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WATER, FOOD AND ENERGY SUPPLY CHAINS FOR A GREEN ECONOMY†

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ABSTRACT

A new paradigm for sustainable, integrated, water resources management is emerging from international conferences around the world. Its most succinct description is 'the water–food–energy nexus for a green economy'. The water, food and energy nexus aims at the most efficient, best practice principles applied throughout the full food supply chain. This includes consideration of reducing wastage of the food for various reasons in the supply chain. This paper describes the global opportunities for better efficiency and resources conservation in the water, food, and energy supply chains with examples from Australia. Food wastage equates on average to 243 l day^{-1} of water per person in the food they throw away, which is 1.5 times the daily water use per person in the UK. The concepts of virtual water and water footprint can help in identifying opportunities to save water by targeting reduction of wastage of food that has the highest virtual water content. A green economy aims at achieving optimised supply chain objectives in a manner that espouses the sustainability principle, gives due attention to environmental concerns and helps with eradication of poverty and hunger. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: water–food–energy nexus; green economy; water efficiency; energy efficiency; food waste; virtual water; water footprint; integrated water resource management; supply chain; environment; ecology

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RÉSUMÉ

Un nouveau paradigme pour la gestion durable et intégrée, des ressources en eau est en train d'émerger de conférences internationales à travers le monde. Sa description la plus succincte est 'les connexions entre eau–alimentation–énergie pour une économie verte'. Ces connexions visent à appliquer les principes les plus efficaces et les meilleures pratiques tout au long de la filière d'approvisionnement alimentaire. Il convient notamment de réduire le gaspillage de la nourriture pour diverses raisons dans la chaîne d'approvisionnement. Ce document décrit les opportunités mondiales pour une meilleure efficacité et la conservation des ressources dans les filières d'approvisionnement en eau, nourriture et d'énergie, à partir d'exemples pris en Australie. Le gaspillage alimentaire équivaut en moyenne à 243 l d'eau par jour/personne dans la nourriture qu'ils jettent, soit 1.5 fois la consommation d'eau journalière d'un habitant du Royaume-Uni. Les concepts d'eau virtuelle et d'empreinte de l'eau peuvent aider à identifier les possibilités d'économiser l'eau en ciblant la réduction du gaspillage de nourriture qui a la plus haute teneur en eau virtuelle. L'économie verte vise à accomplir les objectifs optimisés de la filière d'approvisionnement de manière à épouser les principes de développement durable, donner toute l'attention voulue aux préoccupations environnementales et contribuer à l'éradication de la pauvreté et de la famine. Copyright © 2014 John Wiley & Sons, Ltd.

MOTS CLÉS: connexions eau–alimentation–énergie; économie verte; efficacité de l'eau; efficacité énergétique; les déchets alimentaires; eau virtuelle; empreinte sur l'eau; gestion intégrée des ressources en eau; filières d'approvisionnement; environnement; écologie

INTRODUCTION

An obvious initial task is to describe what we mean by the terms in the title of this paper, as they may mean very different things to different people. In the context of the International Commission on Irrigation and Drainage (ICID) we

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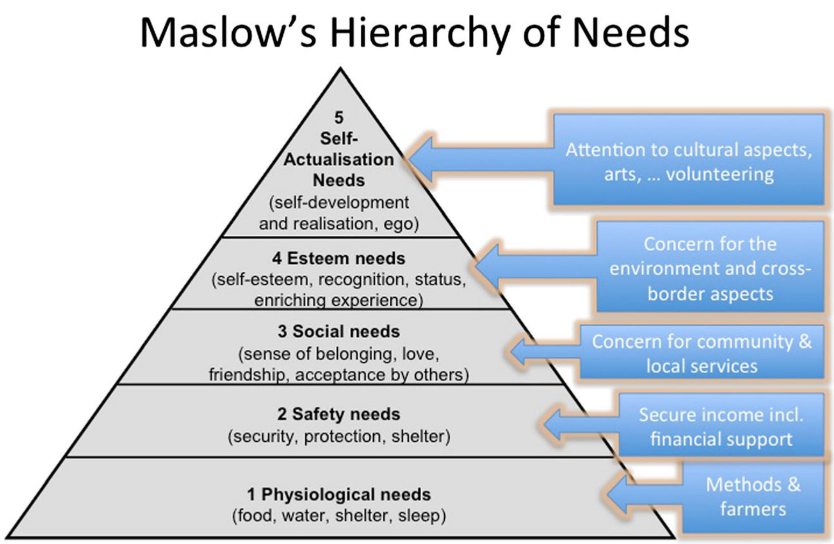

Figure 1. Maslow's hierarchy of needs (Maslow, 1954, adapted by Vlotman, 2011). This figure is available in colour online at wileyonlinelibrary.com/journal/ird

generally consider efficient water use for food production but rarely include considerations of efficient energy use and efficient food use. In recent years the water–energy–food nexus has gained global interest. The concept was discussed and described at the RIO + 20 (20–22 June 2012) and the Stockholm Water Conference 2012 (26–31 August 2012, Stockholm International Water Institute (SIWI), 2012) and comes up more and more in discussions elsewhere. What does this mean in the ICID context? This paper will describe a water–food–energy nexus, sometimes referred to as the water–energy–food nexus. The three components are considered exchangeable without loss of meaning; herein we will refer to it as the water–food–energy nexus. At ICID where water and food are the main and traditional focus of the ICID network, this paper will include consideration of the inextricable energy link in food production. We will also consider the loss of water and energy when food is wasted and not recycled.

The term 'green economy' highlights other dimensions of food production that are not normally considered by the ICID network. The objective of the majority of ICID colleagues is to improve water use with the aim of producing more food in their countries. Doing this with due attention to a sustainable environment and ecology is generally not a priority. A review of papers presented at ICID conferences over the last few years clearly shows that a large number were aimed at producing more food with less water but with no mention of the effects on the environment and ecology. However, other papers do address the more ecologically sound production of food, with attention given to elements of the environment/ecology and production of food concurrently.

We are faced with an interesting division within ICID member countries that can be explained by Maslow's hierarchy of needs (Figure 1). It is helpful to be cognisant of what Maslow says in relationship to many aspects of our societies or countries. Countries where food is typically in short supply are in the lower two tiers, while food-affluent countries lie in tiers three and up. Only with a full belly and enough money in the bank will the average farmer start to think about wider environmental aspects of his food production. It is our duty at ICID to assist people in the first two tiers to become environmentally aware and work towards green production so that it becomes as common for them as for the driver of food self-sufficiency. ICID can use the water–food–energy nexus as a useful coat hanger to achieve ICID's mission (Box 1).

Box 1. ICID Mission statement.
The **Mission** of the International Commission on Irrigation and Drainage is to stimulate and promote the development of the arts, sciences and techniques of engineering, agriculture, economics, ecology and social science in managing water and land resources for irrigation, drainage, flood control and river training applications, including research and development and capacity building, adopting comprehensive approaches and up-to-date techniques for sustainable agriculture in the world.

There are several statements about water, food and energy that, in isolation, seem to be reasonable aspirations for a healthy world society:

- *water security*—United Nations Millennium Development Goals (United Nations (UN), 2012*)* regard 'access to safe drinking water (and sanitation)' as a human right, which implies that someone must have a duty to provide that right. This refers to tier 1 in Maslow's hierarchy of needs;

- *food security*—also regarded as a human right and defined by the Food and Agricultural Organisation (FAO) (1996) as 'availability and access to sufficient, safe and nutritious food to meet the dietary needs and food preferences for an active and healthy life'; also pointing to tier 1 of Maslow's hierarchy of needs;
- *energy security*—'Access to clean, reliable and affordable energy' is also seen by the UN as desirable—but not elevated to the status of a human right? This need is may be more a tier 2 need in Figure 1.

The reality is that there are many substantial interactions between the objectives of securing access to water, energy and food. Energy generation uses large volumes of water. Conversely, water efficiency projects (pumped schemes, groundwater storage, etc.) consume large amounts of energy. Although water-intensive energy production and energy-intensive water savings may be justifiable in regions with ample supplies of one resource and limited supplies of the other, the environmental impacts should be considered. Energy production is likely to result in carbon emissions and related pollution, as well as consumption of water. More efficient food production in water terms (more crop per drop) may be at the expense of reduced water for the environment, as well as consuming more energy.

Consumptive use of water on a global scale comprises approximately 7% of the total available water (Gleick, 2011), and of the 7%, 70% is used for agriculture; the numbers vary widely, however, per country. Available water is defined as water that can be accessed by human intervention for business or personal use: the consumptive use component. The remaining water runs off or recharges to soil moisture and groundwater. A good amount is also evaporated, which is seen by many as a loss but is not if the whole hydrologic cycle is considered (see Figure 3). Evaporation is in that context an essential element of the water cycle that will result in rainfall.

In short, the water, food and energy nexus means that the three sectors water, food and energy are inextricably linked, and that actions in one area more often than not have impacts in one or both of the others. The word 'nexus' in this context is fashionable. It has many meanings and uses but in the context of this article the concept of a 'nexus' implies optimisation. We need to somehow optimise the mix of energy and water that we use to produce the food that is needed. Clearly not wasting food will 'save' water. These savings should not be expressed in terms of how many cubic metres can be returned to the environment or ecology, but as an effective use of water to produce kilograms of food or as effective use of water to produce food for the average daily food need of a person.

The concept of a 'green economy' adds other dimensions to the water–food–energy nexus as alluded to above. The United Nations Environmental Programme (United Nations Environment Programme (UNEP), 2011) launched the Green Economy Initiative (GEI) in 2008 and defines a green economy as 'one that results in improved human wellbeing and social equity while significantly reducing environmental risks and ecological scarcities. In its simplest expression a green economy can be thought of as one that is low carbon, resource efficient and socially inclusive.' A green economy can thus be seen as one that contributes to sustainable development. However, the definition is so broad that it is not very helpful in thinking about optimising energy, water and food use. Should we demand a certain level of 'greenness' before we consider optimising, or should the aim be just to become progressively greener as we make our use of resources more efficient?

How do we work in the 'socially inclusive' aspect? In Australia, for the Murray-Darling Basin Plan, social inclusiveness has been implemented through 'localism'. Localism is defined as including the local communities in preparing plans for more efficient water use, for returning water to the environment and reducing the impact of taking water from food production to meeting environmental targets for a healthy river, flood plains and connected wetlands.

The free market concept that market forces will lead to optimal solutions for energy, water and food efficiencies does not help much. The unfortunate reality is that markets are poor at capturing environmental effects—the slogan that 'the polluter pays' is extremely difficult to apply, and is generally applied by regulatory rather than market forces, despite initiatives like carbon trading which create a somewhat artificial market through regulation.

In order for us to improve efficiencies of water, energy and food usage it is helpful to have a closer look at the water–food–energy supply chains that interact from the farm to the consumer; from field to fork (Boselie, 2002).

SUPPLY CHAINS

Supply chains are useful in mapping out the flow of resources and goods and help us to visualise the processes that take place. There are many possible variations of supply chains and each will display an actual, potential or scientific chain of events or goods undergoing transformation from raw material to product. Several possible examples will be given, but elements of the chain may vary from country to country. In fact these chains may vary within a country as well, depending on the institutional or business model that is considered (Figure 2). Management of a chain may be centralised or dependent on several institutions and companies, each providing their own individual service to the chain.

The objectives of chain management are improvement in the physical and/or economic environment of the chain. To achieve this, barriers will have to be broken, or institutional arrangements realigned. Rather than looking from the institution via the process to achieve efficiency in the chain (Figure 2), one should use the efficiency of the chain, or any point in it for that matter, as the starting point and adjust the process and institutional arrangements as necessary. A recommended approach is the bottom-up one. Start with the end users, see what their objectives are, design a process to achieve those objectives and prepare institutional arrangements with key stakeholders from top to bottom, to make the chain work as a unit.

As Jägerskog and Jønch-Clausen (2012) and SIWI (2012) in the *Feeding a Thirsty World – Challenges and Opportunities for a Water and Food Secure Future* observe:

> The conditions that challenge agriculture today are very different from those of the 1960s. From a water perspective, rivers are drying up, groundwater is being depleted, and 'water crisis' is now a commonly used term. Agriculture now consumes 70–80% of all human water withdrawals, with severe consequences for many ecosystems and the related services on which we all depend. We now know that we can no longer view water as an inexhaustible and free input to a global food production system (Comprehensive Assessment of Water Management in Agriculture, 2007). Higher incomes, changing diets, and urbanisation will impose new demands on agricultural water. Biofuel production will compete with food production for available resources. Climate change will bring more frequent droughts and floods, and will influence temperature regimes in ways that will increase the challenges faced by farmers in how they manage water. Economic growth will deepen competition between agricultural and non-agricultural water uses.

The water supply chain, improving water efficiency and saving water

The water supply chain is embedded in the hydrological cycle, a manifestation of which is shown in Figure 3. Water scientists use the hydrological water cycle to explain the relationships in the water chain. The cycle comprises land, sea and air. Elements of the water supply chain occur in parallel, concurrently and in series. It will depend on local conditions, which combinations are present and how economic, energy and food linkages exist. Water chains can have objectives of higher efficiency (water saving), less environmental downstream impact (water quality), and least costs to the consumers and users (both human and environmental).

Depending on the use of the water, a water supply chain will typically comprise the 'source– distribution network– water use–removal of excess/waste water–recharge to source' chain. Efficiency of water use is generally considered within each oval. The key performance indicator (KPI) will be defined according the specific details of the water use sector: agricultural, industrial, municipal or environmental.

Tables I and II show well-known water use and potential efficiency facts. It is beyond the scope of this article to go into detail, but they are essential in identifying where efficiency gains may be possible.

Achieving food security is a complex challenge involving a host of factors. Two of the most critical are water and energy, both essential components to produce food. World Water Day 2012 was devoted to 'Water and Food Security', and the 2012 World Water Week in Stockholm also made this subject its primary focus. Both global events place 'water' at the centre while recognising the broader overall complexity of food security.

At the Rio + 20 Summit that took place in June 2012 'water' was recognised as a key issue in the final text 'The Future We Want', including its role as a critical factor for the green economy. In preparation for the Rio Summit, the Bonn 2011 Conference had highlighted the 'Water, Energy and Food Security Nexus', stressing the importance of

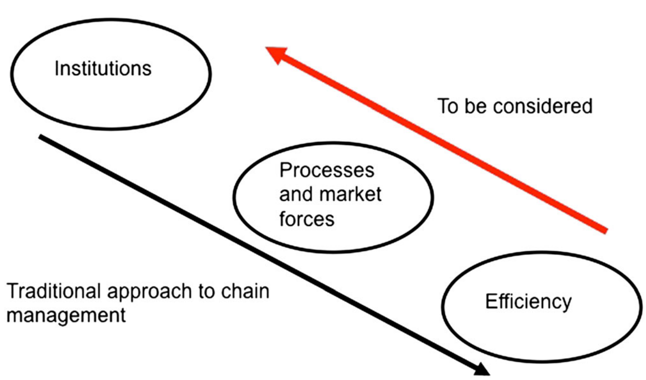

Figure 2. A supply chain seen as a single manageable organisation. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

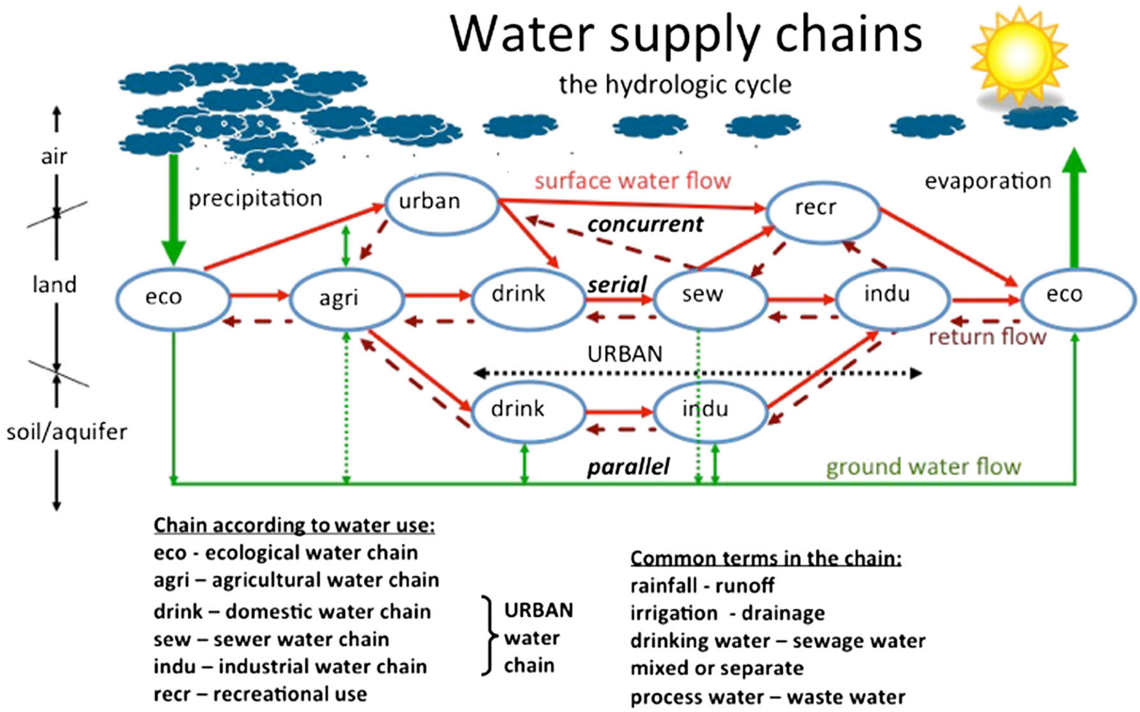

Figure 3. Water supply chains, i.e. the hydrological water cycle (after Vlotman, 2004). This figure is available in colour online at wileyonlinelibrary.com/journal/ird

Table I. Benchmark for drinking water distribution efficiency (%) (Vlotman, 2004)

Type of network	Bad	Insufficient	Average	Good
Urban	< 60	60–75	75–85	> 85
Intermediate	< 55	55–70	70–80	> 80
Rural	< 50	50–65	65–75	>75

addressing water in this broader context. Although not explicitly stated, the central role that ecosystems play in this nexus was implicitly recognised in the Bonn outcomes (Jägerskog and Jønch-Clausen, 2012).

Table II. Agricultural water efficiency (Vlotman and Harwood, 2011)

Method	Efficiency (%)	Remarks
Flood irrigation	50–85	New water management control technologies
Sprinkler irrigation	65–90	From high pressure to low pressure application
Trickle irrigation	75–95	Reliability, durability and water management
Subsurface irrigation	50–95	Shallow soil management
Controlled drainage	50–85	Maintain and manage high water table as appropriate
State of the art water management	85–100	Soil moisture management and delivery system management combined

The energy supply chain

Food security is an increasingly global problem and is also becoming a more important political priority of increasing complexity as the prospects for supplying food are strongly impacted by population growth, the effects of climate change, new technologies, sharply increasing energy demands and shifts in consumption patterns. It therefore makes sense to have a closer look at a possible description of the energy chain (Figure 4). Starting from various energy sources, not least solar and hydropower, energy flows through distribution networks to a variety of users including agriculture (farm use) and agri-industries. Local production of energy may feed back into the supply network. This production can be from solar energy, biowaste, etc. and a bit more is described in detail below. We are concerned about the energy used at each point in the energy chain to produce, manufacture and distribute food products. In addition, waste or unused portions of food are a concern as they imply loss of virtual energy and virtual water. Virtual water is a well-described principle with few practical applications but of great interest from the policy and social inclusion points of view. A similar approach may be taken with virtual energy, i.e. how much energy was used to produce the product we

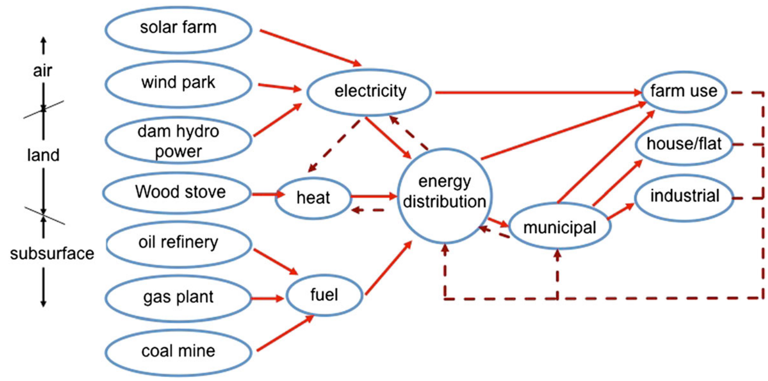

Figure 4. The energy chain. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

are consuming, including energy (fuel for cars, etc.) used in distribution. As with virtual water, virtual energy may point to locations in the energy supply chain where efficiency improvements may be possible and most effective.

Reuse of waste products is a source of potential water and energy savings (Vlotman, 2002). For instance, sewage water treatment plants produce three potential reuse products: water, sludge and energy. Treated sewage water can be used for irrigation of parks, lawns, etc. or for cooling water in the industry, for boiler-water and processing water. When further treated it can be used again as drinking water. When treated effluent is discharged into drains, numerous potential downstream uses are possible. The sludge can be used as manure in agriculture, as aggregate in road construction, as a source of nutrients, metals, etc. Sludge can also be used as an energy source, such as biogas and biopetrol. Problems with the application of sludge can include hygiene, heavy metals and organic micropollution. The energy contained in the relatively warm treated effluent can be extracted via heat exchangers. The sludge also has an important energy value in the form of biogas.

CSIRO (2011) in their annual water report for Australia identified that the largest energy use associated with water is in heating of water in domestic, commercial and industrial applications. Water heating accounts for about 25% of all residential energy use but it could be halved through water-efficient appliances and more efficient water heaters. Even greater energy benefits may be gained in industry, where reductions in steam and hot water losses, reduced pumping in manufacturing, and cooling result in significant energy savings.

Since the mid 1980s substantial energy savings have been implemented at field scale when high-pressure high-energy centre-pivot and linear-move irrigation systems switched from overhead sprinkling to drop-tube application of water. This switch may not be appropriate for all crops, but the majority of systems in Australia could easily make this move. Energy and water savings in this manner are substantial in North America (Gillies *et al.*, 2013) but less so in Australia, where most systems are low-energy surface irrigation systems. Still, low-energy precision application (LEPA) systems would result in substantial water savings compared to furrow and border flood irrigation systems (Table II). It is clear that there are many other possible examples of energy use, generation and reuse that can be described, but the intent here is to merely point to some options and to encourage readers to go beyond them.

The food supply chain; waste and efficiency

As before, if we are to make efficiency gains in how we produce, transport, use and reuse food we need to first assess the food supply chain: from field to fork. The food supply chain is really a business model with the economic gain being the main driver (Figure 5). Traditional business links are shown in solid lines, while the dashed lines show recent and to be developed more food-efficient supply and use links. Energy can be saved when using some of the direct links from producer to consumer and cutting out the various middlemen. Both water and energy are used at each element in the chain and hence it is useful to consider efficiency measures at each of these. They will result in reduction of costs as well. Waste recycling potentially also recovers water and energy in a similar fashion as the use of the by-products of sewage water treatment described above.

Food wastage accounts for 1380 km^3 of (virtual) water being wasted globally every year and equivalent to a value of US\$252 billion. Translated in a volume easier to understand, it equates to per person waste of on average 243 l of water a day in the food they throw away—over one and a half times what they use in their homes (UK-based statistic). In the USA alone it is estimated that 40% of all food purchased is thrown away. Scary statistics are bandied around about how much virtual water is contained in certain food items as if we are wasteful with water in that aspect. This is not necessarily true if we assess the wastage and redistribute the food for actual intended use. It will not save millions of cubic metres of water that can be used for the

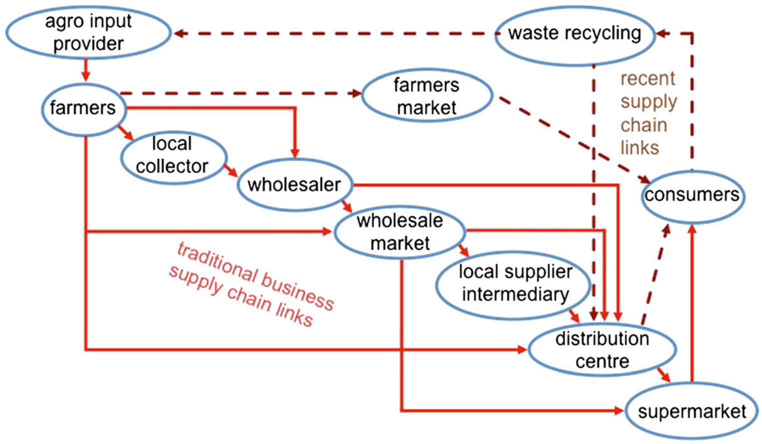

Figure 5. The food or agri-product supply chain. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

environment or the green economy, as the water is already virtual, but reducing the wastage will go a long way to achieving the global estimated food requirements in 2050 (FAO, 2011; Jägerskog and Clausen, 2012).

The FAO reported recently that enough food is produced worldwide to feed everybody and yet 14.9% of the world's population are undernourished or hungry (FAO, 2011). Clearly efficiency gains are to be made in food distribution, some of which may require higher energy inputs, a necessary trade-off to achieve higher effectiveness and efficiency in water use. Situations will differ from location to location.

In southern Australia, the irrigation areas of Sunraysia, about 650 km from Melbourne, the capital city of Victoria, produce table grapes, citrus and vegetables including low-value and heavy items such as melons. Typically these are transported by truck (despite the availability of freight rail) to a wholesale market or to major supermarket wholesale outlets in Melbourne, and some eventually find their way back (via more road transport) to supermarkets in Sunraysia, a 1300 km road journey ending mere kilometres from where the produce was grown. Imagine the potential loss of product during distribution links in this particular food chain, and the related energy waste.

Similarly, roses grown in Egypt are transported to the Netherlands for auction and then supplied back to retailers in Egypt, to be sold as roses from Holland. The various swine flu epidemics (USA in 1998 and UK in 2009) made painfully clear the inefficient transport of livestock that was suddenly prohibited. Have we made these supply chains more efficient in energy and water use since then?

Food production in southern Australia and California, USA, is similar in many aspects but summer and winter are reversed. Because the market seems to dictate that all food products should be available for the whole year, produce is transported continually between the two regions. Apart from the obvious waste of energy in transporting bulky produce halfway around the world, populations in these areas seem to be losing the joy of eating fresh locally produced food 'in season'.

As in the UK and USA, a huge amount of food is wasted in Australia. Despite the generally high living standards and a reasonably good social security system, there is a section of the community that, if not actually starving, is undernourished. These people may include refugees, international students of modest means, homeless people who often have mental health issues or drug addictions, unemployed people and low-income families with children where the income earner is in poor health.

To overcome food wastage and at the same time reach the needy, a fairly comprehensive system, staffed largely by volunteers and funded from a range of sources including some government support, has emerged. It consists of a central warehouse known as Foodshare that handles packaged and long-life food, and a central kitchen (Fareshare) that handles fresh food that would otherwise be thrown away. Fareshare produces fresh meals through a number of regional distributary warehouses, and some hundreds of front-line or 'retail agencies' (church groups, Salvation Army, municipal councils, etc.) that distribute food to the needy (Figure 6).

Foodshare (Foodbank, 2013) and Fareshare (2013) between them, and their associated 'retailers', produced some 7 million meals in 2012, at a claimed cost of 50 cents to US$1 per meal, which is perhaps 5–10% of the commercial value. At 21 meals per week for a person, that supports a population of some 330 000, or about 6% of the population of the state of Victoria in Australia. These are startling figures for a First World and affluent country, but they demonstrate that such efforts to eliminate food wastage can be significant and result in more efficient use of virtual water and energy embedded in the food products: more crop per drop.

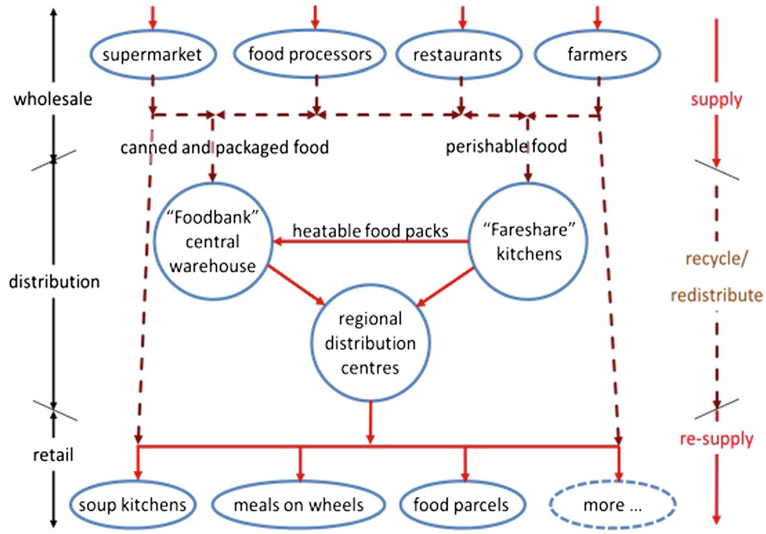

Figure 6. Food reclamation arrangements Victoria, Australia. This figure is available in colour online at wileyonlinelibrary.com/journal/ird

A further development is the rise of local 'farmers' markets' (Figure 5), often set up by organisations such as Rotary clubs. These provide an opportunity for farmers to sell fresh produce that is perfectly wholesome, but does not meet supermarket standards because it is undersized, oversized, misshapen or has surface spots from hail, etc. The produce is priced well below supermarket prices, but distribution may be costly, especially in terms of time required by the farmer. Nevertheless, one farmer claimed that if he supplied only supermarkets his business could support only one family unit and he would plough a lot of produce back into the ground, but, because he also targets farmers' markets, the business supports three families. More crop per drop; same input providing three instead of one food need; such efficiencies will go a long way to feeding our increased populations by 2050.

In developing countries similar arrangements will be possible, but perhaps at a different scale and different level of complexity. Certain elements of the food supply chain shown in Figures 5 and 6 may not exist and hence we need to peruse those food supply chains for other and additional options to save on virtual water and energy.

Major energy savings both in electricity and fossil fuels are possible if we transport our food less and consume as close as possible to the source. In areas where food production is surplus to local needs, we need to accept that some of the scale and business advantages achieved come at higher energy and potential food wastage costs.

However, do we need to produce as much surplus food, i.e. waste it? We have lost the seasonality of foods, i.e. availability of food in certain seasons only, which seems to occur when development in countries reaches tiers 3 and above in Maslow's hierarchy of needs. Availability of food outside season is a luxury, tier 5 in Maslow's hierarchy of needs. We may wish to reconsider whether we can afford this luxury in times of water shortage, rising cost of energy, and scarcity of a resources including land.

Finally, consider wastage of food at home. There is a lot we can do here by being more effective and efficient in our eating habits. We should use leftover food the next day(s), we should not buy more food than we need and consume before it spoils. This will be cheaper and leaves more food in the supermarket for use by others. If supermarkets sell less that means more food can stay at the source, which then can be used to feed other people; we save water and energy down in the supply chain, which can be distributed elsewhere. No need to produce more food in that case and thus we are more efficient and reach more people per kilogram of production. This is another example of more (consumed) crop per drop of water.

CONCLUSIONS

The water–food–energy nexus has been introduced in this article and we allude to the fact that it is only the tip of the iceberg of what ought to be considered when the objective is reduction of water, energy and food wastage. The primary purpose was to introduce the water–food–energy nexus concept that is discussed at various global forums to the ICID network. We have tried to put the nexus concept firmly in the context of the overarching food supply chain and describe the water and energy supply chains to gain insights into possible efficiency gains in quantity and quality of food production. Various examples are given. The water and energy supply chains are inextricably linked with food production. The linkage to the green economy concept, as promoted by the UN, should come naturally to primary food producers in both developed and less developed countries.

The green economy espouses due attention to the environment while producing food now and in the future. Although not given here, there are many examples where local producers, by paying a lot of attention to the local environment and also investing in the local ecology, achieved a higher level of sustainability of their primary objective of food production. The key to a green economy is social inclusion of primary producers in these deliberations. Pages are limited in this article so our next instalment will be an article on going green at the farm, being self-sufficient in food and producing environmentally friendly surplus food.

It is our social and professional duty to disseminate our insights into the water–food–energy nexus to all. We hope this article has stimulated your thinking and inspires you to produce similar and more detailed consideration of the nexus and alternative more crop per drop options.

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