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ORIGINAL PAPER

Future threats to agricultural food production posed by environmental degradation, climate change, and animal and plant diseases – a risk analysis in three economic and climate settings

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Abstract Global food security is one of the most pressing issues for humanity, and agricultural production is critical for achieving this. The existing analyses of specific threats to agricultural food production seldom bring out the contrasts associated with different levels of economic development and different climatic zones. We therefore investigated the same biophysical threats in three modelled types of countries with different economic and climatic conditions. The threats analysed were environmental degradation, climate change and diseases and pests of animals and plants. These threats were analysed with a methodology enabling the associated risks to be compared. The timeframe was 2012–2050 and the analysis was based on three underlying assumptions for 2050: the world population will have increased to 9 billion people, there will be a larger middle class in the world and climate change will be causing more extreme weather events, higher temperatures and altered precipitation. It is suggested that the risks, presented by the biophysical threats analysed, differ among the three modelled types of countries and that climate zone, public stewardship and economic strength are major determinants of these differences. These determinants are far from evenly spread among the world's major food producers, which implies that diversification of risk monitoring and international assessment of agricultural production is critical for assuring global food security in 2050.

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Introduction

Global food security is one of the most pressing issues for humanity. The first of the UN's eight millennium development goals is to reduce the proportion of the world's population that suffers from hunger by half between 1990 and 2015 (UN 2000). Agricultural production is critical for achieving global food security (Godfray et al. 2010; Nayyar and Dreier 2012), as are factors such as economic development for everyone, fair international trade agreements, and sound global and national governance (Rosegrant and Cline 2003; von Braun 2009).

Agricultural production of food depends on several policy, economic and biophysical conditions. Biophysical threats to agricultural food production, or parts of it, such as scarcity of natural resources (Childers et al. 2011; Khouri et al. 2011), climate change (Battisti and Naylor 2009; Thornton 2010), and land degradation (FAO 2011; Pimentel 2006) have recently been analysed separately. Moreover, agricultural hazards have generally been assessed within a single geopolitical unit—e.g. globally (Cordell et al. 2009), or in relation to a particular regional or national territory (Khouri et al. 2011; Thornton et al. 2011). This itemized approach has the important drawback of ignoring interactions among threats.

Well aware of the complexity of the issues related to agricultural production and attached ideological controversies, we here aim to assess the risks presented by some well-recognised biophysical threats jointly and globally. We assume that risks, capacity for risk management and risk perceptions vary depending on the economic and climatic conditions. We therefore investigate the same set of threats in three constructed type-countries: type A-country, similar to present-day Sahel countries; type B-country, similar to present day SE Asian Countries; and type C-country, similar to present day Northern European countries. Obviously, within each type-country there might be different agroecological zones with varying vulnerabilities to the threats. The set of threats analysed in respective sub-section are:

- environmental degradation
- climate change
- pests and diseases of animals and plants

These threats are assessed for their probability to materialize and their impact on food production in the three type countries. This method enables the risks associated with each of the threats to be compared. After assessing the risks presented by the various threats, we compare the outcomes in the type countries and discuss the threats to future food production in the context of global food security.

Methods

Risk analysis

The risk analysis was based on an expert study of peer-reviewed literature conducted by the authors of this paper. In the analyses of different threats to future food production, risks were treated as a function of two factors: the *probability* that a threat will materialize, or become actual, and the *impact* the threat would have on agricultural production if it did indeed materialize. We graded each of these on a simple ternary scale as follows:

- **Probability** estimates were categorized as: *Low* - the threat will materialize less than once during the next 40 years; *Moderate* - the threat will materialize more than once every 10 years; or *High* - the threat will materialize more than once annually.
- **Impacts** of a threat that has materialized were categorized as: *Small* - less than 20 % of the production is lost in the type of country being analysed and the damage will be restored within 1 year; *Medium* – more than 20 % of the production is lost, but the damage will be restored within 1 year; or *Large* - more than 20 % of the production is lost and the damage will persist over several consecutive years.

Three economic and climate settings

The three types of country were modelled on some basic economic and wealth indicators and climate zone characteristics as described below.

> Type A country. Average per capita income per year is less than 1000 USD, and life expectancy is less than 55 years. There are weak institutions in this country. The country is located in a tropical climate zone with wet and dry seasons. This zone extends northward and southward from the equator to 15–25° latitude. Every month has an average temperature above 18 °C, and annual precipitation is greater than 1,500 mm. There is an extended dry season; precipitation is concentrated in the wet season.
>
> Type B country. Average per capita income per year is 4,000–9,000 USD, and life expectancy is around 70 years. The efficiency of institutions in this country is intermediate. Such a country is often referred to as an emerging economy. It is situated in the tropical monsoon climate

zone, extending north and south from the equator up to 25° latitude. In this climate every month has an average temperature above 20 °C. Annual precipitation, falling primarily in the hottest months, is greater than 1,500 mm. During the dry season there is little precipitation.

Type C country. Average per capita income per year is 30 000–50 000 USD, and life expectancy is about 80 years. The efficiency of institutions in this country is good. The country is located in the temperate climate zone, where there are comparably warm summers and cold winters. The average temperature of the warmest month is above 10 ° C, while the coldest month is below −3 ° C. The annual precipitation of 1,000 mm is distributed over the year.

Baseline scenario

The timeframe of the analysis is from now to 2,050. By the end of this period world population is expected to have reached 9 billion, according to the so-called ‘medium variant’ outlined in World Population Prospects (UN 2011). Further, the proportion of middle class people will rise from an estimated 27 % in 2,009 to 42 % by 2,020, and to as much as 59 % in 2030 (Kharas 2010). Hence, the middle class is expected to increase in numbers and as a fraction of total world population. Middle class food consumption generally involves increased demand for high value foods such as meats, fresh vegetables and fruits, which tends to put greater pressure on the agricultural sector. By contrast, poor households consume a higher proportion of grain, or cereals, and tubers (Seal et al. 2003).

The Intergovernmental Panel on Climate Change (IPCC 2007) has presented a range of future climate scenarios. The present study focuses on the scenario with moderate average temperature increase (1–2 °C) and increasing frequency of weather extremes (Hansen et al. 2012) with considerable differences in changes between temperate and tropical climate zones (Parry et al. 2007)

Description of the threats

Environmental degradation

Land degradation The United Nations Environmental Programme (UNEP 2007) defines ‘land degradation’ as a long-term loss of ecosystem function and services caused by disturbances from which the system cannot recover unaided. The degradation can be caused either by natural phenomena or by human activities, and of course land degradation of natural origin can be reinforced by the action of man. However, our understanding of land degradation, and its extent and causes, is fragmented, and there is no consensus on its global importance (De Jong et al. 2011).

According to expert opinion, an estimated 15 % of the global land area is seriously affected by land degradation, and 46 % and 38 % are moderately and lightly affected, respectively (Bridges and Oldeman 1999). These estimates have been criticized as subjective and as exaggerations of the extent of land degradation, especially in arid and semi-arid regions ((Nkonya et al. 2011) and references therein). More recent measurements of vegetation cover (Bai et al. 2008), as revealed by the time series of Normalized Difference Vegetation Index (NDVI) (1981–2006), highlighted *ongoing* land degradation in humid areas. With the exception of Australia, dryland areas did not stand out. Re-greening trends were found in the Sahel. This global trend in land degradation was later confirmed for Sub-Saharan Africa (Vlek et al. 2010). Africa south of the equator experienced the greatest land degradation, with 13 % of the global *ongoing* degradation. Some of what has, in the past, been regarded as anthropogenic land degradation around the Sahara can probably be attributed to climatic fluctuations (De Jong et al. 2011). The use of NDVI as a proxy for land degradation has also been criticized from a methodological viewpoint. New global estimates of land degradation based on expert opinion, taking into consideration soil factors, ecosystem services and land-use classes, are currently under development (FAO 2011).

Contrary to what is widely believed, land degradation often seems to decrease with increasing population densities at local level, and possibly also globally (Andersson et al. 2011; Bai et al. 2008; Nkonya et al. 2011). This is perhaps explained by the intensified use of good agricultural soils and the reduced pressure on marginal land that follow a rise in population density. Increased utilization of agricultural land and leakage of nutrients inevitably lead to nutrient depletion (Sheldrick et al. 2002; Stoorvogel et al. 1993) if replenishment strategies are not actively pursued.

Policies operating at different levels can directly influence land degradation, e.g. through payments for ecosystem services and subsidies. Access to markets and appropriate land tenure systems provide the means and incentives for increased agricultural productivity and investment ((Nkonya et al. 2011) and references therein).

Chemical and radioactive pollution Chemical and radioactive pollution of land may be the result of the continuous release of substances from disparate sources, or of more dramatic events such as industrial accidents or the deliberate delivery or release of toxic waste. Although it is known that chemical pollutants reach agricultural soils by a number of different routes, including air, rain, irrigation, and direct application as pesticides, even in countries with developed monitoring systems it is difficult to estimate how seriously the soil is contaminated (Montanarella 2007). While human exposure to contamination can be linked to adverse health effects (Cheng 2003; Oberson and Lafon 2010), it is difficult to find evidence in the international literature of severe, large-scale production losses, or of losses of agricultural land, that are due to acute pollution; the exception here is metal pollution (Zheljazkov 1996). Even so, land has been deemed unsuitable for agricultural production after industrial accidents, based on risk assessments focusing on food safety. For instance, after the 1986 nuclear accident in Chernobyl, in the Ukraine, approximately 4,000 km^2 of land were set aside as unsuitable for habitation (IAEA 2001).

Losses in agricultural production due to heavy metal contamination and surface ozone exposure might be important in some areas (Chepurnykh and Osmanov 1988). Here the significance of ozone may grow in the future (Avnery et al. 2011). Experimental data shows that cadmium at concentrations of less than 1 micro Molar, which can be found in certain soils, can adversely affect the photosynthetic capability of some plants (Prasad 1995) and, additionally, it has been suggested that decreased yields of rice in Iran are associated with concurrent increases in cadmium burden (Kalantari 2006). Soil burdens of cadmium are directly linked to, and correlate with, agricultural production, as the main source of cadmium is phosphate rock fertilizer. Cadmium is also present in sewage sludge used as fertilizer (Pan et al. 2010).

Some industrial chemicals (such as polychlorinated biphenyls, or PCBs), industrial contaminants (such as dioxins) and low-use pesticides (such as DDT) are considered persistent organic pollutants. There is evidence that these substances (PCBs being a case in point) can be toxic to plants, but at levels several orders of magnitude higher than found in soils irrigated with water contaminated by these chemicals (Holoubek et al. 2009; Wang et al. 2010; Weber and Mrozek 1979). However, these substances are of real concern from the perspective of food safety, as they may reach humans via contaminated foodstuffs of animal origin, particularly seafood (Guo et al. 2009; Zhao et al. 2006).

Microbial pollution of soil and water Microbial pollution is defined as pollution with pathogens, including bacteria, viruses and parasites. The pathogens may be zoonotic, i.e., affecting both humans and animals, or species specific and may enter agricultural systems in various ways. They can be borne by polluted water or by organic material that is used as fertilizer (Hunter 2003; Tirado et al. 2010). Pathogens of animal origin can accumulate in the environment following an outbreak of disease of the kind resulting in large amounts of pathogen-contaminated animal waste (e.g. manure or carcasses). Such waste might contaminate water sources, or the land on which the waste is collected, stored, buried or subsequently spread as fertilizer. Hence, microbial pollution of an agricultural environment can pose health risks to both humans and animals and may render agricultural activity impossible. As with chemical pollution, it is difficult to determine the extent of agricultural losses that are due to large-scale microbial pollution through a review of the literature. In addition, microbial pollution is more often an obstacle to food safety than food security.

Water contaminated by human and animal pathogens is generally unsuitable as drinking water, as it might cause infections and consequent loss of production. For the same reason, such water is also unsuitable for the irrigation of crops that are to be consumed raw or used as feed for animals. In general the importance of maintaining the good microbial quality of freshwater is internationally acknowledged (Fewtrell et al. 2005). Similarly, pathogen-contaminated fertilizers can pose a risk if they are applied to crops intended to be consumed raw by humans or animals. Both animal manure and human faecal material are sources of pathogens (Barrett et al. 2000). In type C countries, exposures may follow the release of untreated sewage water into the water supply system following extreme weather conditions or accidents such as ruptured sewage pipes (Cabral 2010). In type B and type A countries the release of human pathogens can also be associated with absent or insufficient wastewater treatment, or poor sanitation and outdoor defecation (Bartram and Cairncross 2010).

Climate change

Extreme weather events As climate change progresses, heat waves, droughts, storms, heavy precipitation and floods are expected to become more frequent (Hansen et al. 2012; Parry et al. 2007). Subsequent damage, such as erosion, leakage of soil minerals, landslides and the contamination of soil and crops by animal or human pathogens, salt or chemicals, all lead to loss of land for agricultural production (Miraglia et al. 2009; Lindgren et al. 2011). Direct effects include damage on infrastructure that may affect food production and reductions in harvests and livestock caused by floods or drought. Several infectious diseases affecting livestock, such as anthrax and blackleg, may emerge after extreme weather events (Bezirtzoglou et al. 2011; Skovgaard 2007).

Further, after flooding, especially when it is combined with high temperatures, an increase in insects that may act as vectors for pathogens may be observed. For instance, the livestock disease, Rift Valley Fever, depends on still water, which serves as ovipositplaces for its vector mosquitoes (Githeko et al. 2000; Nardone et al. 2010). Similarly, extreme weather events might alter pathogen transmission dynamics and the presence of insects and pests, and this may in turn impair crop production (Jaggard et al. 2010; Miraglia et al. 2009).

Gradual changes: animal production Heat stress can increase mortality and cause metabolic diseases in production animals. It can also reduce fertility, feed intake and immunological response, which in all cases tend to result in decreased production (Nardone et al. 2010; Sartori et al. 2002; Thornton et al. 2009). The intensive indoor production of pigs and chickens is especially vulnerable to raised temperatures, as increased mortality may result if supplemental cooling is not provided. Owing to its high metabolic rate, the modern, high-yielding dairy cow is also sensitive to heat stress (Black et al. 2008; Sartori et al. 2002). Extended periods of drought may also lead directly to shortages of feed and drinking water, further reducing production.

Increased temperature also affects vector borne diseases. It does so by, for example, increasing the intensity of blood meals in female mosquitoes, the vector's reproductive rate, and the virus's replication rate while in the vector (Pinto et al. 2008). A northward spread in the northern hemisphere of ticks and biting midges—vectors for Lyme disease and blue tongue, respectively—has already been noticed (Forman et al. 2008; Van den Bossche and Coetzer 2008). Moreover, the raised presence of harmful mycotoxins that is due to humidity and warm climate makes storing food and feed perilous. Further, climate-change driven modifications of the composition of grass species can affect the productivity of grazing animals by lowered forage quality owing to lignification (Thornton et al. 2009).

Gradual changes: crop production Within the concept of anthropogenic climate change, several distinct factors, which affect crop production rather differently, can be isolated. Experimental evidence suggests that increase of atmospheric CO_2 concentration stimulates both photosynthesis and biomass production in a range of crop (C_3) species (see e.g. (Ainsworth and Long 2005)). However, recent evidence suggests that elevated temperatures have a negative impact on the same physiological processes, and that the combined effect of both increased CO_2 and temperature may lead to decreased photosynthesis and biomass production (Ruiz-Vera et al. 2013). In addition, heat stress during pollination will increase the vulnerability of several commodity crops (Sage and Kubien 2007; Semenov and Shewry 2011), especially in areas where crops are grown close to the critical temperature limit for photosynthesis (Ruiz-Vera et al. 2013). In contrast, higher temperatures may prolong cultivation seasons and lead to higher yields in northern latitudes and colder areas (Eckersten et al. 2011).

Climatic variability is expected to increase and will affect the production of major crops negatively (Lobell et al. 2008). The increase in inter-annual weather variation could make crop failures more likely, by making crop management designed to maximize yield and quality and minimize environmental impacts more difficult. Moreover, crop production may decline as a result of rising biotic stresses caused *inter alia* by pests and the invasion of alien weed species (Anderson et al. 2004; Garrett et al. 2011). Hence, the effect of climate change on crop production is both direct (on ecosystems) and indirect (dependent upon our ability to adapt cropping system, management and profitability to the changes caused by these impacts). Their ability to develop and apply new technologies will determine the extent to which different countries and regions succeed in adapting to climate change (Varshney et al. 2011).

Pests and diseases in animals and plants

Transboundary animal diseases Transboundary animal diseases are highly contagious and easily transmitted within and between livestock populations. They therefore threaten the economic health of the livestock sector, the livelihood of farmers, and ultimately food security. Zoonotic transboundary animal diseases may impede livestock production for public health reasons. A good example of this is the global epidemic of the highly pathogenic avian influenza (H5N1) originating in East Asia in 2003 (Kaufman 2008; Sims et al. 2005).

The massive outbreak of foot-and-mouth disease in Great Britain, 2001, with losses estimated at around 3.1 billion GBP, illustrates well the threat from transboundary animal diseases to livestock production and food security (Thompson et al. 2002). The impact of a contagious disease depends on the virulence of the pathogen, the production system, livestock and farm density, biosecurity routines, the capacity of veterinary services, the extent of trade in the animals and animal products, and human and wildlife population densities and their proximity to livestock (Otte et al. 2007; Rossiter and Al Hammadi 2009; Stegeman et al. 2002). The relative weight of these factors varies and can depend on economic development (Forman et al. 2009; Graham et al. 2008) and governance.

There has been a notable increase in the number of farmed animals in East Asia, especially in poultry and pigs reared in confined production systems (Thornton 2010). Generally, large-scale intensive animal production units are established in densely populated areas (Steinfeld et al. 2006). In these large-scale systems, outbreaks of infection may be devastating—something that serves to highlight the importance of effective biosecurity (Sherman 2010). The urbanization in type A and type B countries also brings with it an increase in small-scale, backyard animal production in cities, where there is bound to be contact between humans and animals.

Changes in ecosystems can also facilitate the transmission of transboundary animal diseases between wild and domestic animals (Harrus and Baneth 2005). A classic example of this is the transmission of the Nipah virus from fruit bats to domestic pigs, and ultimately to humans, in Malaysia in 1999 (Chua 2003). Once established, an infection can rapidly spread to countries with vulnerable livestock populations through international travel and through trade in animals, animal products, and foodstuffs, threatening livestock production (Sherman 2010; Thornton 2010). The importance of trade was apparent in the outbreak of swine fever in Great Britain in 1986. The disease was thought to have been caused by the feeding of unprocessed food swills containing imported pig meat (Williams and Matthews 1988).

Plant diseases Key elements of plant disease epidemics that determine the occurrence and severity of a particular plant disease include abundance and susceptibility of the host (crop plant), abundance and virulence of the pathogen, and favourable environmental conditions (Agrios 2004).

Agricultural practices that increase host density such as increase of field aggregation, field size and crop species uniformity tend to increase the severity of plant disease epidemics (Ayliffe et al. 2008; Stuthman et al. 2007), as such practices both increase host vulnerability and facilitate movement of the plant pathogen. In addition, genetic uniformity of cultivars contributes to a greater vulnerability of the host, and low genetic variation is associated with few traits conferring resistance to a particular pathogen (Tadesse et al. 2010). Thus, if the pathogen evolves to overcome the genetic resistance, the result can be crop failure on a massive scale (Forbes and Jarvis 1994). Abundance of plant pathogens is also largely influenced by international exchange of seed and planting stock. In fact, global trade and exchange has contributed to the dispersal of many pathogens into regions of the world where they previously did not exist (Zadoks 2008). Also, the movement of people from and between low and middle-income countries, carrying there own food and dodging border controls, may contribute to the spread of pathogens. Hence, the specialized agriculture commonly found in the industrial world with large fields devoted to uniform crop cultivars, higher planting densities and increased usage of fertilizers may increase the risk of spread of a plant disease (Stuthman et al. 2007). However, it is generally difficult to predict the spread of plant diseases (Garrett et al. 2011) and the magnitude of their effects depend both on environmental conditions and plant-pathogen interactions (Wellings 2007).

Results

A summary of the criteria used for classification of probability and impact in the risk assessment is given in Table 1. The risk assessments as well as the justification of the assessments are presented in the following.

Environmental degradation

Land degradation

The probability of land degradation in a type A country, which has a pronounced dry season followed by heavy rains, is assessed as high (Fig. 1a), with water erosion a key factor. An intensification of agricultural production, and appropriate soil protection measures on suitable soils, is less likely, owing to the lack of appropriate land tenure systems, policies and infrastructure, as well as limits on functioning markets with incentives for investment. Sustained poverty with increasing population density would result in a high probability of increased land degradation through the over-utilization of resources, nutrient depletion, and the conversion of marginal lands into agriculture land. This trend is liable to be reinforced by a climate with more extreme events, such as longer drought periods followed by intensive rains and flooding (see also subsection “Climate change” below). The impact of land degradation here is estimated to be large, as considerable parts of the land would be affected and the damage would be only partially reversible.

A type B country may experience a temporary increase in environmental degradation as a result of economic growth and the exploitation of land. However, if the economic growth is accompanied by appropriate policies, both in agricultural production and environmental protection, there could be a decrease in land degradation. Hence, the probability of degradation is estimated to be high, and the impact of such degradation is estimated to be medium, as means of rehabilitation could be available.

A type C country would be capable of counteracting most causes of land degradation. It would also be able to mask some of the effects of degradation through its increased use of, for example, fertilizer. The probability of land degradation is therefore estimated to be moderate, and the impact small.

Chemical and radioactive pollution

It is estimated that, in a type A country, chemical production will increase and the chemical industry will continue to grow from a comparatively low level (OECD 2001). This will, in turn, increase the risk of acute chemical spills, with possible implications for food safety. The use of phosphate fertilizers can vary among type A countries, from virtually nil to levels

Table 1 The criteria for probability and impact used to compare the risks of the different threats to food production 2012–2050

Probability	Low	Moderate	High
	< 1in a 40 year period	> 1 in a 10 year period	> 1 yearly
Impact	Small	Medium	Large
	< 20 % lost, and restored within 1 year	> 20 % lost, and restored within 1 year	> 20 % lost, and the damage will last over several years

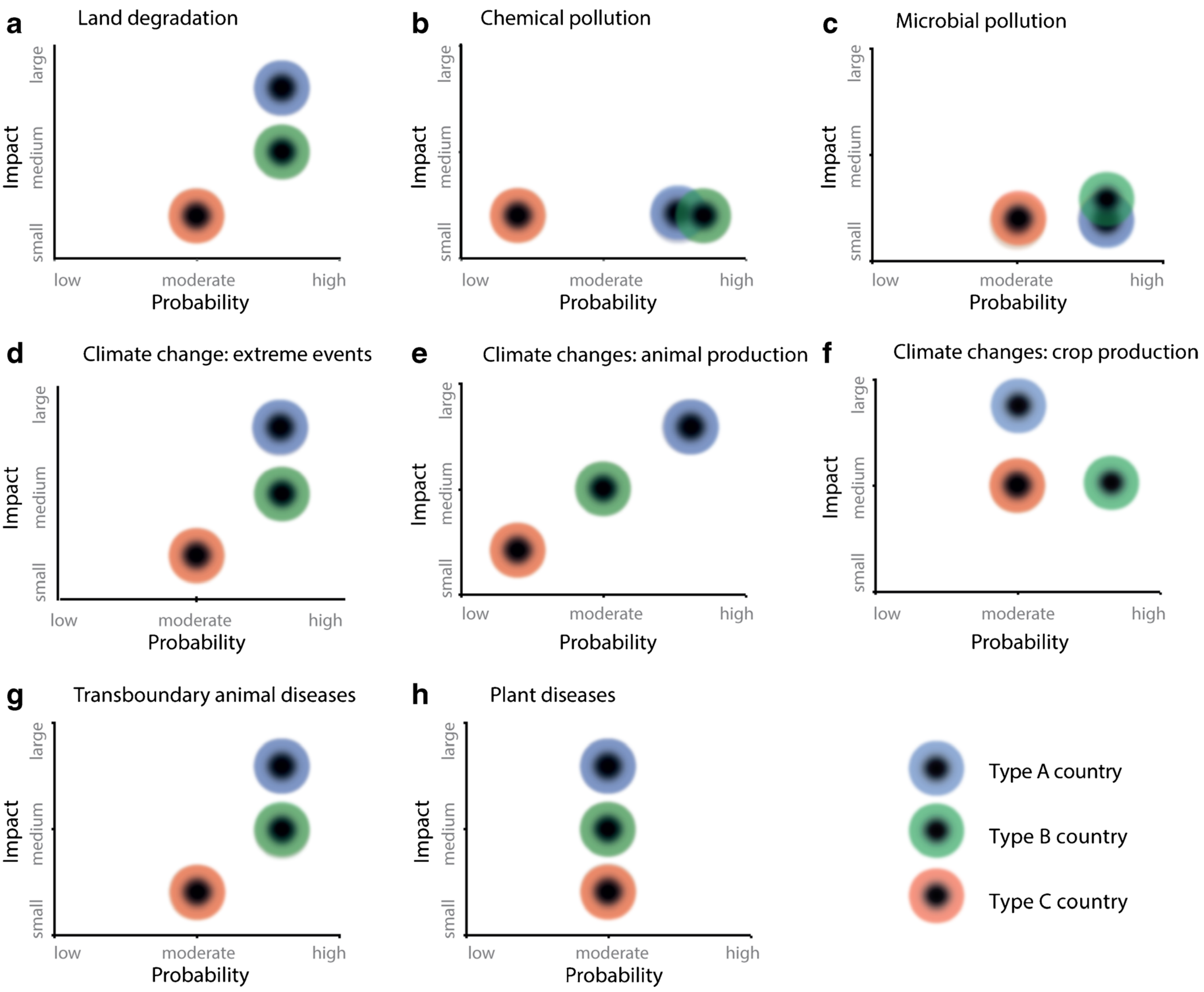

Fig. 1 Risk assessment of threats to agricultural production in a low-income country in the tropical climate zone (Type A country), in a middle-income country in the tropical climate zone (Type B country) and in a high-income country in the temperate climate zone (Type C country). *Graphs* show estimated risks of detrimental effects on agricultural production by land degradation (**a**), Chemical and radioactive pollution (**b**), Microbial pollution of soil and water (**c**), Extreme weather events (**d**), Gradual effects of climate change on animal production (**e**) and crop production (**f**), Transboundary animal disease (**g**) and plant disease (**h**)

similar to those in developed countries (FAO 2012). Phosphate fertilizers may need to be used to increase, or maintain, food production, but they lead to increasing levels of cadmium in the soil that is mainly a food safety problem. Further, in countries where water is scarce, contaminated water is used for irrigation. Thus, the probability of increased chemical pollution of agricultural land in the type A country is high. However, the overall impact on agricultural production within the timeframe of this review is estimated to be small (Fig. 1b).

A type B country will likely face an even greater expansion in its chemical and metal industries, and correspondingly a rise in associated risks. There are indeed areas with high levels of chemical pollution in emerging economies, e.g. China. Again, the threat to food safety is presented mainly by the use of cadmium-contaminated fertilizers. In the long run cadmium levels may also affect crop yields. Nuclear accidents in type B countries cannot be excluded, but previous experience shows that although vast lands have been excluded from food production by such accidents, agriculture remains possible in neighbouring areas. Overall, the probability of an increase in chemical pollution of agricultural lands in a type B country is estimated to be high, while its impact on agricultural production is estimated to be small.

In a type C country organic contaminants and metals can be found at a variety of levels as a result of their historical and ongoing release into the environment. However, neither the continuous release of these substances nor acute accidents are likely to have any major ensuing effect on agricultural production. Nuclear accidents in type C countries should be assessed in much the same way as they are in a type B country. In type C countries phosphate fertilizers are widely used, and concerns therefore arise about the safety of cadmium levels in food. The probability of dramatically increased chemical and radioactive pollution of agricultural lands in the type C country is low, and its impact on agricultural production is small.

Microbial pollution of soil and water

In a type A country the probability of microbial contamination is high, considering both the outbreak of diseases within livestock populations and the spread of pathogens from manure, sewer leakage and open defecation (Fig. 1c). However, the impact is likely to be small: the pollution will often be restricted to a local area as a consequence of limited water distribution and low intensity of agricultural production.

In a type B country proper wastewater treatment is often not implemented. As mitigating resources might also be limited, there is a high probability of contamination. In addition, the highly intensive agricultural production systems used in type B countries may promote the systemic spread of pathogens. Hence the impact here is rated as medium to small.

In a type C country, with developed sewer systems, sewer disruption is less likely to occur. The presence of many of the pathogens in agriculture produced in a type C country can also be handled later in the food chain—e.g. by means of slaughterhouse practices such as the freezing or heat treatment of carcasses, various decontamination procedures followed during the production process, and recommendations on preparing food at household level such as washing the item before use. These mitigators, which can be costly, are likely to reduce the probability of microbial pollution in type C countries to moderate, and the impacts of such pollution are likely to be small.

Climate change

Extreme weather events

In a type A country the probability of flooding and storms is expected to be high, and the ensuing impacts large, especially in low coastal zones, where poorly built farms and grazing systems could readily be destroyed by floods (Fig. 1d). The impact of drought is expected to be large in view of the limited irrigation. For livestock, both direct lack of drinking water and the risk of starvation arising from destroyed pastures and forage production could follow. Mass movements of animals may follow extreme weather events and cause epizootics, e.g. by increasing contact and disease transmission among animals from different areas, as well as between livestock and wildlife. Heat extremes might have a less severe impact in the tropics, where the animal breeds are generally well adapted to high temperatures.

In a type B country the impacts of extreme weather events may be almost as devastating as they are in a type A country, even if buildings and draining systems are somewhat more stable. Droughts would ruin crops and interfere with forage production in type B countries, too, although the impacts are likely to be less serious given the more developed water supply systems. Semi-cyclical weather events, such as El Niño, which may affect several type B countries, could become more extreme as the result of climate change and lead to the destruction of arable and grazing land. Heat waves may cause further problems. These will arise mainly in the intensive indoor animal production of pigs and chickens—a kind of production now rapidly growing in these countries. The probability of extreme weather events is high. Even so, the overall assessment of the impact is medium, as this type of country has greater economic resources to cope with the climate change threats.

A type C country could experience severe effects of flooding and storms during the acute phase, but after these events agricultural production will probably return to normal quite soon. Drought may cause problems, but investment in new technologies ought to mitigate this. The impact of heat waves is rated as medium, but the avoidance of more substantial impacts will require investment in cooling systems that mitigate heat stress in the animals. Generally, the probability of extreme weather events is moderate, but the impact of these events will be small.

Gradual changes: animal production

In type A countries the probability of negative impacts on animal production arising from increased temperature may be high (Fig. 1e). Animal breeds in tropical climate zones are often well adapted to high temperatures. All the same, productivity may decrease when temperatures rise. For pastoralist livestock production even small increases in temperature in marginal areas may reduce productivity or even destroy herds. Also, in production systems based on forage production, the impact may be large, as here there tend to be limited opportunities to buy supplementary feed from other areas. Thus the capacity to adapt to changes in the supply of feed is generally poor.

In a type B country the probability of negative effects on animal production owing to gradual changes of climate are rated as medium, as this type of country has, in general, better ability to cope with the threats of climate change. However, densely populated areas, especially in coastal regions, may be faced with land destruction following rises in sea level, salt and flooding. This would affect animal production markedly. As a consequence of rapid economic development, urbanization and other factors, animal production is largely shifting from smallholder and backyard farms to huge industrialized systems of intensified production. The vulnerability of these different systems also varies. Grazing animal production systems may run into trouble. However, supplementary feed and water may be more readily available here than they are in type A countries. Increasing temperatures may represent a challenge for the indoor production of pigs and chickens, because cooling systems are expensive and therefore scarce.

In a type C country the probability for impacts on animal production due to gradual changes of climate is small. In fact, a prolonged vegetation period in the temperate climate zone may have a positive impact on animal production. The impact of gradual climate change on animal production is rated as small, in view of the fact that investment in new technologies may allow climate problems to be overcome, but production costs may increase. Examples here include the extraction of fresh water from seawater and the cooling, or reconstruction of stables to mitigate heat stress on the animals. Although animal production will be affected significantly when critical temperatures or levels of precipitation are reached in an area, production will probably soon function again after adjustments have been made to the production systems.

Gradual change: crop production

In a type A country, where there is generally reliance on a few dominant species, the negative impact on crop production of factors attributed to climate change is large, because the resources in these areas, such as technology and infrastructure, needed to adapt agriculture to any changes are scarce (Fig. 1f). A further reason is the increased risk of prolonged drought, which might cause complete crop failure with fatal consequences for local food supply. The probability that this will occur is rated as moderate.

Gradual climate change, and the agricultural intensification that is expected to occur in a type B country, are both drivers of emerging infectious diseases in plants (e.g. through altering the distribution of invertebrate vectors and by introducing new pathogens). Wet weather tends to favour fungal and bacterial pathogens; dry conditions favour insect vectors and viruses.

In addition, increased average night-time temperatures may also reduce the efficiency of radiation use in commodity C_3 plants such as wheat and soy, which may lead to lower productivity and lower yields. The probability of negative effects occurring is rated as high, whereas the impact, which depends heavily on targeted breeding efforts and the adoption of new technologies, is rated as medium.

Increasing average temperatures and a higher frequency of heat stress incidents during critical parts of the cultivation season (e.g. pollination) may also affect crop productivity negatively in the type C country. However, in parts of the temperate world and for certain crops, production is today essentially temperature-limited. In these areas, the impact of gradual increases in average temperature and CO_2 may even be positive, because rising temperatures offer opportunities for prolonged periods of vegetation, increased crop yield, additional harvests per season, and the cultivation of new feed crops. The probability of a negative impact on crop production is moderate and the impact, which is very much dependent on successful breeding of heat stress tolerant and pest resistant cultivars, is rated as medium.

Pests and diseases in animals and plants

Transboundary animal diseases

Type A countries are vulnerable to transboundary animal diseases: they tend to have less developed institutions and governance, and they may lack proper public animal health systems. Once introduced, a transboundary animal disease may spread rapidly as the result of lax controls, ineffective preventive measures and poor biosecurity, and may become endemic. The probability of an outbreak of transboundary animal disease in a type A country is assessed as high (Fig. 1g). Its impact on food production is ranked as somewhere between medium and large because the resources needed to control or eradicate diseases are in general poor, even if animal densities tend to be low.

In a type B country the probability of outbreak of a transboundary animal disease is assessed as high, because the animal industry is often rapidly expanding, sometimes with limited attention to biosecurity. Animal farms in densely populated urban and peri-urban areas present the main risks. Here, large intensive units, as well as small and medium-sized farms that keep their animals in backyards, can be expected to operate. For the latter, biosecurity is often insufficient and a large number of humans and livestock live in close proximity. This obviously facilitates cross-species transmission. The impact of the outbreak of a transboundary animal disease in these settings is assessed as medium. It is not quantified as large because there may also be larger-scale intensive production units, operated more professionally and with better biosecurity.

Type C countries have the public structures and resources to control and eliminate transboundary animal diseases. They can largely prevent outbreaks through effective biosecurity mechanisms and respond rapidly when any such outbreaks do occur. Despite this, the probability of a transboundary animal disease outbreak in type C countries is assessed as moderate, because the farms are often large and operate intensive production units in areas with high livestock density. In these production systems there is a real risk of sub-optimal biosecurity: once a transboundary animal disease is introduced it can spread rapidly within a herd, and the short distances between farms facilitates further between-herd transmission. On the other hand, the impact of transboundary animal disease on food production is estimated to be small, given the excellent veterinary services available.

Plant pests and diseases

In many type A countries farmers rely primarily on host plant resistance to control plant disease. If the resistance becomes ineffective owing to changes in the virulence of pathogens, there are few alternative means to avoid crop losses. The arrival of a more aggressive strain of any pathogen may therefore result in an increased need for pesticides and chemicals that are unavailable in type A countries. This situation presents a considerable risk to crop production in type A countries and there the impacts are likely to be large and the probability is moderate (Fig. 1h).

In a type B country the arrival of a new pathogen creates problems for production, but the magnitude of the problem is often less than it is in a type A country. This can be due to factors such as better availability of pesticides and chemicals. The impacts are medium and the probability of occurrence is moderate

In a type C country the impacts of newly arrived plant pathogens on crop production are small and the probability of infection is moderate. In this type of country crop production is expected to withstand influxes of pathogens through increased application, or more efficient use, of suitable pesticides. In addition, breeding, and then introducing, pathogen-resistant cultivars promote resilience in the plant production system. However, legislation designed to reduce chemicals in agriculture, and certain types of certified production system, such as those in the organic sector, that prohibit use of pesticides, may increase the risk of crop failure caused by pests and disease. This will be particularly significant if breeding goals directed towards plant pathogen resistance are not adopted.

Discussion

We have tried to investigate, in a broad and general sense, if a set of biophysical threats to agricultural food production poses similar or different risks in countries with different economic and climatic conditions. Notably, the risk assessment focuses on threats to national agricultural production and not on food security, which also depends on the ability of a country to increase imports. The ability of individual countries to compensate for national losses in agricultural production is dependent on several factors such as overall global agricultural production and food availability — which, in 2050, may be different from today.

In the assessment it is assumed that the world's middle-class population will grow, and that climate changes will continue. As previously stated, the risk assessment includes the probability of a threat materializing, and the ability we have to mitigate and reverse the impacts of that threat. Some threats, such as land degradation, chemical pollution or average temperature increase, are gradual, or chronic, and may have a cumulative impact. Others, including disease outbreaks and extreme weather events, are more direct or acute. The impacts of a single threat may be limited to a specific food commodity. Alternatively, they might involve an entire agricultural system. Obviously, several of the threats analysed here are interconnected, but the causalities or hierarchies among the threats can be difficult to establish.

In a type A country the threats were judged to present the greatest risks. This finding suggests a high probability of several threats materializing, and deficiencies in the resilience of the agriculture production systems, i.e. a limited ability to compensate for and recover from the damage caused by the threats analysed.

Several threats in a type B country were judged to have a probability of materializing similar to a type A country. However, none of these threats would have a large or serious impact. These findings indicate that agricultural production in this type of country occurs under conditions where major threats may actualize, but the resilience is more advanced than it is in type A countries. Notably, the impacts of chemical, radioactive and microbial pollution were assessed as small in all type countries. The one exception was microbial pollution, which was deemed small to medium in type B countries. However, the negative impact of pollution is more closely related to the safety of any foods produced (i.e. its freedom from toxic levels of radioactive substances or pathogenic microbes) than to the reduced ability of a country to produce food. This kind of safety demand is flexible. It varies of course, with level of income and the availability of the relevant food.

In type C countries none of the threats analysed were assessed as presenting a very substantial risk. However, impacts of gradual climate change on crop production have a moderate probability of materializing and may have a considerable impact on the productivity of specific commodity crops. Nevertheless, although several threats here had a moderate probability of materializing, the impacts were generally assessed as small. This is likely to be attributable to the actuality that public stewardship and functional institutions as well as economic resources (including know-how and technological development) are critical in mitigating and reversing adverse impacts.

We suggest that the assessed high probability for several of the threats to materialize in type B countries is due to the rapid expansion of agricultural production without concomitant development and implementation of regulations. This vulnerability could be even more serious if contingency plans for threats are insufficiently developed. It might be easier to generate support and marshal resources for response strategies focusing on cumulative impacts than it is to do the same for impacts that are direct, or acute, and are actualized only occasionally. Certainly, funding for 'public insurance' of this sort is generally more difficult to find in type A and type B countries. It is possible that the global spread of avian flu after 2003 was assisted by rapid prior expansion of intensive poultry production in areas where the veterinary infrastructure, biosecurity and legislation were not well developed.

In addition to wealth, geographical location influences the assessment of the risks. In the present analysis, the impacts of climate change are greater at lower latitudes, i.e. where the type A and type B countries are located. However, the negative impact of gradual temperature increase on the productivity of certain commodity crops such as soy, wheat and maize may affect the productivity of these crops in both type C and type B countries. As animal feed is commonly produced for a global market, this may also have a secondary negative impact on the profitability and sustainability of animal production.

Locally within a particular country, a materialized threat may have a severe impact on the livelihood and food security of affected farmers. Nationally and globally, impacts on food security depend on whether the threat is general, and affects most kinds of production in a region (as, for example, extreme weather events and land degradation do), or specific (such as a plant pest infecting just one specific crop variety). Equally, at the global level, impacts on food security depend on the commodity under threat: if corn production or chicken production were seriously compromised, more people would be adversely affected than would be the case if the production of peppers or rabbits were compromised.

Conclusion

The overall conclusion of this study is that geographical location, public stewardship and economic strength appear to be the major determinants of differences in the risks presented by several biophysical threats to agricultural production in different kinds of countries. As these determinants are far from evenly spread among the world's major food producers, diversified risk monitoring and international assessment of agricultural production will play a critical role in assuring global food security in 2050.

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References

Agrios, G. N. (2004). *Plant Pathology* (5th ed.). Amsterdam: Elsevier, Academic Press.

Ainsworth, E. A., & Long, S. P. (2005). What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. *New Phytologist, 165*(2), 351–371.

Anderson, P. K., Cunningham, A. A., Patel, N. G., Morales, F. J., Epstein, P. R., & Daszak, P. (2004). Emerging infectious diseases of plants: pathogen pollution, climate change and agrotechnology drivers. *Trends in Ecology and Evolution, 19*(10), 535–544.

Andersson, E., Brogaard, S., & Olsson, L. (2011). The political ecology of land degradation. *Annual Review of Environment and Resources, 36*, 295–319.

Avnery, S., Mauzerall, D. L., Liu, J. F., & Horowitz, L. W. (2011). Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage. *Atmospheric Environment, 45*(13), 2284–2296.

Ayliffe, M., Singh, R., & Lagudah, E. (2008). Durable resistance to wheat stem rust needed. *Current Opinion in Plant Biology, 11*(2), 187–192.

Bai, Z. G., Dent, D. L., Olsson, L., & Schaepman, M. E. (2008). Proxy global assessment of land degradation. *Soil Use and Management, 24*(3), 223–234.

Barrett, M., Howard, G., Pedley, S., Taylor, R., & Nalubega, M. (2000). A comparison of the extent and impacts of sewage contamination on urban groundwater in developed and developing countries. *Schriftenreihe des Vereins für Wasser-, Boden- und Lufthygiene, 105*, 179–185.

Bartram, J., & Cairncross, S. (2010). Hygiene, sanitation, and water: forgotten foundations of health. *PLoS Medicine, 7*(11), e1000367.

Battisti, D. S., & Naylor, R. L. (2009). Historical warnings of future food insecurity with unprecedented seasonal heat. *Science, 323*(5911), 240–244.

Bezirtzoglou, C., Dekas, K., & Charvalos, E. (2011). Climate changes, environment and infection: facts, scenarios and growing awareness from the public health community within Europe. *Anaerobe, 17*(6), 337–340.

Black, P. F., Murray, J. G., & Nunn, M. J. (2008). Managing animal disease risk in Australia: the impact of climate change. *Revue scientifique et technique, 27*(2), 563–580.

Bridges, E. M., & Oldeman, L. R. (1999). Global assessment of human-induced soil degradation. *Arid Soil Research and Rehabilitation, 13*(4), 319–325.

Cabral, J. P. (2010). Water microbiology. Bacterial pathogens and water. *International Journal of Environmental Research and Public Health, 7*(10), 3657–3703.

Cheng, S. P. (2003). Heavy metal pollution in China: Origin, pattern and control. *Environmental Science and Pollution Research, 10*(3), 192–198.

Chepurnykh, N. V., & Osmanov, O. I. (1988). Two approaches to calculating economic losses in crop production due to contamination of the atmosphere by industry. Vestnik Sel'skokhozyaistvennoi Nauki Moscow, USSR No. 4 pp. 73–81.

Childers, D. L., Corman, J., Edwards, M., & Elser, J. J. (2011). Sustainability challenges of phosphorus and food: solutions from closing the human phosphorus cycle. *Bioscience, 61*(2), 117–124.

Chua, K. B. (2003). Nipah virus outbreak in Malaysia. *Journal of Clinical Virology, 26*(3), 265–275.

Cordell, D., Drangert, J. O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change-Human and Policy Dimensions, 19*(2), 292–305.

De Jong, R., De Bruin, S., Schaepman, M., & Dent, D. (2011). Quantitative mapping of global land degradation using Earth observations. *International Journal of Remote Sensing, 32*(21), 6823–6853.

Eckersten, H., Herrmann, A., Kornher, A., Halling, M., Sindhøj, E., & Lewan, E. (2011). Predicting silage maize yield and quality in Sweden as influenced by climate change and variability. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science, 62*(2), 151–165.

FAO (2011). *The state of the world's land and water resources for food and agriculture (SOLAW) - Managing systems at risk*. http://www.fao.org/docrep/015/i1688e/i1688e00.pdf. Accessed January 30th 2013.

FAO (2012). FAOSTAT. http://www.faostat.fao.org. Accessed May 10th 2012.

Fewtrell, L., Kaufmann, R. B., Kay, D., Enanoria, W., Haller, L., & Colford, J. M., Jr. (2005). Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. *Lancet Infectious Diseases, 5*(1), 42–52.

Forbes, G. A., & Jarvis, M. C. (1994). Host resistance for management of potato late blight. In G. W. Zehnder, M. L. Powelson, R. K. Jansson, &

K. V. Raman (Eds.), *Advances in potato pest biology and management* (pp. 439–457). St. Paul, MN: American Phytopathological Society.

Forman, S., Hungerford, N., Yamakawa, M., Yanase, T., Tsai, H. J., Joo, Y. S., et al. (2008). Climate change impacts and risks for animal health in Asia. *Revue scientifique et technique, 27*(2), 581–597.

Forman, S., Le Gall, F., Belton, D., Evans, B., Francois, J. L., Murray, G., et al. (2009). Moving towards the global control of foot and mouth disease: an opportunity for donors. *Revue scientifique et technique, 28*(3), 883–896.

Garrett, K. A., Forbes, G. A., Savary, S., Skelsey, P., Sparks, A. H., Valdivia, C., et al. (2011). Complexity in climate-change impacts: an analytical framework for effects mediated by plant disease. *Plant Pathology, 60*(1), 15–30.

Githeko, A. K., Lindsay, S. W., Confalonieri, U. E., & Patz, J. A. (2000). Climate change and vector-borne diseases: a regional analysis. *Bulletin of the World Health Organization, 78*(9), 1136–1147.

Godfray, H. C., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., et al. (2010). Food security: the challenge of feeding 9 billion people. *Science, 327*(5967), 812–818.

Graham, J. P., Leibler, J. H., Price, L. B., Otte, J. M., Pfeiffer, D. U., Tiensin, T., et al. (2008). The animal-human interface and infectious disease in industrial food animal production: rethinking biosecurity and biocontainment. *Public Health Report, 123*(3), 282–299.

Guo, Y., Yu, H. Y., & Zeng, E. Y. (2009). Occurrence, source diagnosis, and biological effect assessment of DDT and its metabolites in various environmental compartments of the Pearl River Delta, South China: a review. *Environmental Pollution, 157*(6), 1753–1763.

Hansen, J., Sato, M., & Ruedy, R. (2012). Perception of climate change. *Proceedings of the National Academy of Sciences of the United States of America, 109*(37), E2415–E2423.

Harrus, S., & Baneth, G. (2005). Drivers for the emergence and re-emergence of vector-borne protozoal and bacterial diseases. *International Journal for Parasitology, 35*(11–12), 1309–1318.

Holoubek, I., Dusek, L., Sanka, M., Hofman, J., Cupr, P., Jarkovsky, J., et al. (2009). Soil burdens of persistent organic pollutants - their levels, fate and risk. Part I. Variation of concentration ranges according to different soil uses and locations. *Environmental Pollution, 157*(12), 3207–3217.

Hunter, P. R. (2003). Climate change and waterborne and vector-borne disease. *Journal of Applied Microbiology, 94*(Suppl), 37S–46S.

IAEA (2001). Present and future environmental impact of the Chernobyl accident. http://www-pub.iaea.org/MTCD/Publications/PDF/te_1240_prn.pdf. Accessed January 30th 2013.

IPCC (2007). Climate Change 2007: Synthesis Report. http://ipcc.ch/publications_and_data/ar4/syr/en/main.html. Accessed January 30th 2013.

Jaggard, K. W., Qi, A., & Ober, E. S. (2010). Possible changes to arable crop yields by 2050. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 365*(1554), 2835–2851.

Kalantari, M. R. (2006). Soil pollution by heavy metals and its remediation Mazandaran (Iran). *Journal of Applied Sciences, 6*, 2110–2116.

Kaufman, J. A. (2008). China's heath care system and avian influenza preparedness. *Journal of Infectious Diseases, 197*, S7–S13.

Kharas, H. (2010). The emerging middle class in developing countries, OECD. http://www.oecd.org/dev/44457738.pdf. Accessed January 30th 2013.

Khouri, N., Shideed, K., & Kherallah, M. (2011). Food security: perspectives from the Arab World. *Food Security, 3*, S1–S6.

Lindgren, E., Albihn, A., & Andersson, Y. (2011). Climate change, water-related health impacts, and adaptation: highlights from the Swedish Government's commission on climate and vulnerability. In J. D. Ford & L. Berrang-Ford (Eds.), *Climate change adaptation in developed nations - from theory to practice* (Vol. 42, pp. 177–188). Dordrecht: Springer Science C Business Media B.V.

Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science, 319*(5863), 607–610.

Miraglia, M., Marvin, H. J., Kleter, G. A., Battilani, P., Brera, C., Coni, E., et al. (2009). Climate change and food safety: an emerging issue with special focus on Europe. *Food and chemical toxicology, 47*(5), 1009–1021.

Montanarella, L. (2007). Trends in Land Degradation in Europe. In M. V. K. Sivakumar, & N. u. N. (Eds.), *Environmental Science and Engineering; Climate and Land Degradation* (pp. 83-104). Berlin: Springer-Verlag.

Nardone, A., Ronchi, B., Lacetera, N., Ranieri, M. S., & Bernabucci, U. (2010). Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Science, 130*(1–3), 57–69.

Nayyar, D., & Dreier, L. (2012). Putting the New Vision for Agriculture into Action : A Transformation Is Happening, Word Economic Forum. http://www.weforum.org/reports/putting-new-vision-agriculture-action-transformation-happening. Accessed January 30th 2013.

Nkonya, E., Gerber, N., Baumgartner, P., von Braun, J., De Pinto, A., Graw, V., et al. (Eds.). (2011). *The economics of land degradation, toward an integrated global assessment* (Vol. 66). Frakfyrt am Main: International Academic Publishers. Development Economics and Policy.

Oberson, D., & Lafon, D. (2010). Environmental pollutions and effects on reproduction: a glance at the past. *Archives Des Maladies Professionnelles Et De L Environnement, 71*(2), 141–150.

OECD (2001). Environmental outlook for the chemicals industry. http://www.oecd.org/env/ehs/2375538.pdf. Accessed January 30th 2013.

Otte, J. M., Roland-Holst, D., Pfeiffer, D. U., Soares-Magalhaes, J., Rushton, J., Graham, J. P., et al. (2007). Industrial livestock production and global health risks. *Pro-Poor Livestock Policy Initiative Research Report* (pp. 1-21): FAO. http://www.fao.org/ag/againfo/programmes/en/pplpi/docarc/rep-hpai_industrialisationrisks.pdf. Accessed February 8th 2014.

Pan, J. L., Plant, J. A., Voulvoulis, N., Oates, C. J., & Ihlenfeld, C. (2010). Cadmium levels in Europe: implications for human health. *Environmental Geochemistry and Health, 32*(1), 1–12.

Parry, M., Canziani, O., Palutikof, J., van der Linden, P. J., & Hanson, C. E. (Eds.). (2007). *Climate change 2007: impacts, adaptation and vulnerability.* Cambridge: Cambridge University Press.

Pimentel, D. (2006). Soil erosion: a food and environmental threat. *Environment, Development and Sustainability, 8*(1), 119–137.

Pinto, J., Bonacic, C., Hamilton-West, C., Romero, J., & Lubroth, J. (2008). Climate change and animal diseases in South America. *Revue scientifique et technique, 27*(2), 599–613.

Prasad, M. N. V. (1995). Cadmium toxicity and tolerance in vascular plant. *Environmental and Experimental Botany, 35*(4), 525–545.

Rosegrant, M. W., & Cline, S. A. (2003). Global food security: challenges and policies. *Science, 302*(5652), 1917–1919.

Rossiter, P. B., & Al Hammadi, N. (2009). Living with transboundary animal diseases (TADs). *Tropical Animal Health and Production, 41*(7), 999–1004.

Ruiz-Vera, U. M., Siebers, M., Gray, S. B., Drag, D. W., Rosenthal, D. M., Kimball, B. A., et al. (2013). Global warming can negate the expected CO2 stimulation in photosynthesis and productivity for soybean grown in the Midwestern United States. *Plant Physiology, 162*(1), 410–423.

Sage, R. F., & Kubien, D. S. (2007). The temperature response of C(3) and C(4) photosynthesis. *Plant, Cell & Environment, 30*(9), 1086–1106.

Sartori, R., Sartor-Bergfelt, R., Mertens, S. A., Guenther, J. N., Parrish, J. J., & Wiltbank, M. C. (2002). Fertilization and early embryonic development in heifers and lactating cows in summer and lactating and dry cows in winter. *Journal of Dairy Science, 85*(11), 2803–2812.

Seal, J., Regmi, A., & Bernstrein, J. (2003). International evidence of food consumption patterns. *USDA Technical Bulletin, 1904*. http://

www.ers.usda.gov/publications/tb-technical-bulletin/tb1904.aspx#.UvUFnf3LfbI. Accessed February 8th 2014.

Semenov, M. A., & Shewry, P. R. (2011). Modelling predicts that heat stress, not drought, will increase vulnerability of wheat in Europe. *Science Reports, 1*, 66.

Sheldrick, W. F., Syers, J. K., & Lingard, J. (2002). A conceptual model for conducting nutrient audits at national, regional, and global scales. *Nutrient Cycling in Agroecosystems, 62*(1), 61–72.

Sherman, D. M. (2010). A global veterinary medical perspective on the concept of one health: focus on livestock. *Ilar Journal, 51*(3), 281–287.

Sims, L. D., Domenech, J., Benigno, C., Kahn, S., Kamata, A., Lubroth, J., et al. (2005). Origin and evolution of highly pathogenic H5N1 avian influenza in Asia. *Veterinary Record, 157*(6), 159.

Skovgaard, N. (2007). New trends in emerging pathogens. *International Journal of Food Microbiology, 120*(3), 217–224.

Stegeman, J. A., Elbers, A. R., Boum, A., & de Jong, M. C. (2002). Rate of inter-herd transmission of classical swine fever virus by different types of contact during the 1997-8 epidemic in The Netherlands. *Epidemiology and Infection, 128*(2), 285–291.

Steinfeld, H., Wassenaar, T., & Jutzi, S. (2006). Livestock production systems in developing countries: status, drivers, trends. *Revue scientifique et technique, 25*(2), 505–516.

Stoorvogel, J., Smaling, E. M. A., & Janssen, B. H. (1993). Calculating soil nutrient balances in africa at different scales. I. Supra-national scale. *Fertiliser Research, 35*, 227–235.

Stuthman, D. D., Leonard, K. J., & Miller-Garvin, J. (2007). Breeding crops for durable resistance to disease. *Advances in Agronomy, 95*, 319–367.

Tadesse, W., Manes, Y., Singh, R. P., Payne, T., & Braun, H. J. (2010). Adaptation and performance of CIMMYT spring wheat genotypes targeted to high rainfall areas of the world. *Crop Science, 50*(6), 2240–2248.

Thompson, D., Muriel, P., Russell, D., Osborne, P., Bromley, A., Rowland, M., et al. (2002). Economic costs of the foot and mouth disease outbreak in the United Kingdom in 2001. *Revue scientifique et technique, 21*(3), 675–687.

Thornton, P. K. (2010). Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B-Biological Sciences, 365*(1554), 2853–2867.

Thornton, P. K., van de Steeg, J., Notenbaert, A., & Herrero, M. (2009). The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agricultural Systems, 101*(3), 113–127.

Thornton, P. K., Jones, P. G., Ericksen, P. J., & Challinor, A. J. (2011). Agriculture and food systems in sub-Saharan Africa in a 4 degrees C+world. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences, 369*(1934), 117–136.

Tirado, M. C., Clarke, R., Jaykus, L. A., McQuatters-Gollop, A., & Franke, J. M. (2010). Climate change and food safety: a review. *Food Research International, 43*(7), 1745–1765.

UN (2000). United Nation Millennium Declaration A/RES/55/2. http://www.un.org/millennium/declaration/ares552e.pdf. Accessed February 8th 2014.

UN (2011). World Population Prospects: The 2010 Revision, Highlights and Advance Tables. http://esa.un.org/unpd/wpp/Documentation/pdf/WPP2010_Highlights.pdf. Accessed December 30th 2013.

UNEP (2007). Global Environmental Outlook 4. http://www.unep.org/geo/GEO4/report/GEO-4_Report_Full_en.pdf. Accessed December 30th 2013.

Van den Bossche, P., & Coetzer, J. A. (2008). Climate change and animal health in Africa. *Revue scientifique et technique, 27*(2), 551–562.

Varshney, R. K., Bansal, K. C., Aggarwal, P. K., Datta, S. K., & Craufurd, P. Q. (2011). Agricultural biotechnology for crop improvement in a variable climate: hope or hype? *Trends in Plant Science, 16*(7), 363–371.

Vlek, P. L. G., Le, Q. B., & Temne, L. (2010). Advances in soil science. In L. Rattan & B. L. Stewart (Eds.), *Food security and soil quality.* Boca, Raton: CRC Press.

von Braun, J. (2009). Addressing the food crisis: governance, market functioning, and investment in public goods. *Food Security, 1*(1), 9–15.

Wang, T., Wang, Y. W., Fu, J. J., Wang, P., Li, Y. M., Zhang, Q. H., et al. (2010). Characteristic accumulation and soil penetration of polychlorinated biphenyls and polybrominated diphenyl ethers in wastewater irrigated farmlands. *Chemosphere, 81*(8), 1045–1051.

Weber, J. B., & Mrozek, E. (1979). Polychlorinated biphenyls - phytotoxicity, absorption and translocation by plants, and inactivation by activated carbon. *Bulletin of Environmental Contamination and Toxicology, 23*(3), 412–417.

Wellings, C. R. (2007). Puccinia striiformis in Australia: a review of the incursion, evolution, and adaptation of stripe rust in the period 1979–2006. *Australian Journal of Agricultural Research, 58*(6), 567–575.

Williams, D., & Matthews, D. (1988). Outbreaks of classical swine fever in Great Britain in 1986. *Veterinary Record, 122*(20), 479–483.

Zadoks, J. (2008). The potato murrain on the European continent and the revolutions of 1848. *Potato Research, 51*(1), 5–45.

Zhao, X. R., Zheng, M. H., Zhang, B., Zhang, Q. H., & Liu, W. B. (2006). Evidence for the transfer of polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzofurans from soil into biota. *Science of the Total Environment, 368*(2–3), 744–752.

Zheljazkov, V. D. (1996). International symposium on medicinal and aromatic plants. *Acta Horticulturae, 426*, 397–417.

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