Chapter 2
Aquaponics: Closing the Cycle on Limited Water, Land and Nutrient Resources

Alyssa Joyce, Simon Goddek, Benz Kotzen, and Sven Wuertz

Abstract Hydroponics initially developed in arid regions in response to freshwater shortages, while in areas with poor soil, it was viewed as an opportunity to increase productivity with fewer fertilizer inputs. In the 1950s, recirculating aquaculture also emerged in response to similar water limitations in arid regions in order to make better use of available water resources and better contain wastes. However, disposal of sludge from such systems remained problematic, thus leading to the advent of aquaponics, wherein the recycling of nutrients produced by fish as fertilizer for plants proved to be an innovative solution to waste discharge that also had economic advantages by producing a second marketable product. Aquaponics was also shown to be an adaptable and cost-effective technology given that farms could be situated in areas that are otherwise unsuitable for agriculture, for instance, on rooftops and on unused, derelict factory sites. A wide range of cost savings could be achieved through strategic placement of aquaponics sites to reduce land acquisition costs, and by also allowing farming closer to suburban and urban areas, thus reducing transportation costs to markets and hence also the fossil fuel and CO_2 footprints of production.

Keywords Aquaponics · Sustainable agriculture · Eutrophication · Soil degradation · Nutrient cycling

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2.1 Introduction

The term ‘tipping point’ is currently being used to describe natural systems that are on the brink of significant and potentially catastrophic change (Barnosky et al. 2012). Agricultural food production systems are considered one of the key ecological services that are approaching a tipping point, as climate change increasingly generates new pest and disease risks, extreme weather phenomena and higher global temperatures. Poor land management and soil conservation practices, depletion of soil nutrients and risk of pandemics also threaten world food supplies.

Available arable land for agricultural expansion is limited, and increased agricultural productivity in the past few decades has primarily resulted from increased cropping intensity and better crop yields as opposed to expansion of the agricultural landmass (e.g. 90% of gains in crop production have been a result of increased productivity, but only 10% due to land expansion) (Alexandratos and Bruinsma 2012; Schmidhuber 2010). Global population is estimated to reach 8.3–10.9 billion people by 2050 (Bringezu et al. 2014), and this growing world population, with a corresponding increase in total as well as per capita consumption, poses a wide range of new societal challenges. The United Nations Convention to Combat Desertification (UNCCD) *Global Land Outlook Working Paper* 2017 report notes worrying trends affecting food production (Thomas et al. 2017) including land degradation, loss of biodiversity and ecosystems, and decreased resilience in response to environmental stresses, as well as a widening gulf between food production and demand. The uneven distribution of food supplies results in inadequate quantities of food, or lack of food of sufficient nutritional quality for part of the global population, while in other parts of the world overconsumption and diseases related to obesity have become increasingly common. This unbalanced juxtaposition of hunger and malnutrition in some parts of the world, with food waste and overconsumption in others, reflects complex interrelated factors that include political will, resource scarcity, land affordability, costs of energy and fertilizer, transportation infrastructure and a host of other socioeconomic factors affecting food production and distribution.

Recent re-examinations of approaches to food security have determined that a ‘water-energy-food nexus’ approach is required to effectively understand, analyse and manage interactions among global resource systems (Scott et al. 2015). The nexus approach acknowledges the interrelatedness of the resource base – land, water, energy, capital and labour – with its drivers, and encourages inter-sectoral consultations and collaborations in order to balance different resource user goals and interests. It aims to maximize overall benefits while maintaining ecosystem integrity in order to achieve food security. Sustainable food production thus requires reduced utilization of resources, in particular, water, land and fossil fuels that are limited, costly and often poorly distributed in relation to population growth, as well as recycling of existing resources such as water and nutrients within production systems to minimize waste.

In this chapter, we discuss a range of current challenges in relation to food security, focusing on resource limitations and ways that new technologies and interdisciplinary approaches such as aquaponics can help address the water-food-energy nexus in relation to the UN's goals for sustainable development. We concentrate on the need for increased nutrient recycling, reductions in water consumption and non-renewable energy, as well as increased food production on land that is marginal or unsuitable for agriculture.

2.2 Food Supply and Demand

2.2.1 Predictions

Over the last 50 years, total food supply has increased almost threefold, whereas the world's population has only increased twofold, a shift that has been accompanied by significant changes in diet related to economic prosperity (Keating et al. 2014). Over the last 25 years, the world's population increased by 90% and is expected to reach the 7.6 billion mark in the first half of 2018 (Worldometers). Estimates of increased world food demand in 2050 relative to 2010 vary between 45% and 71% depending on assumptions around biofuels and waste, but clearly there is a production gap that needs to be filled. In order to avoid a reversal in recent downward trends undernourishment, there must be reductions in food demand and/or fewer losses in food production capacity (Keating et al. 2014). An increasingly important reason for rising food demand is per capita consumption, as a result of rising per capita income, which is marked by shifts towards high protein foods, particularly meat (Ehrlich and Harte 2015b). This trend creates further pressures on the food supply chain, since animal-based production systems generally require disproportionately more resources, both in water consumption and feed inputs (Rask and Rask 2011; Ridoutt et al. 2012; Xue and Landis 2010). Even though the rate of increasing food demand has declined in recent decades, if current trajectories in population growth and dietary shifts are realistic, global demand for agricultural products will grow at 1.1–1.5% per year until 2050 (Alexandratos and Bruinsma 2012).

Population growth in urban areas has put pressure on land that has been traditionally used for soil-based crops: demands for housing and amenities continue to encroach on prime agricultural land and raise its value well beyond what farmers could make from cultivation. Close to 54% of the world's population now lives in urban areas (Esch et al. 2017), and the trend towards urbanization shows no signs of abating. Production systems that can reliably supply fresh foods close to urban centres are in demand and will increase as urbanization increases. For instance, the rise of vertical farming in urban centres such as Singapore, where land is at a premium, provides a strong hint that concentrated, highly productive farming systems will be an integral part of urban development in the future. Technological advances are increasingly making indoor farming systems economical, for instance the development of LED horticultural lights that are extremely long lasting and energy efficient has increased competitiveness of indoor farming as well as production in high latitudes.

Analysis of agrobiodiversity consistently shows that high- and middle-income countries obtain diverse foods through national or international trade, but this also implies that production and food diversity are uncoupled and thus more vulnerable to interruptions in supply lines than in low-income countries where the majority of food is produced nationally or regionally (Herrero et al. 2017). Also, as farm sizes increase, crop diversity, especially for crops belonging to highly nutritious food groups (vegetables, fruits, meat), tends to decrease in favour of cereals and legumes, which again risks limiting local and regional availability of a range of different food groups (Herrero et al. 2017).

2.3 Arable Land and Nutrients

2.3.1 Predictions

Even as more food needs to be produced, usable land for agricultural practices is inherently limited to roughly 20–30% of the world's land surface. The availability of agricultural land is decreasing, and there is a shortage of suitable land where it is most needed, i.e. particularly near population centres. Soil degradation is a major contributor to this decline and can generally be categorized in two ways: displacement (wind and water erosion) and internal soil chemical and physical deterioration (loss of nutrients and/or organic matter, salinization, acidification, pollution, compaction and waterlogging). Estimating total natural and human-induced soil degradation worldwide is fraught with difficulty given the variability in definitions, severity, timing, soil categorization, etc. However, it is generally agreed that its consequences have resulted in the loss of net primary production over large areas (Esch et al. 2017), thus restricting increases in arable and permanently cropped land to 13% in the four decades from the early 1960s to late 1990s (Bruinsma 2003). More importantly in relation to population growth during that time period, arable land per capita declined by about 40% (Conforti 2011). The term 'arable land' implies availability of adequate nutrients to support crop production. To counteract nutrient depletion, worldwide fertilizer consumption has risen from 90 kg/ha in 2002 to 135 kg in 2013 (Pocketbook 2015). Yet the increased use of fertilizers often results in excesses of nitrate and phosphates ending up in aquatic ecosystems (Bennett et al. 2001), causing algal blooms and eutrophication when decaying algal biomass consumes oxygen and limits the biodiversity of aquatic life. Large-scale nitrate and phosphate-induced environmental changes are particularly evident in watersheds and coastal zones.

Nitrogen, potassium and phosphorus are the three major nutrients essential for plant growth. Even though demand for phosphorus fertilizers continues to grow exponentially, rock phosphate reserves are limited and estimates suggest they will be depleted within 50–100 years (Cordell et al. 2011; Steen 1998; Van Vuuren et al. 2010). Additionally, anthropogenic nitrogen input is expected to drive terrestrial ecosystems towards greater phosphorous limitations, although a better understanding of the processes is critical (Deng et al. 2017; Goll et al. 2012; Zhu et al. 2016). Currently, there are no substitutes for phosphorus in agriculture, thus putting constraints on future agricultural productivity that relies on key fertilizer input of mined phosphate (Sverdrup and Ragnarsdottir 2011). The 'P-paradox', in other words, an excess of P impairing water quality, alongside its shortage as a depleting non-renewable resource, means that there must be substantial increases in recycling and efficiency of its use (Leinweber et al. 2018).

Modern intensive agricultural practices, such as the frequency and timing of tillage or no-till, application of herbicides and pesticides, and infrequent addition of organic matter containing micronutrients can alter soil structure and its microbial biodiversity such that the addition of fertilizers no longer increases productivity per hectare. Given that changes in land usage have resulted in losses of soil organic carbon estimated to be around 8%, and projected losses between 2010 and 2050 are 3.5 times that figure, it is assumed that soil water-holding capacity and nutrient losses will continue, especially in view of global warming (Esch et al. 2017). Obviously there are trade-offs between satisfying human needs and not compromising the ability of the biosphere to support life (Foley et al. 2005). However, it is clear when modelling planetary boundaries in relation to current land use practices that it is necessary to improve N and P cycling, principally by reducing both nitrogen and phosphorus emissions and runoff from agricultural land, but also by better capture and reuse (Conijn et al. 2018).

2.3.2 Aquaponics and Nutrients

One of the principal benefits of aquaponics is that it allows for the recycling of nutrient resources. Nutrient input into the fish component derives from feed, the composition of which depends on the target species, but feed in aquaculture typically constitutes a significant portion of input costs and can be more than half the total annual cost of production. In certain aquaponics designs, bacterial biomass can also be harnessed as feed, for instance, where biofloc production makes aquaponic systems increasingly self-contained (Pinho et al. 2017).

Wastewater from open-cage pens or raceways is often discharged into waterbodies, where it results in nutrient pollution and subsequent eutrophication. By contrast, aquaponic systems take the dissolved nutrients from uneaten fish feed and faeces, and utilizing microbes that can break down organic matter, convert the nitrogen and phosphorous into bioavailable forms for use by plants in the hydroponics unit. In order to achieve economically acceptable plant production levels, the presence of appropriate microbial assemblages reduces the need to add much of the supplemental nutrients that are routinely used in stand-alone hydroponic units. Thus aquaponics is a near-zero discharge system that offers not only economic benefit from both fish and plant production streams, but also significant reductions in both environmentally noxious discharges from aquaculture sites. It also eliminates the problem of N- and P-rich runoff from fertilizers used in soil-based agriculture. In decoupled aquaponic systems, aerobic or anaerobic bioreactors can also used to treat sludge and recover significant macro- and micronutrients in bioavailable forms for subsequent use in hydroponic production (Goddek et al. 2018) (see Chap. 8). Exciting new developments such as these, many of which are now being realized for commercial prodution, continue to refine the circular economy concept by increasingly allowing for nutrient recovery.

2.4 Pest, Weed and Disease Control

2.4.1 Predictions

It is generally recognized that control of diseases, pests and weeds is a critical component of curbing production losses that threaten food security (Keating et al. 2014). In fact, increasing the use of antibiotics, insecticides, herbicides and fungicides to cut losses and enhance productivity has allowed dramatic increases in agricultural output in the latter half of the twentieth century. However, these practices are also linked to a host of problems: pollution from persistent organic compounds in soils and irrigation water, changes in rhizobacterial and mycorrhizal activity in soils, contamination of crops and livestock, development of resistant strains, detrimental effects on pollinators and a wide range of human health risks (Bringezu et al. 2014; Ehrlich and Harte 2015a; Esch et al. 2017; FAO 2015b). Tackling pest, weed and disease control in ways that reduce the use of these substances is mentioned in virtually every call to provide food security for a growing world population.

2.4.2 Control of Pests, Weeds and Diseases

As a closed system with biosecurity measures, aquaponic systems require far fewer chemical pesticide applications in the plant component. If seed and transplant stocks are carefully handled and monitored, weed, fungal and bacterial/algal contaminants can be controlled in hydroponic units with targeted measures rather than the widespread preventive application of herbicides and fungicides prevalent in soil-based agriculture. As technology continues to advance, developments such as positive pressure greenhouses can further reduce pest problems (Mears and Both 2001). Design features to reduce pest risks can cut costs in terms of chemicals, labour, application time and equipment, especially since the land footprint of industrial-scale aquaponics systems is small, and systems are compact and tightly contained, as compared to the equivalent open production area of vegetable and fruit crops of conventional soil-based farms.

The use of RAS in aquaponic systems also prevents disease transmissions between farmed stocks and wild populations, which is a pressing concern in flow-through and open-net pen aquaculture (Read et al. 2001; Samuel-Fitwi et al. 2012). Routine antibiotic use is generally not required in the RAS component, since it is a closed system with few available vectors for disease introduction. Furthermore, the use of antimicrobials and antiparasitics is generally discouraged, as it can be detrimental to the microbiota that are crucial for converting organic and inorganic wastes into usable compounds for plant growth in the hydroponic unit (Junge et al. 2017). If disease does emerge, containment of both fish and plants from the surrounding environment makes decontamination and eradication more manageable. Although closed systems clearly do not completely alleviate all disease and pest problems (Goddek et al. 2015), proper biocontrol measures that are already practised in stand-alone RAS and hydroponics result in significant reductions of risk. These issues are discussed in further detail in subsequent chapters (for fish, see Chap. 6; for plants, further details in Chap. 14).

2.5 Water Resources

2.5.1 Predictions

In addition to requiring fertilizer applications, modern intensive agricultural practices also place high demands on water resources. Among biochemical flows (Fig. 2.1), water scarcity is now believed to be one of the most important factors constraining food production (Hoekstra et al. 2012; Porkka et al. 2016). Projected global population increases and shifts in terrestrial water availability due to climate change, demand more efficient use of water in agriculture. As noted previously, by 2050, aggregate agriculture production will need to produce 60% more food globally (Alexandratos and Bruinsma 2012), with an estimated 100% more in developing countries, based on population growth and rising expectations for standards of living (Alexandratos and Bruinsma 2012; WHO 2015). Famine in some regions of the world, as well as malnutrition and hidden hunger, indicates that the balance between food demand and availability has already reached critical levels, and that food and water security are directly linked (McNeill et al. 2017). Climate change predictions suggest reduced freshwater availability, and a corresponding decrease in agricultural yields by the end of the twenty-first century (Misra 2014).

The agriculture sector currently accounts for roughly 70% of the freshwater use worldwide, and the withdrawal rate even exceeds 90% in most of the world's least-developed countries. Water scarcity will increase in the next 25 years due to expected population growth (Connor et al. 2017; Esch et al. 2017), with the latest

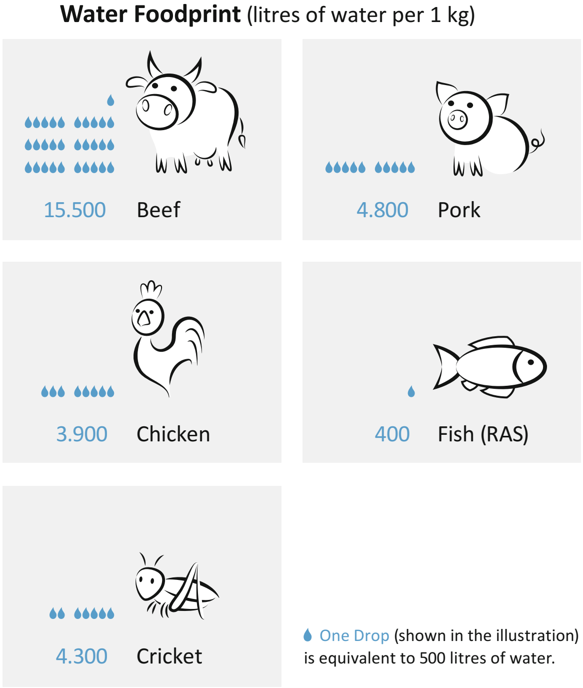

Fig. 2.1 Water footprint (L per kg). Fish in RAS systems use the least water of any food production system

modelling forecasting declining water availability in the near future for nearly all countries (Distefano and Kelly 2017). The UN predicts that the pursuit of business-as-usual practices will result in a global water deficit of 40% by 2030 (Water 2015). In this respect, as groundwater supplies for irrigation are depleted or contaminated, and arid regions experience more drought and water shortages due to climate change, water for agricultural production will become increasingly valuable (Ehrlich and Harte 2015a). Increasing scarcity of water resources compromises not only water security for human consumption but also global food production (McNeill et al. 2017). Given that water scarcity is expected even in areas that currently have relatively sufficient water resources, it is important to develop agricultural techniques with low water input requirements, and to improve ecological management of wastewater through better reuse (FAO 2015a).

The UN World Water Development Report for 2017 (Connor et al. 2017) focuses on wastewater as an untapped source of energy, nutrients and other useful by-products, with implications not only for human and environmental health but also for food and energy security as well as climate change mitigation. This report calls for appropriate and affordable technologies, along with legal and regulatory frameworks, financing mechanisms and increased social acceptability of wastewater treatment, with the goal of achieving water reuse within a circular economy. The report also points to a 2016 World Economic Forum report that lists the water crisis as the global risk of highest concern in the next 10 years.

The concept of a water footprint as a measure of humans' use of freshwater resources has been put forwards in order to inform policy development on water use. A water footprint has three components: (1) blue water, which comprises the surface and groundwater consumed while making products or lost through evaporation, (2) green water that is rainwater used especially in crop production and (3) grey water, which is water that is polluted but still within existing water quality standards (Hoekstra and Mekonnen 2012). These authors mapped water footprints of countries worldwide and found that agricultural production accounts for 92% of global freshwater use, and industrial production uses 4.4% of the total, while domestic water only 3.6%. This raises concerns about water availability and has resulted in public education efforts aimed at raising awareness about the amounts of water required to produce various types of food, as well as national vulnerabilities, especially in water-scarce countries in North Africa and the Middle East.

2.5.2 Aquaponics and Water Conservation

The economic concept of comparative productivity measures the relative amount of a resource needed to produce a unit of goods or services. Efficiency is generally construed to be higher when the requirement for resource input is lower per unit of goods and services. However, when water-use efficiency is examined in an environmental context, water quality also needs to be taken into account, because maintaining or enhancing water quality also enhances productivity (Hamdy 2007).

The growing problem of water scarcity demands improvements in water-use efficiencies especially in arid and semiarid regions, where availability of water for agriculture, and water quality of discharge, are critical factors in food production. In these regions, recirculation of water in aquaponic units can achieve remarkable water re-use efficiency of 95–99% (Dalsgaard et al. 2013). Water demand is also less than 100 L/kg of fish harvested, and water quality is maintained within the system for production of crops (Goddek et al. 2015). Obviously, such systems must be constructed and operated to minimize water losses; they must also optimize their ratios of fish water to plants, as this ratio is very important in maximizing water re-use efficiency and ensuring maximal nutrient recycling. Modelling algorithms and technical solutions are being developed to integrate improvements in individual units, and to better understand how to effectively and efficiently manage water (Vilbergsson et al. 2016). Further information is provided in Chaps. 9 and 11.

In light of soil, water and nutrient requirements, the water footprint of aquaponic systems is considerably better than traditional agriculture, where water quality and demand, along with availability of arable land, costs of fertilizers and irrigation are all constraints to expansion (Fig. 2.1).

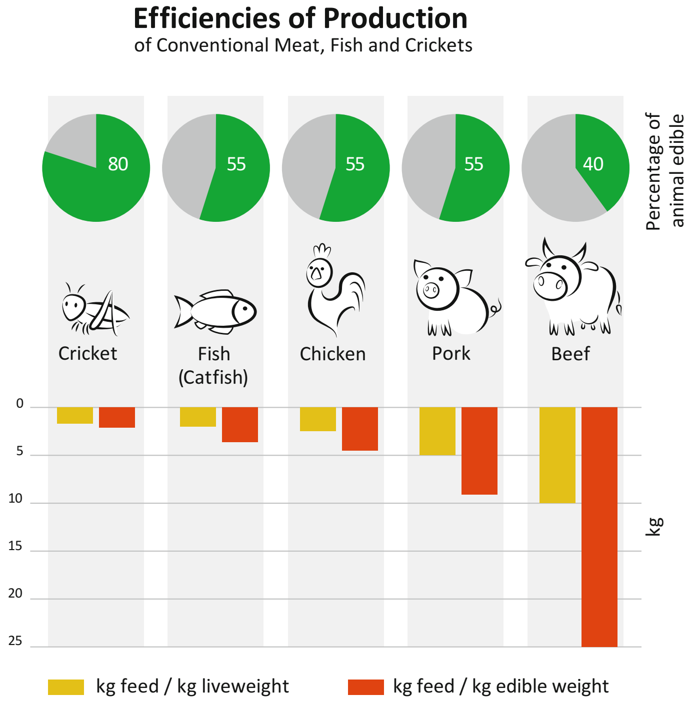

Fig. 2.2 Feed conversion ratios (FCRs) based as kg of feed per live weight and kg of feed for edible portion. Only insects, which are eaten whole in some parts of the world, have a better FCR than fish

2.6 Land Utilization

2.6.1 Predictions

Globally, land-based crops and pasture occupy approximately 33% of total available land, and expansion for agricultural uses between 2000 and 2050 is estimated to increase by 7–31% (350–1500 Mha, depending on source and underlying assumptions), most often at the expense of forests and wetlands (Bringezu et al. 2014). While there is currently still land classed as ‘good’ or ‘marginal’ that is available for rain-fed agriculture, significant portions of it are far from markets, lack infrastructure or have endemic diseases, unsuitable terrain or other conditions that limit development potential. In other cases, remaining lands are already protected, forested or developed for other uses (Alexandratos and Bruinsma 2012). By contrast, dryland ecosystems, defined in the UN’s Commission on Sustainable Development as arid, semiarid and dry subhumid areas that typically have low productivity, are threatened by desertification and are therefore unsuitable for agricultural expansion but nevertheless have many millions of people living in close proximity (Economic 2007). These facts point to the need for more sustainable intensification of food production closer to markets, preferably on largely unproductive lands that may never become suitable for soil-based farming.

The two most important factors contributing to agricultural input efficiencies are considered by some experts to be (i) the location of food production in areas where climatic (and soil) conditions naturally increase efficiencies and (ii) reductions in environmental impacts of agricultural production (Michael and David 2017). There must be increases in the supply of cultivated biomass achieved through the intensification of production per hectare, accompanied by a diminished environmental burden (e.g. degradation of soil structure, nutrient losses, toxic pollution). In other words, the footprint of efficient food production must shrink while minimizing negative environmental impacts.

2.6.2 Aquaponics and Land Utilization

Aquaponic production systems are soilless and attempt to recycle essential nutrients for cultivation of both fish and plants, thereby using nutrients in organic matter from fish feed and wastes to minimize or eliminate the need for plant fertilizers. For instance, in such systems, using land to mine, process, stockpile and transport phosphate or potash-rich fertilizers becomes unnecessary, thus also eliminating the inherent cost, and cost of application, for these fertilizers.

Aquaponics production contributes not only to water usage efficiency (Sect. 2.5.2) but also to agricultural input efficiency by reducing the land footprint needed for production. Facilities for instance, can be situated on nonarable land and in suburban or urban areas closer to markets, thus reducing the carbon footprint associated with rural farms and transportation of products to city markets. With a smaller footprint, production capacity can be located in otherwise unproductive areas such as on rooftops or old factory sites, which can also reduce land acquisition costs if those areas are deemed unsuitable for housing or retail businesses. A smaller footprint for production of high-quality protein and vegetables in aquaponics can also take pressure away from clearing ecologically valuable natural and semi-natural areas for conventional agriculture.

2.7 Energy Resources

2.7.1 Predictions

As mechanization spreads globally, open-field intensive agriculture increasingly relies heavily on fossil fuels to power farm machinery and for transportation of fertilizers as well as farm products, as well as to run the equipment for processing, packaging and storage. In 2010, the OECD International Energy Agency predicted that global energy consumption would grow by up to 50% by 2035; the FAO has also estimated that 30% of global energy consumption is devoted to food production and its supply chain (FAO 2011). Greenhouse gas (GHG) emissions associated with fossil fuels (approximately 14% in lifecycle analysis) added to those from fertilizer manufacturing (16%) and nitrous oxide from average soils (44%) (Camargo et al. 2013), all contribute substantially to the environmental impacts of farming. A trend in the twenty-first century to produce crop-based biofuels (e.g. corn for ethanol) to replace fossil fuels has increased pressure on the clearing of rainforests, peatlands, savannas and grasslands for agricultural production. However, studies point to creation of a 'carbon debt' from such practices, since the overall release of CO_2 exceeds the reductions in GHGs they provide by displacing fossil fuels (Fargione et al. 2008). Arguably a similar carbon debt exists when clearing land to raise food crops via conventional agriculture that relies on fossil fuels.

In a comparative analysis of agricultural production systems, trawling fisheries and recirculating aquaculture systems (RAS) were found to emit GHGs 2–2.5 times that of non-trawling fisheries and non-RAS (pen, raceway) aquaculture. In RAS, these energy requirements relate primarily to the functioning of pumps and filters (Michael and David 2017). Similarly, greenhouse production systems can emit up to three times more GHGs than open-field crop production if energy is required to maintain heat and light within optimal ranges (ibid.). However, these GHG figures do not take into account other environmental impacts of non-RAS systems, such as eutrophication or potential pathogen transfers to wild stocks. Nor do they consider GHG from the production, transportation and application of herbicides and pesticides used in open-field cultivation, nor methane and nitrous oxide from associated livestock production, both of which have a 100-year greenhouse warming potential (GWP) 25 and 298 times that of CO_2, respectively (Camargo et al. 2013; Eggleston et al. 2006).

These sobering estimates of present and future energy consumption and GHG emissions associated with food production have prompted new modelling and approaches, for example, the UN's water-food-energy nexus approach mentioned in Sect. 2.1. The UN's Sustainable Development Goals have pinpointed the vulnerability of food production to fluctuations in energy prices as a key driver of food insecurity. This has prompted efforts to make agrifood systems 'energy smart' with an emphasis on improving energy efficiencies, increasing use of renewable energy sources and encouraging integration of food and energy production (FAO 2011).

2.7.2 Aquaponics and Energy Conservation

Technological advances in aquaponic system operations are moving towards being increasingly 'energy smart' and reducing the carbon debt from pumps, filters and heating/cooling devices by using electricity generated from renewable sources. Even in temperate latitudes, many new designs allow the energy involved in heating and cooling of fish tanks and greenhouses to be fully reintegrated, such that these systems do not require inputs beyond solar arrays or the electricity/heat generated from bacterial biogas production of aquaculture-derived sludge (Ezebuiro and Körner 2017; Goddek and Keesman 2018; Kloas et al. 2015; Yogev et al. 2016). In addition, aquaponic systems can use microbial denitrification to convert nitrous oxide to nitrogen gas if enough carbon sources from wastes are available, such that heterotrophic and facultative anaerobic bacteria can convert excess nitrates to nitrogen gas (Van Rijn et al. 2006). As noted in Sect. 2.7.1, nitrous oxide is a potent GHG and microbes already present in closed aquaponics systems can facilitate its conversion into nitrogen gas.

2.8 Summary

As the human population continues to increase, there is increasing demand for high-quality protein worldwide. Compared to meat sources, fish are widely recognized as being a particularly healthy source of protein. In relation to the world food supply, aquaculture now provides more fish protein than capture fisheries (FAO 2016). Globally, human per capita fish consumption continues to rise at an annual average rate of 3.2% (1961–2013), which is double the rate of population growth. In the period from 1974 to 2013, biologically unsustainable 'overfishing' has increased by 22%. During the same period, the catch from what are deemed to be 'fully exploited' fisheries has decreased by 26%. Aquaculture therefore provides the only possible solution for meeting increased market demand. It is now the fastest growing food sector and therefore an important component of food security (ibid.)

With the global population estimated to reach 8.3–10.9 billion people by 2050 (Bringezu et al. 2014), sustainable development of the aquaculture and agricultural sectors requires optimization in terms of production efficiency, but also reductions in utilization of limited resources, in particular, water, land and fertilizers. The benefits of aquaponics relate not just to the efficient uses of land, water and nutrient resources but also allow for increased integration of smart energy opportunities such as biogas and solar power. In this regard, aquaponics is a promising technology for producing both high-quality fish protein and vegetables in ways that can use substantially less land, less energy and less water while also minimizing chemical and fertilizer inputs that are used in conventional food production.

References

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/50: the 2012 revision, ESA Work. Paper 12–03. UN Food Agriculture Organization (FAO), Rome

Barnosky AD, Hadly EA, Bascompte J, Berlow EL, Brown JH, Fortelius M, Getz WM, Harte J, Hastings A, Marquet PA (2012) Approaching a state shift in Earth/'s biosphere. Nature 486:52–58

Bennett EM, Carpenter SR, Caraco NF (2001) Human impact on erodable phosphorus and eutrophication: a global perspective: increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication. AIBS Bull 51:227–234

Bringezu S, Schütz H, Pengue W, OBrien M, Garcia F, Sims R (2014) Assessing global land use: balancing consumption with sustainable supply. UNEP/International Resource Panel, Nairobi/ Paris

Bruinsma J (2003) World agriculture: towards 2015/2030: an FAO perspective. Earthscan, London

Camargo GG, Ryan MR, Richard TL (2013) Energy use and greenhouse gas emissions from crop production using the farm energy analysis tool. Bioscience 63:263–273

Conforti P (2011) Looking ahead in world food and agriculture: perspectives to 2050. Food and Agriculture Organization of the United Nations (FAO), Rome

Conijn J, Bindraban P, Schröder J, Jongschaap R (2018) Can our global food system meet food demand within planetary boundaries? Agric Ecosyst Environ 251:244–256

Connor R, Renata A, Ortigara C, Koncagül E, Uhlenbrook S, Lamizana-Diallo BM, Zadeh SM, Qadir M, Kjellén M, Sjödin J (2017) The United Nations world water development report 2017. In: Wastewater: the untapped resource, The United Nations world water development report. UNESCO, Paris

Cordell D, Rosemarin A, Schröder J, Smit A (2011) Towards global phosphorus security: a systems framework for phosphorus recovery and reuse options. Chemosphere 84:747–758

Dalsgaard J, Lund I, Thorarinsdottir R, Drengstig A, Arvonen K, Pedersen PB (2013) Farming different species in RAS in Nordic countries: current status and future perspectives. Aquac Eng 53:2–13

Deng Q, Hui D, Dennis S, Reddy KC (2017) Responses of terrestrial ecosystem phosphorus cycling to nitrogen addition: a meta-analysis. Glob Ecol Biogeogr 26:713–728

Distefano T, Kelly S (2017) Are we in deep water? Water scarcity and its limits to economic growth. Ecol Econ 142:130–147

Economic UNDo (2007) Indicators of sustainable development: guidelines and methodologies. United Nations Publications, New York

Eggleston H, Buendia L, Miwa K, Ngara T, Tanabe K (2006) IPCC guidelines for national greenhouse gas inventories. Inst Glob Environ Strateg, Hayama, Japan 2:48–56

Ehrlich PR, Harte J (2015a) Food security requires a new revolution. Int J Environ Stud 72:908–920

Ehrlich PR, Harte J (2015b) Opinion: to feed the world in 2050 will require a global revolution. Proc Natl Acad Sci 112:14743–14744

Esch Svd, Brink Bt, Stehfest E, Bakkenes M, Sewell A, Bouwman A, Meijer J, Westhoek H, Berg Mvd, Born GJvd (2017) Exploring future changes in land use and land condition and the impacts on food, water, climate change and biodiversity: scenarios for the UNCCD Global Land Outlook. PBL Netherlands Environmental Assessment Agency, The Hague

Ezebuiro NC, Körner I (2017) Characterisation of anaerobic digestion substrates regarding trace elements and determination of the influence of trace elements on the hydrolysis and acidification phases during the methanisation of a maize silage-based feedstock. J Environ Chem Eng 5:341–351

FAO (2011) Energy-smart food for people and climate. Food and Agriculture Organization of the United Nations, Rome

FAO (2015a) Environmental and social management guidelines. Food and Agriculture Organization of the United Nations, Rome

FAO (2015b) Statistical pocketbook 2015. Food and Agriculture Organization of the United Nations, Rome

FAO (2016) The state of world fisheries and aquaculture 2016. Contributing to food security and nutrition for all. Food and Agriculture Organization of the United Nations, Rome, p 200

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. Science 319:1235–1238

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK (2005) Global consequences of land use. Science 309:570–574

Goddek S, Keesman KJ (2018) The necessity of desalination technology for designing and sizing multi-loop aquaponics systems. Desalination 428:76–85

Goddek S, Delaide B, Mankasingh U, Ragnarsdottir KV, Jijakli H, Thorarinsdottir R (2015) Challenges of sustainable and commercial aquaponics. Sustainability 7:4199–4224

Goddek S, Delaide BPL, Joyce A, Wuertz S, Jijakli MH, Gross A, Eding EH, Bläser I, Reuter M, Keizer LCP, Morgenstern R, Körner O, Verreth J, Keesman KJ (2018) Nutrient mineralization and organic matter reduction performance of RAS-based sludge in sequential UASB-EGSB reactors. Aquac Eng 83:10–19. https://doi.org/10.1016/J.AQUAENG.2018.07.003

Goll DS, Brovkin V, Parida B, Reick CH, Kattge J, Reich PB, Van Bodegom P, Niinemets Ü (2012) Nutrient limitation reduces land carbon uptake in simulations with a model of combined carbon, nitrogen and phosphorus cycling. Biogeosciences 9:3547–3569

Hamdy A (2007) Water use efficiency in irrigated agriculture: an analytical review. Water use efficiency and water productivity: WASAMED project, pp 9–19

Herrero M, Thornton PK, Power B, Bogard JR, Remans R, Fritz S, Gerber JS, Nelson G, See L, Waha K (2017) Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planetary Health 1:e33–e42

Hoekstra AY, Mekonnen MM (2012) The water footprint of humanity. Proc Natl Acad Sci 109:3232–3237

Hoekstra AY, Mekonnen MM, Chapagain AK, Mathews RE, Richter BD (2012) Global monthly water scarcity: blue water footprints versus blue water availability. PLoS One 7:e32688

Junge R, König B, Villarroel M, Komives T, Jijakli MH (2017) Strategic points in aquaponics. Water 9:182

Keating BA, Herrero M, Carberry PS, Gardner J, Cole MB (2014) Food wedges: framing the global food demand and supply challenge towards 2050. Glob Food Sec 3:125–132

Kloas W, Groß R, Baganz D, Graupner J, Monsees H, Schmidt U, Staaks G, Suhl J, Tschirner M, Wittstock B, Wuertz S, Zikova A, Rennert B (2015) A new concept for aquaponic systems to improve sustainability, increase productivity, and reduce environmental impacts. Aquac Environ Interact 7:179–192

Leinweber P, Bathmann U, Buczko U, Douhaire C, Eichler-Löbermann B, Frossard E, Ekardt F, Jarvie H, Krämer I, Kabbe C (2018) Handling the phosphorus paradox in agriculture and natural ecosystems: scarcity, necessity, and burden of P. Ambio 47:3–19

McNeill K, Macdonald K, Singh A, Binns AD (2017) Food and water security: analysis of integrated modeling platforms. Agric Water Manag 194:100–112

Mears D, Both A (2001) A positive pressure ventilation system with insect screening for tropical and subtropical greenhouse facilities. Int Symp Des Environ Control Trop Subtrop Greenh 578:125–132

Michael C, David T (2017) Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environ Res Lett 12:064016

Misra AK (2014) Climate change and challenges of water and food security. Int J Sustain Built Environ 3:153–165

Pinho SM, Molinari D, de Mello GL, Fitzsimmons KM, Emerenciano MGC (2017) Effluent from a biofloc technology (BFT) tilapia culture on the aquaponics production of different lettuce varieties. Ecol Eng 103:146–153

Pocketbook FS (2015) World food and agriculture (2015). Food and Agriculture Organization of the United Nations, Rome

Porkka M, Gerten D, Schaphoff S, Siebert S, Kummu M (2016) Causes and trends of water scarcity in food production. Environ Res Lett 11:015001

Rask KJ, Rask N (2011) Economic development and food production–consumption balance: a growing global challenge. Food Policy 36:186–196

Read P, Fernandes T, Miller K (2001) The derivation of scientific guidelines for best environmental practice for the monitoring and regulation of marine aquaculture in Europe. J Appl Ichthyol 17:146–152

Ridoutt BG, Sanguansri P, Nolan M, Marks N (2012) Meat consumption and water scarcity: beware of generalizations. J Clean Prod 28:127e133

Samuel-Fitwi B, Wuertz S, Schroeder JP, Schulz C (2012) Sustainability assessment tools to support aquaculture development. J Clean Prod 32:183–192

Schmidhuber J (2010) FAO's long-term outlook for global agriculture–challenges, trends and drivers. International Food & Agriculture Trade Policy Council

Scott CA, Kurian M, Wescoat JL Jr (2015) The water-energy-food nexus: enhancing adaptive capacity to complex global challenges, Governing the nexus. Springer, Cham, pp 15–38

Steen I (1998) Management of a non-renewable resource. Phosphorus Potassium 217:25–31

Sverdrup HU, Ragnarsdottir KV (2011) Challenging the planetary boundaries II: assessing the sustainable global population and phosphate supply, using a systems dynamics assessment model. Appl Geochem 26:S307–S310

Thomas, R., Reed, M., Clifton, K., Appadurai, A., Mills, A., Zucca, C., Kodsi, E., Sircely, J., Haddad, F., vonHagen, C., 2017. Scaling up sustainable land management and restoration of degraded land

Van Rijn J, Tal Y, Schreier HJ (2006) Denitrification in recirculating systems: theory and applications. Aquac Eng 34:364–376

Van Vuuren DP, Bouwman AF, Beusen AH (2010) Phosphorus demand for the 1970–2100 period: a scenario analysis of resource depletion. Glob Environ Chang 20:428–439

Vilbergsson B, Oddsson GV, Unnthorsson R (2016) Taxonomy of means and ends in aquaculture production–part 2: the technical solutions of controlling solids, dissolved gasses and pH. Water 8:387

Water U (2015) Water for a sustainable world, The United Nations world water development report. United Nations Educational, Scientific and Cultural Organization, Paris

WHO (2015) Progress on sanitation and drinking water: 2015 update and MDG assessment. World Health Organization, Geneva

Xue X, Landis AE (2010) Eutrophication potential of food consumption patterns. Environ Sci Technol 44:6450–6456

Yogev U, Barnes A, Gross A (2016) Nutrients and energy balance analysis for a conceptual model of a three loops off grid, aquaponics. Water 8:589

Zhu Q, Riley W, Tang J, Koven C (2016) Multiple soil nutrient competition between plants, microbes, and mineral surfaces: model development, parameterization, and example applications in several tropical forests. Biogeosciences 13:341