let alone sub-national or basin scales. Nevertheless, conventional agricultural and trade statistics (available through national statistical agencies, FAOSTAT and UNCOMSTAT) already capture some elements of the required accounting at a range of scales (i.e. crop production and inputs, including stocks and flows of nutrients and agrochemicals). Through national strategies in response to climate change (the fourth dimension of the water–energy–food–climate nexus), some of the missing elements required to enable ecosystem accounting tools to be used for quantitative basin-level assessment of trade-offs in the nexus are gaining increased attention.

The potential for agricultural activity to increase stocks of groundwater recharge and stocks of carbon through sequestration in soils and vegetation is not yet accounted for in any of the national strategies or accounting frameworks. However, necessary methods for carbon accounting are increasingly available and promoted through climate adaptation and mitigation efforts (Braimoh, 2012). In the meantime, national emissions accounts have been established in many countries of the region, providing the basis for a systematic approach to tracking the flows of carbon associated with agriculture and other sectors (UNFCCC, 2006).

Conclusions

In this article, the scope for four-dimensional hydro-eco-agrological assessments and improving nexus decision making has been illustrated through case studies in six selected basins. Underlying the case studies are varying levels of data availability concerning the water, energy and food stocks, flows and processes (major sources are indicated in the references). Some flows, such as inputs of climatic data and extents of vegetated areas, are increasingly well quantified, whereas others, such as groundwater extraction volumes and energy uses in the product cycle, remain more challenging to effectively quantify due to data-collection challenges. Adaptive management strategies should use the best available data and methodologies, including decision-support tools, to improve this situation through monitoring and assessment, coupled with the continued implementation of ‘best-bet’ green water management strategies. Providing resources, imperatives and review fora for this continuous learning-while-doing should be an essential element of nexus implementation policies.

The desirability and the challenge of achieving systematic quantitative assessments enabling more precise and effective weighing of nexus trade-offs associated with water management decision making has been explored through the qualitative assessment presented in this article. Discussion of the feasibility of progression from the qualitative assessment of nexus trade-offs to the systematic quantitative ecosystem accounting approach that is advocated focuses on the contribution of ongoing strategic work addressing climate change adaptation and mitigation as the fourth dimension of the water–energy–food–climate nexus. This ensures the progressive development of national frameworks for data generation and collation that will be key to the intended tracking of the other three dimensions (water, energy and food).

Although the focus of this article is primarily on assessment methods for policy formulation and improvement, rather than on advocating particular hardware fixes, the various patterns of livestock and human water uses illustrated have very different energy implications, and suggestions emerging e.g. in Palestine to give further attention to smallholders’ access to sustainable energy sources and technologies heighten attention to the potential of this entry point for strategic intervention. Other recurring themes in the case studies offering potential entry points for nexus policies concern tightening of the internal efficiencies and feedbacks in recycling of water and nutrients in the production systems, including domestic, urban and industrial parts of the systems, and where produce is exported; use of systems to reward organic, sustainable or good agricultural production methods; and improved environmental monitoring.

Overall, the nexus approach is challenging but has significant potential to reveal, advocate and maximize the contribution of rural communities' green water management practices to the achievement of sectorial goals to cultivate a model of water, energy, food and climate security that will be accessible to the bottom billion in the drylands and help them maintain their quality of life. The case for increased strategic support for these practices appears stronger when weighed from the water–energy–food–climate nexus perspective, rather than purely from the point of view of water balance and food production.

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No potential conflict of interest was reported by the authors.

Supplemental data

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