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# The Quadruple Squeeze: Defining the safe operating space for freshwater use to achieve a triply green revolution in the Anthropocene

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**Abstract** Humanity has entered a new phase of sustainability challenges, the Anthropocene, in which human development has reached a scale where it affects vital planetary processes. Under the pressure from a quadruple squeeze—from population and development pressures, the anthropogenic climate crisis, the anthropogenic ecosystem crisis, and the risk of deleterious tipping points in the Earth system—the degrees of freedom for sustainable human exploitation of planet Earth are severely restrained. It is in this reality that a new green revolution in world food production needs to occur, to attain food security and human development over the coming decades. Global freshwater resources are, and will increasingly be, a fundamental limiting factor in feeding the world. Current water vulnerabilities in the regions in most need of large agricultural productivity improvements are projected to increase under the pressure from global environmental change. The sustainability challenge for world agriculture has to be set within the new global sustainability context. We present new proposed sustainability criteria for world agriculture, where world food production systems are transformed in order to allow humanity to stay within the safe operating space of planetary boundaries. In order to secure global resilience and thereby raise the chances of planet Earth to remain in the current desired state, conducive for human development on the long-term, these planetary boundaries need to be respected. This calls for a triply green revolution, which not only more than doubles food production in many regions of the world, but which also is environmentally sustainable, and invests in the untapped opportunities to use green water in rainfed agriculture as a key source of future productivity enhancement. To achieve such a global transformation of agriculture, there is a need for more innovative options for water interventions at the landscape scale, accounting for both green and blue water, as well as a new focus on cross-scale interactions, feed-backs and risks for unwanted regime shifts in the agro-ecological landscape.

## INTRODUCTION

Humanity has reached the global phase of sustainability challenges. Growing evidence over the past decade shows that mankind is causing undesired environmental impacts at regional to planetary scales (Steffen et al. 2004). It is increasingly clear that humanity embarked on the “great acceleration” of the human enterprise in the mid 1950s when the industrial metabolism reached a critical scale, with negative impacts on the environment accelerating, and causing, for the first time in human history, ecological impacts at a global level. These environmental trends show an abrupt “hockey-stick” shape, where centuries of relatively slow and linear change (equivalent to the shaft), abruptly shift in a negative direction over a short time period (equivalent to the blade), creating multiple hockey stick shapes for fundamental ecosystem functions such as climate regulation, land productivity, freshwater flows, and biodiversity, and for ecosystem services, such as fisheries and terrestrial foods.

In the last decade, the understanding of the integrated risks from these multiple, accelerated pressures has improved, and has also been observed in terms of impacts on large scale ecosystems on the planet (Carpenter et al. 2009; Eisenman and Wettlaufer 2009; Reid et al. 2009; Shakhova et al. 2010). It has now been established that the Earth system functions as an integrated, self-regulating and complex system (Lovelock 2006), but there is still limited knowledge of the earth system forces in play, particularly in terms of feedback dynamics, when multiple environmental hockey sticks play—as they certainly often do–as a well-trained hockey team at a planetary level. The ecological resilience of the Earth system to the human induced energy imbalance in the climate system due to emissions of carbon dioxide, is an important example of this interplay between biophysical processes on the planet that are subject to exponential negative trends. Roughly 50% of our global emissions of carbon dioxide are absorbed by terrestrial land systems and the oceans, providing a gigantic buffer to a planetary disturbance of the climate system. At the same time, the ecological trendlines for the world's oceans and land areas show negative "hockey stick" patterns for critical parameters affecting the long-term ability of these systems to sequester carbon, e.g., trends of rapid rise in eutrophication, overfishing, and land degradation.

Conceptually, therefore, we can talk of a new phase in the quest for sustainable development. We have entered the global era of sustainability, with evidence that humanity is hitting hard wired processes at the planetary level. This means that human development cannot—as one may argue it could until 50 years ago—be separated from the global commons, such as the climate system, the global freshwater cycle, and the global nutrient cycles. It also means that an integrated social-ecological approach to human development is required, which moreover integrates the importance of resilience and the capacity of systems to remain in a—for humans—desired state without crossing thresholds and falling, often abruptly and irreversibly, into undesired states.

It is thus in the Anthropocene that the challenge of feeding humanity needs to be resolved. The number of hungry in the world remains at approximately one billion people, and in order to feed the world in 2050 global food production may have to increase by at least 70% (IAASTD 2009). This requires nothing less than a new green revolution, which moreover will have to occur mostly in the world's most social-ecologically vulnerable regions. Finite land and freshwater resources will form the limiting factors for this challenge. This paper explores the boundaries that define the challenge of meeting the freshwater needs to feed a world in 2050 in the Anthropocene.

## THE QUADRUPLE SQUEEZE

This "new" social-ecological challenge is complex, and can—in a simplified form—be conceptualised as a "quadruple squeeze" on humanity's ability to secure long term sustainable development on planet Earth (Fig. 1). The first squeeze consists of the demographic growth requirements, which arises from the projected expansion of the current 6.8 billion people in the world to a population that is projected to surpass nine billion in only 40 years (UN DESA 2009). Moreover, the planetary pressure from the demographic squeeze is characterized by a 20/80 dilemma, with the old "industrialized" and rich economies which represent only a minority on the planet (the 20% of the world's population that predominantly suffer from what Ashok Khosla, president of the IUCN, has defined as "affluencia", Ashok Khosla, personal communication) having caused the bulk of the historic acceleration of environmental pressures on the planet, while the poor majority (80% of the world's population suffering from "povertitis", Ashok Khosla, personal communication) are most vulnerable to the impacts of global environmental degradation, and are—at least to a significant extent—on a positive development trajectory towards improved human welfare and economic growth (Rockström et al. 2010a). However, the trend so far, is that this positive development momentum occurs in an unsustainable way, contributing to a major acceleration, petrifying the hockey stick pattern, of negative pressures on the planet.

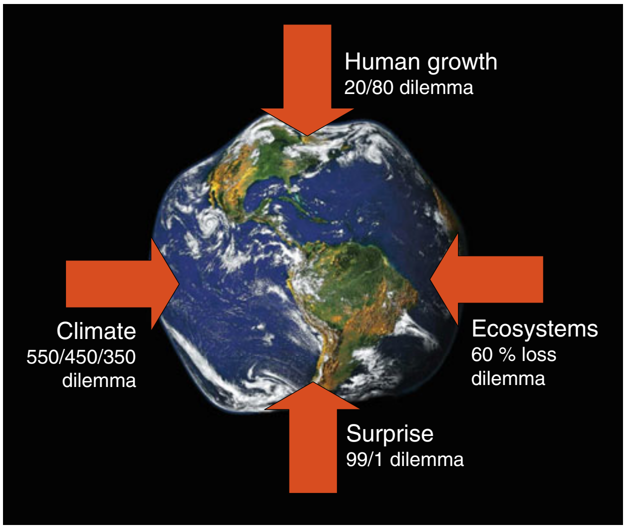

**Fig. 1** A quadruple squeeze on humanity's ability to secure long term sustainable development on planet Earth

The second squeeze consists of the global anthropogenic climate crisis, which, despite being only one among several global environmental challenges, occurs globally, affects essentially all other biophysical systems on the planet, and may trigger fundamental shifts in preconditions for human development. The climate "squeeze" is characterised by a dilemma represented here by 550/450/350. The policy interpretation of the IPCC 4th assessment report (AR4) is that a stabilisation of the concentration of CO2 at 450 ppm may provide a good enough chance of avoiding a global average temperature increase exceeding 2°C (considered as a threshold for dangerous climate change) (WBGU 2009). Projections indicate that the world is rapidly moving towards concentrations of 550 ppm and beyond (International Energy Agency 2008; Richardson et al. 2009). Post-IPCC AR4 science suggests that the systems on Earth may be more sensitive to anthropogenic warming than previously thought, e.g., when including feedbacks caused by surface albedo change from melting ice sheets, which indicate that a stabilisation at 350 ppm in fact may be necessary to reduce risks of dangerous climate change (Hansen et al. 2008). We have today reached 390 ppm.

Anthropogenic climate change is a major disturbance regime on the planet, which one would have hoped occurred at a state of high planetary resilience. Unfortunately, evidence indicates that this is not the case, and that we in fact face a global ecosystem crisis—the third squeeze—simultaneously with the global climate crisis. The UN Millennium Ecosystem Assessment (MEA 2005) showed that humans have accelerated the degradation of ecosystems during the past 50 years, deteriorating the capacity of 60% of key ecosystem functions and services to continue delivering human wellbeing and resilience in the future. Two key functions are the capacities of ecosystems to function as sinks of carbon and to regulate water flows in landscapes. Some 50% of the global emissions of greenhouse gases (GHGs) are absorbed by marine and terrestrial ecosystems, a capacity that may be on the decline (Canadell et al. 2007).

The fourth planetary "squeeze" is the growing insights of the universality of surprise in ecosystem change. We have developed our predominant social and economic paradigms on the erroneous notion that ecosystems change occurs in incremental, generally linear, and thereby predictable (and controllable) ways. Instead, empirical evidence suggests the reverse. Ecosystems change in non-linear ways as a response to disturbance regimes, often abruptly and irreversibly. Multiple stable states separated by thresholds characterise systems ranging from lakes to savannahs (Scheffer et al. 2001). Critical tipping elements have been identified in the climate system (Lenton et al. 2008), water related regime shifts in agricultural systems (Gordon et al. 2008), and key tipping points in the Earth system (Schellnhuber 2009). The surprise and non-linear reality generates a dilemma that 99% of change in ecosystems tends to occur from 1% of events (S. Carpenter, personal communication), such as major shifts in forests or marine systems after fires and storms, etc. Stewardship of ecosystems that adapt to surprise requires redundancy and buffering capacity in order to build resilience to shocks and disturbance, which reduces the operating space for human development (Chapin et al. 2010).

The quadruple squeeze creates a complex social-ecological cocktail of planetary interactions that pose critical challenges for human development. We may have entered a new geological era, the Anthropocene, where humanity now constitutes the major driving force of change at the planetary scale (Steffen et al. 2007). Based on scientific evidence, sustainability or collapse is a question that now must be posed (Constanza et al. 2007).

## WATER VULNERABILITIES

A large number of poor people depend on agriculture for livelihood security and agriculture plays a key role in economic development (World Bank 2005) and poverty reduction (Irz and Roe 2000). For instance, in sub-Saharan Africa agriculture accounts for 35% of GDP and employs more than 70% of the population (World Bank 2000). Presently around 3 billion people live in the tropics and sub-tropics (World Bank 2008), and approximately a fifth of the world population lives in water-constrained, agricultural areas (Rockström and Karlberg 2009). More than 20 years ago, Falkenmark (1986) found a correlation between poverty and water stress. Since then it has also been shown that the countries suffering from the largest prevalence of malnutrition, according to the UN Millennium Development Project, are commonly located in the semi-arid and dry sub-humid regions of the world (SEI 2005). Clearly, there are strong linkages between poverty, hunger and water, which make many poor people vulnerable to changes in water availability and distribution in time and space. It is important to understand these "inherent" vulnerabilities when addressing the need for a new green revolution, and the threats posed by the risk of reinforced water scarcity induced by anthropogenic global environmental change.

Agriculture in the tropical zone is largely dependent on the green water resource, i.e., the water that infiltrates and is stored in the soil profile (Falkenmark and Rockström 2004). Blue water additions for irrigation, i.e., water in rivers, lakes and groundwater, only play a small part in the total water balance. Absolute water scarcity in the tropics is rarely the reason for the low yields commonly experienced in the area, although drought is often blamed for crop failure and crop reductions (Rockström et al. 2010b). Rainfall in the tropical zone is erratic and rainfall variability generates dry-spells almost every rainy season in the semi-arid and dry-subhumid regions (Barron et al. 2003). Poor water resources management commonly results in an inability to bridge these intra-seasonal dry-spells, and this causes the lion share of all yield reductions commonly ascribed to drought. In other words, a large share of the yield reductions could be avoided with better water management—a great opportunity for agriculture in the tropical drylands (Rockström et al. 2010b).

A global assessment of land and water availability for food production indicates that there is in fact enough water

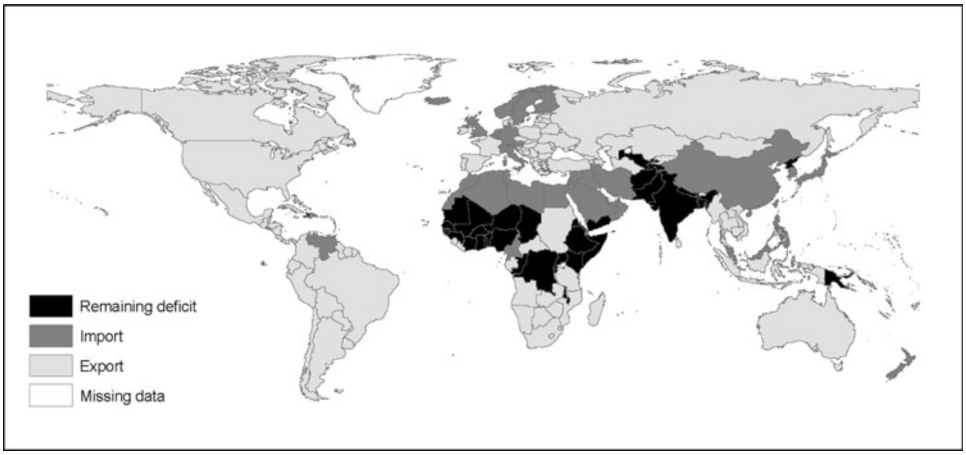

**Fig. 2** Countries with a surplus of water (export), water deficit countries that can compensate their lack of water for food production with trade (import), and water deficit countries that will have to rely on national solutions to meet their remaining deficits. Based on data from Rockström et al. (2009a)

globally to produce sufficient food both today and also in 2050 (Falkenmark et al. 2009). However, in some areas of the world, there are local deficits to meet the national water requirements for food production (Fig. 2). These counties will, as a first option, have to rely on food imports, and secondly, when the economic situation in the country does not allow for trade to cover the food deficit, will have to resort to national solutions such as unsustainable expansion of agriculture or food aid.

An assessment of water vulnerability and food production for the African continent depicts an alarming picture for the future. In the year 2000, the water requirement to feed the 800 million inhabitants on the continent was approximately 1000 $km^3$ $year^{-1}$, assuming a food water requirement of 1300 $m^3$ $cap^{-1}$ $year^{-1}$ (Falkenmark and Rockström 2004). Our estimates show that on agricultural land in Africa, the estimated water availability in the year 2000 for food production was in the same order of magnitude as water requirements, i.e. also around 1000 $km^3$ $year^{-1}$ (calc. based on Rockström et al. 2009a). In other words, according to these estimates it is possible to produce enough food to meet requirements from a land and water perspective; however, this analysis does not account for inequalities in resources distribution and wealth for example. A projection to 2050 shows a less optimistic picture for the continent. Assuming water productivity improvements that reduce food water requirements to 1000 $m^3$ $cap^{-1}$ $year^{-1}$ (Rockström et al. 2009a), the total water requirement for food for the African continent is expected to double compared with the year 2000 due to population growth. At the same time, the amount of water available for food production is expected to increase by 500 $km^3$ $year^{-1}$ due to irrigation expansion and intensification of water use on grazing lands, also accounting for climate change (calc. based on Rockström et al. 2009a). The net effect is that Africa will not be able to meet the total continental water requirement for food by 2050.

As the climate becomes more extreme in the future many poor that depend on agriculture as their main source of income may become even more vulnerable. In large parts of the tropical zone, there is more than a 90% chance that the summer-averaged temperature will exceed the highest temperature on record in 2090, which is expected to significantly reduce crop yields (Battisti and Naylor 2009). It is also in the tropical zone that the countries classified as most vulnerable to climate-related water challenges can be found (Sullivan and Huntingford 2009). Due to climate change, global crop production is expected to decrease by around 10% by 2050 (Rost et al. 2009). However, this figure does not include the effect of increased $CO_2$ fertilisation (Tubiello and Ewert 2002; Long et al. 2006; Challinor and Wheeler 2008), temperature stress (Battisti and Naylor 2009) and increased tropospheric ozone which also has been shown to negatively affect yields (Emberson et al. 2009). The consequences of these multiple and simultaneous drivers of change in agriculture are poorly understood. To conclude, it is clear that a more erratic future climate is likely to increase the water related vulnerability of farmers in the tropical zone, many of which are impoverished already today.

## DEFINING A SAFE OPERATING SPACE FOR FRESHWATER USE

Resilience provides the capacity of a system to cope with shocks and undergo change while retaining essentially the same structure and function (Walker et al. 2009). Resilience is here broadly understood as the ability of social-ecological systems (SES) to persist in a desired state, the capacity to adapt within a given state, and to transform into new development trajectories in situations of crisis (Folke and Rockström 2009). Even minor disturbances can push the system into a new regime if its resilience is low. Characteristic of a regime shift is that returning to the original regime is either very difficult or even impossible. A resilience approach entails identifying alternate system regimes and the thresholds between them, and the internal slow variables within the SES that interact and can cause the system to shift into an unproductive state due to external shocks (Walker et al. 2009).

Agriculture and water related regime shifts were described by Gordon et al. (2008). The study suggests that commonly it is possible to identify a productive (desirable) regime and a non-productive (undesirable) regime in agro-ecosystems. In tropical agricultural systems some farmers are currently locked into unproductive states, in which they lack capital to invest in agricultural inputs such as fertilisers and good crop varieties, and they commonly exhaust asset holdings accumulated from good years during periods of drought (Enfors and Gordon 2008). It has been suggested that investments in agricultural water management interventions would not only result in increases of average yields, but would also lead to reduced risks for crop failure (Rockström et al. 2010b). As the return of investments become more reliable, farmers may be more likely to invest in additional inputs such as fertilisers, better crop varieties and improved management strategies. Local communities show a high dependency on local ecosystem services both as a supplement for crop production generating off-farm incomes (Cooper et al. 2008), and increasingly so in times of failing on-farm yields (e.g., gathering of wild growing fruits and vegetables; charcoal) (Enfors and Gordon 2008).

The challenge for world food production over the coming 40–50 years is to achieve a major production increase while building resilience in the face of the pressures from the quadruple squeeze. A first attempt to translate the global sustainability challenge in the Anthropocene was recently made with the introduction of the "planetary boundaries" concept, aimed at providing a safe operating space for humanity at the planetary scale (Rockström et al. 2009b, c). The concept evolves from linking global change with resilience science, and provides a framework to identify physical boundaries for key earth system processes associated with thresholds that may jeopardise the desired stability of the planet to continue providing favourable conditions for human development. This analysis identified nine key earth system processes (climate change, stratospheric ozone depletion, ocean acidification, land use change, freshwater depletion, rate of biodiversity loss, interference with the global N and P cycles, chemical pollution and aerosol loading). Together, the nine boundaries associated with these processes provide a first attempt of defining a global safe operating space for humanity in the Anthropocene, with the aim of avoiding large scale undesired ecological surprise.

Importantly, several of the proposed planetary boundaries are coupled to world agriculture. Agricultural expansion is the largest anthropogenic transformation of land use on the planet, currently covering some 35% of the total land area (~12% for cropland) (Foley et al. 2005; Ramankutty et al. 2008). Moreover, agriculture is estimated to be a major source of GHG emission, accounting for ~30% of global annual emissions (including the effects of deforestation), and constitutes, over the past 50 years, the largest driver behind loss of biodiversity, ecosystem change, and increase in freshwater use (MEA 2005).

A first attempt to define the specifications for a new revolution in agriculture as defined by these planetary boundaries is presented in Box 1, and will require major shifts in agricultural production systems world-wide. Agriculture must transform from being a source to a sink of GHGs. The food production increase essentially will have to occur on current cropland, except for certain regions in Africa, central Europe and parts of Latin America, where there still appears to exist land that can be converted to agriculture in a sustainable way. Blue water extraction for irrigation is limited, and thus any yield improvements have to be linked with corresponding improvements in water productivity. Plant nutrient cycles (N and P) must be managed more efficiently and management interventions in agriculture have to be implemented in such a way that the

**Box 1** Global specification of sustainability requirements for world agriculture in order to stay within the Planetary Boundaries

| Planetary boundary | "Green" revolution specification |
|---|---|
| Climate change | To stay within 350 ppm requires an agricultural system that goes from being a source to a global sink. |
| Land use change | Cropland can only expand from 12 to 15%. Higher yields have to be produced on current croplands by increasing productivity. |
| Freshwater use | Keep global consumptive use of blue water <4000 km$^3$/year. We are at 2,600 km$^3$/year today, and thus irrigation expansion is limited. |
| Interference with global N and P cycles | Reduce to 25% of current N extraction from atmosphere. |
| | Not increase P inflow to oceans. |
| Rate of biodiversity loss | Reduce loss of biodiversity to <10 E/MSY from current 100–1000 E/MSY (E/MSY = extinctions per million species per year). |

rate of species loss does not exceed the biodiversity threshold.

This requires nothing less than a triply green revolution of agriculture (as compared to Gordon Conways call for a doubly green revolution (Conway 1997)): more yields (green) have to be produced, in a green (sustainable) way, by improving especially the green water productivity. It will thus not suffice to "minimise environmental impacts" of conventional, fossil-fuel based and resource depleting farming systems. Instead, the green sustainability leg of such a revolution would require that agricultural development contributes to allow humanity to stay within the safe operating space provided by the planetary boundaries. Second, since the main water source for agricultural production is green water, this entails managing the green water resource more efficiently than is currently done.

## A NEW SPECIFICATION FOR A TRIPLY GREEN REVOLUTION

A triply green revolution in agriculture thus entails more efficient green water use on current croplands. Water is the bloodstream of the landscape and efficient integrated water and land resources management (IWLRM) requires governance across scales. A stronger emphasis on green water management entails a down-scaling of the focus of water resource management, from the current emphasis on river basins, to a stronger focus on management of smaller meso-scale catchments (10–1000 km$^2$) (Rockström et al. 2010b). It is here that green water flows are actively involved in producing bio-resource values for human wellbeing, and providing regulatory flows—both green and blue—across scales as water flows through the landscape. Managing green water flows for increased resilience at the meso-scale are determined by several processes (Fig. 3). Increased green water use for biomass production, be it for food, fiber, fuel, or forestry, has to be balanced against downstream environmental water flow requirements (e.g., King et al. 2003), to reduce the risk for unwanted downstream impacts (e.g. Calder 1999). Today, there is a lack of research describing the downstream consequences of upstream implementation of agricultural water management interventions (Karlberg et al. 2009).

Land-use change is also a decision about water (Fig. 3). It is estimated that the land-use conversions to agriculture that took place during the last 300 years have resulted in a decrease in green water flow and an increase in recharge and stream-flow (Scanlon et al. 2007). A study in West Africa showed that clear-cutting of tropical forests increases the annual stream-flow by 35–65%, depending on the basin, although forests occupy less than 5% of the total basin area (Li et al. 2007).

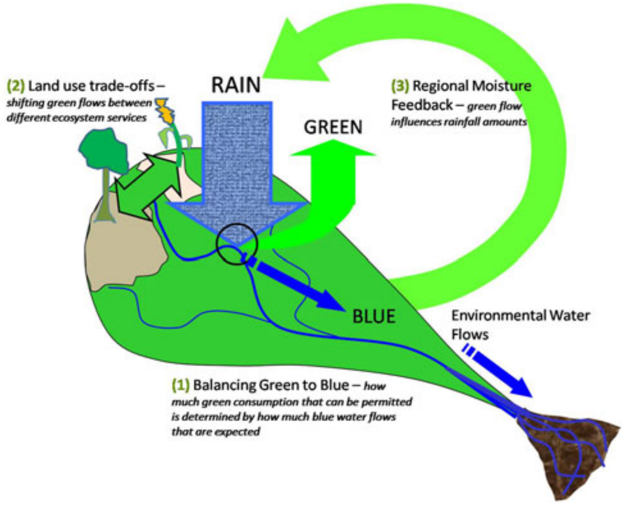

**Fig. 3** Management of green water flows for resilience at meso-scale catchments level

A relatively poorly understood area is how vegetation impacts on rainfall amounts via moisture feed backs (Savenije 1996). It seems that systems partly shape the micro-climate that they exist in, and a change in land-use system could therefore also impact on the local climate of the region. In order to develop relevant policy for efficient green water use in agriculture, there is a need for IWLRM to develop into more holistic assessments of blue and green water flows at the landscape scale.

Several agricultural water interventions focus specifically on green water management and have been shown to significantly improve crop yields (Fig. 4). Rockström

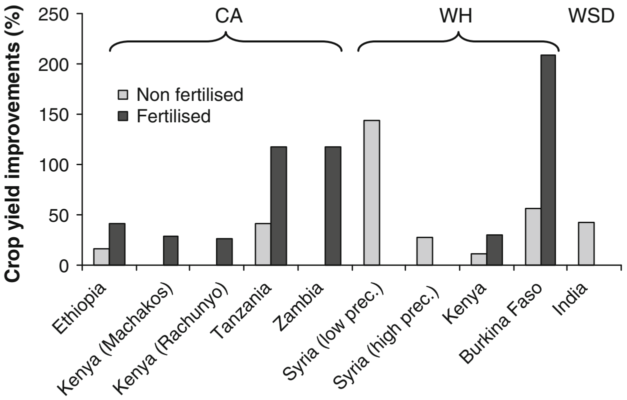

**Fig. 4** Crop yield improvements at different locations, ranging from conservation agriculture (CA), ex-situ water harvesting systems (WH) and watershed development programmes (WSD), (i.e., programmes that combine conservation agriculture with supplementary irrigation). Sources: Conservation Agriculture: Rockström et al. (2009d). Water harvesting systems: Syria, Oweis (1997); Kenya, Barron and Okwach (2005); Burkina Faso, Fox and Rockström (2003). Watershed development programmes (one example): Wani et al. (2008). Prec. = precipitation

(2003) showed that in low-yielding agriculture (i.e., yields below 3 ton $ha^{-1}$), yield improvements also lead to subsequent improvements in water productivity due to larger soil surface coverage. Conservation agriculture is a type of soil and water conservation system which replaces conventional ploughing with lower intervention practices for soil management, and which combined with mulch management, builds organic matter and improves soil structure (Derpsch 1998; Landers et al. 2001). Apart from improving the water holding capacity of the soil, the increased organic matter content in conservation agriculture systems also result in more carbon being stored in the system. Supplementary irrigation with locally collected run-off, so called ex-situ water harvesting systems, is used to bridge dry-spells, which frequent the tropical drylands (Siegert 1994; Fox and Rockström 2000). When these water interventions are combined with fertilisation, the resulting yield and water productivity is even higher (Fig. 4). Productive sanitation systems, i.e., the safe reuse of human urine and faeces as a fertiliser for increased food production, could be combined with agricultural water management interventions to improve crop yields in a sustainable way by reducing the nutrient losses of the food production—human consumption chain.

A triply green revolution of agriculture has to be accomplished within a social-ecological framework, integrating agricultural management with stewardship of landscape capacity to generate ecosystem functions and services. This requires special attention to cross-scale effects, thresholds, and feedback interactions, in order to develop resilient, multi-functional landscapes for the generation of food and other ecosystem services. New innovative approaches to achieve this goal are urgently needed.

## CONCLUSIONS AND WAY FORWARD

Placing the global freshwater challenge within the context of global food security and the impacts of accelerated global environmental change, raises the urgency of developing strategies to build resilience in water resource governance and management. Taking a social-ecological and resilience perspective on the challenge of human development in the Anthropocene, indicates that the water and food nexus is subject to a “quadruple squeeze” from demographic pressure, the global climate crisis, the global ecosystem crisis, and the growing insight of the universality of non-linear dynamics in ecosystem change.

As a consequence of the growing social-ecological pressure on several key earth system processes, nothing less than a triply green revolution will be needed to produce food for a growing world population. Food production will have to increase at record pace, which can only be accomplished through major investments in both green and blue water resource management, and will require a sustainability transformation that enables global agriculture to produce food within the safe operating space of the planetary boundaries.

Farming systems in the world are not configured to deliver a triply green revolution. Neither ecological nor conventional agricultural systems fulfil the green criteria suggested in this article. What is urgently needed is a new definition of sustainable agricultural systems as well as new, innovative technologies that enable major productivity improvements. Elements of knowledge to develop these triply green systems are presented in this article—particularly the opportunities of major improvements in water productivity and yield increase through various agricultural water interventions. A major research initiative is needed to develop, test and promote agricultural systems that contribute to a sustainable future for human-kind in the long-term.

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