



# Potato production systems in different agro ecological regions and their relation with climate change

Position paper

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## Executive summary

Agriculture stands to be greatly affected by climate change. However, it also is a major source of greenhouse gases to the atmosphere, thus itself contributing to climate change. Therefore, climate change is a key issue which has the potential to change the production and processing landscape.

Potato (*Solanum* spp.) is an important cash crop with a high nutritional content and a relative low water footprint compared to other staple crops. Currently, it is the top of most important food crop in terms of human consumption. In future, the demand for potato and products likely are foreseen to grow even further in developing countries as the world population is predicted to grow from 7 billion to 9 billion by 2050 mainly in developing countries. Clearly potato production systems will have to respond to the impacts of climate change and in addition, greenhouse gas emissions energy from arable lands will have to be managed.

Potato yields vary considerably across the world. Many factors contribute to this variation, providing targets for improved agronomic practice and a stimulus to improve varieties to increase production in the poorest-yielding regions. The ability to adapt potato to withstand multiple biotic and abiotic stresses is critical to its future growth as a major food source.

The Global Research Alliance on Agricultural Greenhouse Gases (GRA) brings countries together to find ways to grow more food without increasing greenhouse gas emissions. This position paper has been written for the GRA network and attends to the most important sources of GHG emissions and to factors with a major impact on potato growth and development. It covers management practices that may be effective in reducing GHG emission intensity and adaptation to climate change. Finally, examples of currently running initiatives in international potato research and development are given. As a way forward, an expert judgement of the authors on the regional risks and actions or research priorities needed is presented.

# 1. Introduction

Potato is an important cash crop and is the top of most important food crop in terms of human consumption. The crop favours cool but frost-free seasons and does not perform well in heat. This means that at latitudes between 40° and 60° North or South, farmers produce potato in summer. The growing period available for crop growth is up to 6 months in these regions, with a shorter season available when going uphill. At latitudes between 30° and 40° N or S, the crop is a spring or autumn crop at sea level and a summer crop at elevations above 1,000 m above sea level. Between 20° and 30° N or S, potato is a winter crop at sea level or a summer crop above 1,500 m altitude. In the tropics at latitudes below 20° N or S, the crop can only be grown at elevations of at least 2,000 m (Haverkort, 1989; Haverkort & Verhagen, 2008).

Potato is a truly global crop and cultivated in about 100 countries ([CIPpotato.org/potato/facts](http://CIPpotato.org/potato/facts)). It is the fastest growing food crop in Sub-Saharan Africa, similar trends are observed in Asia (Haverkort, 2011). In high income countries where potato has a strong foothold, improvements focus on quality of the harvested product and the production process. In low and middle income countries sustainably increasing production levels is the key focus.

Climate change is a key issue which has the potential to change the production and processing landscape. Clearly potato production systems will have to respond to the impacts of climate change in addition greenhouse gas emissions energy from arable lands will have to be managed. When interpreting the repercussions of climate change to potato, there is a fundamental difference for areas where potato is grown in a relatively frost-free period (there may be advantages because of a longer growing season) or in a relatively heat-free period (with the disadvantage of still shorter growing seasons). The role of potato production in the mitigation debate will mainly focus around the use of nitrogen.

Linking adaptation and reducing GHG emission intensity is at the core of the mission of the Global Research Alliance on Agricultural Greenhouse Gases (GRA) (<http://www.globalresearchalliance.org>). For potato production systems we will aim to establish a network to share experiences and address both adaptation and mitigation issues. We will do this by building on existing networks and expertise.

The main focus will be on the field and farm level, field because this is where the man-environment interaction takes place, the farm because this is the decision making unit that links to markets and the society. Links with value chain partners will be explored.

The keen interest of the Netherlands is explained by the leading position of the Netherlands in seed potatoes, and although not the top ten of producing countries it is in the top three of exporting countries. Wageningen UR has a leading position in reach related to potato breeding and cultivation, links with the processing industry are strong and has outstanding expertise on the entire potato value chain.

This document provides background on potato production systems, starting with a scoping of global production systems and tries to identify key issues for policy and research. It is meant as a starting point for discussion and collaboration on GRA relevant topics. The outcome of this process will be used to create regional or global networks on the identified topics.

## 2. Global overview

### 2.1 Differences in production levels between regions & countries.

The potato (*Solanum* spp.) is emerging as the most important staple cash crop in the world with a high nutritional content and a relative low water footprint compared to other staple crops. The potato, rich in carbohydrates, micronutrients, dietary antioxidants and vitamins B and C and a protein content comparable to cereal grains (Burlingame, 2009) yields more food on less land than any other major food crop as up to 85% of the plant may constitute edible food for humans, compared to only 50% for most cereal grains (FAO, 2009a).

Since its introduction to Europe in the sixteenth century and its worldwide distribution it has had an important contribution to food and nutrition security (He, 2012). Recently, potato has even become one of the largest food crops (Spooner *et al.*, 2010). FAO data from 2012 show that potato belongs to the top six in the ranking of cash crop production (Figure 1). Globally, circa 20 million hectares are grown producing more than 300 million tons annually.

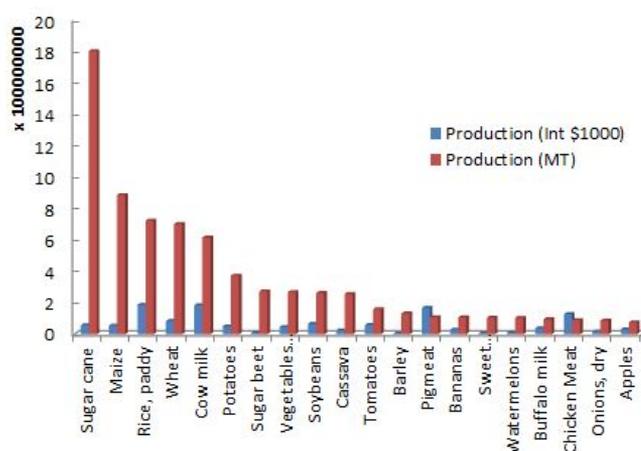


Figure 1. Ranking potato on global cash production based on production area (FAO, 2012)

A FAOSTAT trend analysis reveals how potato production in developing countries has been growing the last decades (Figure 2). The overall trend in potato production from 1991 to 2006 shows a 21 % increase, from 268 million tonnes (Mt) to 325 Mt (FAO, 2012). Underpinning this is the considerable (48 %) increase in potato production from 85 Mt to 165 Mt in the developing world, whereas production in the industrialized world just has decreased 12 % from 183 Mt to 160 Mt. In 2005, production in the developing world matched that in the developed world for the first time. Over the period from 1992 to 2010, Europe had been the major producer of potatoes, with 44.5 % of the global potato harvest in that period, and Asia is ranked a close second (37.5 %) (Figure 3). However, potato production has declined in Europe and increased in Asia. In particular southern and eastern Asia have shown the most rapid expansion over the past few decades with China as the largest potato-producing country in the world at the moment (Hijmans and Spooner 2001). In 2010 alone Asia accounted for 47.5 % of the global potato crop, whereas Europe contributed 33.3 %.

In future, the demand for potato and products likely are foreseen to grow even further in developing countries as the world population is predicted to grow from 7 billion to 9 billion by 2050 mainly in developing countries (Table in Figure 4). However, it is expected that the demand in Europe may

further decline and European companies will need to target growing markets in Asia, South America and even Africa (World Potato Markets, 2011).

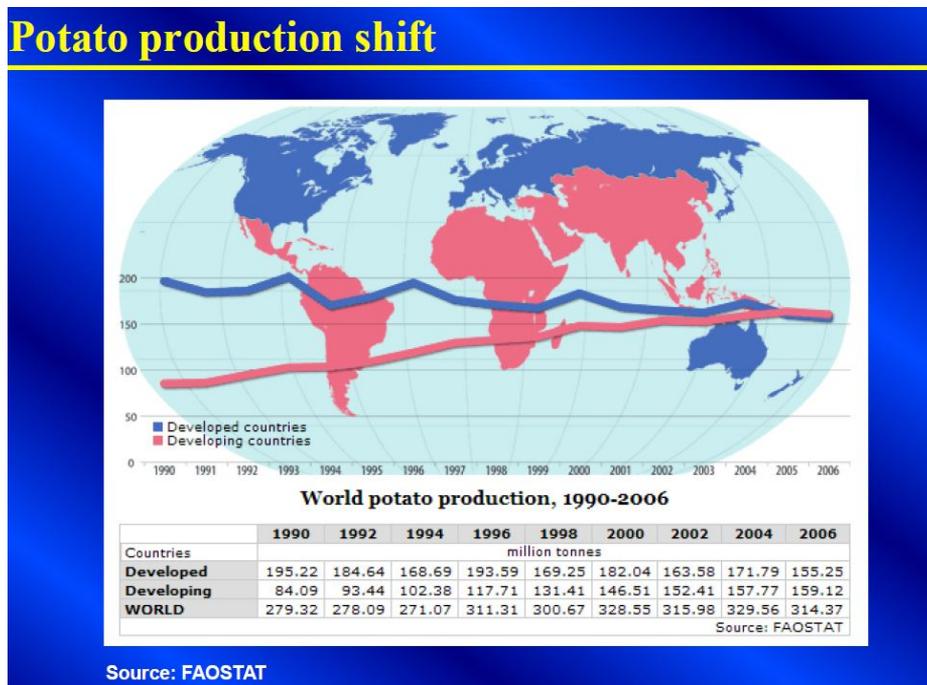


Figure 2. Potato production shift from 1900 until 2006 (FAO, 2012)

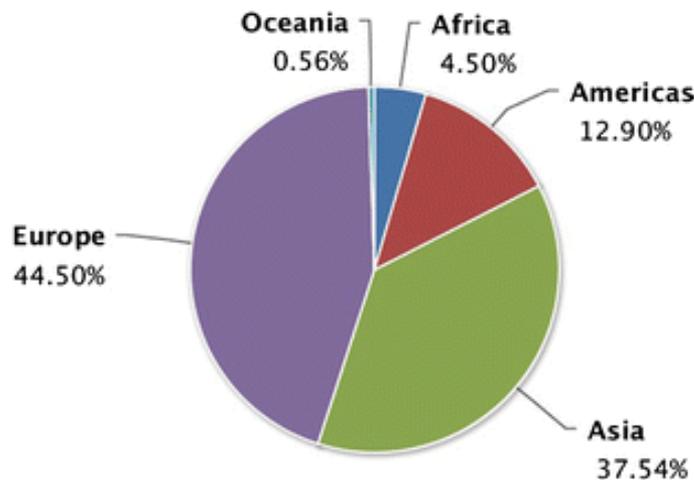


Figure 3. Potato production (as a percentage) by world regions (FAO, 2012)

Population growth 2010- 2050							
Year	World	Asia	Africa	Europe	Latin America	North America	Oceania
2010	6 909	4 167	1 033	733	589	352	36
2020	7 675	4 596	1 276	733	646	383	40
2030	8 309	4 917	1 524	723	690	410	45
2040	8 801	5 125	1 770	708	718	431	48
2050	9 150	5 231	1 998	691	729	448	51

Source: UN

Figure 4. Expected growth of the world until 2050 in the different continents (World potato Markets, 2011)

## 2.2 Potato production

The importance of potato as a dietary staple varies by region. In Europe, especially in Eastern, Central, and North Western Europe, it is an important staple. Outside Europe potato is gaining importance.

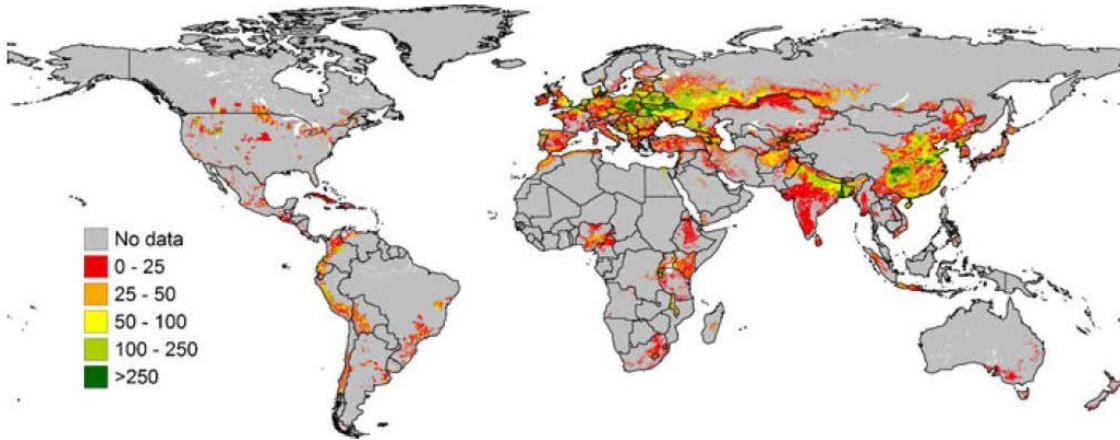


Figure 5. Harvested areas of potatoes around the year 2000 (ha per grid cell) (From: Haverkort *et al.*, 2013)

The global harvested potato area is carefully mapped by Haverkort *et al.* (2013) (Figure 5). It totally amounts to about 20 million hectares and results in a global production of at least 329 million metric tonnes (in 2009). The highest concentrations of production areas are found in the temperate zone of the northern hemisphere where the crop is grown in summer during the frost-free period. In tropical regions, the crop is restricted to the highlands of the Andes approaching 4,000 m elevation, the African Rif, and volcanic mountains of West Africa and Southeast Asia (near sea level). In the subtropics, the crop is grown as a winter crop during the heat-free period such as in the Mediterranean region, North India, and southern China. Potato is absent in tropical lowlands as temperatures are too high for tuber growth, but the crop appears in all other eco-regions and as such is one of the global crops with a most diverse distribution pattern.

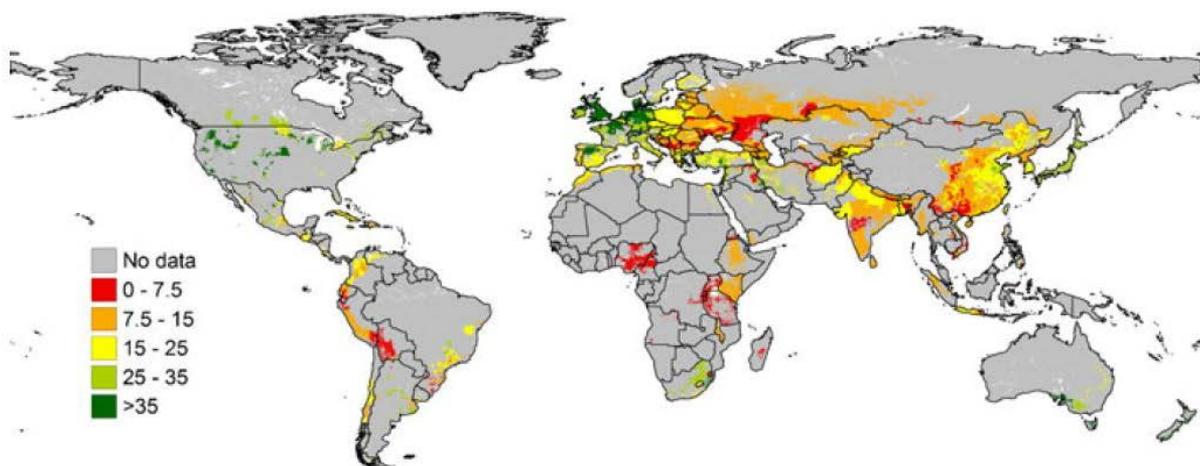


Figure 6. Fresh tuber yield of potatoes around the year 2000 of grid cells with harvested area >0 (tons ha<sup>-1</sup> harvest<sup>-1</sup>)

Production levels greatly vary between regions as is shown in Figure 6 (Haverkort *et al.*, 2013). On 59% of the global potato acreage yield is lower than 15 t ha<sup>-1</sup>. Together, these areas produce 38%

of the global tonnage. Low yields between 7.5 and 15 t ha<sup>-1</sup> are mainly found in Eastern Europe, India, and China. Even lower yields are found in some tropical highlands.

Egypt is Africa's top potato producer, and has increased its production by 144% from 1990 to 2009 (FAOSTAT, 2011). Egypt also ranks among the world's top exporters of fresh and frozen potato products directed mostly to European markets (FAO, 2009a ).

For irrigated agriculture in temperate climates, yields typically vary between 25 and 45 tonnes ha<sup>-1</sup> with a growing season of about 120–150 d crops and requiring from 500 to 700 mm of water for transpiration. From figure 6 it is clear that most potato production areas lag behind. Most likely because of suboptimal circumstances and suboptimal agricultural practices. Climate change and poor management resulting in increased salinity and drought are severe threats to potato production. Water deficits in the middle to late stages of the growing season generally have the largest negative impacts on yield (FAO, 2009a; FAOSTAT, 2011).

## 2.3 Relevance potato on world market

Global interest in potato increased sharply in 2008 as world food prices soared, threatening the food security and stability of dozens of low-income countries (He, 2012). The top 20 potato-producing countries accounting for approximately 80% of global production (Figure 7) with a crop valuation of close to 30 billion international dollars in 2008 (data compiled from FAOSTAT, 2011) . Nevertheless, potato is not a globally traded commodity, and prices are usually determined by local production costs. Thus, potato is increasingly regarded as a vital food-security crop and as a substitute for costly cereal imports.

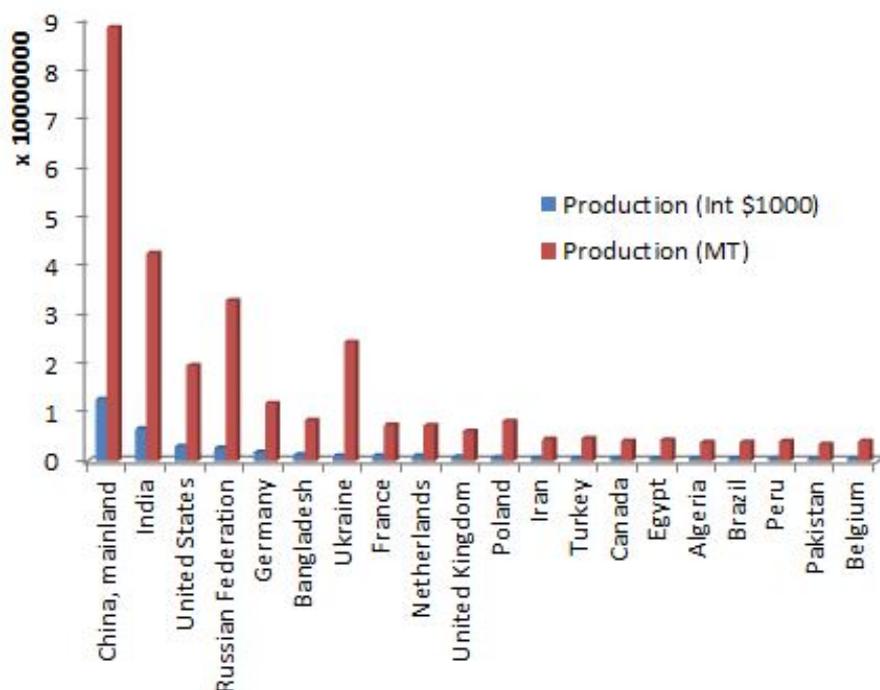


Figure 7. Summary of the top 20 potato-producing nations (2008) comparing valuation in dollars with quantity in metric tonnes (MT of megagrams, Mg) (FAOSTAT, 2012)

### 3. Emissions from agriculture

Agriculture stands to be greatly affected by climate change. However, it also is a major source of greenhouse gases to the atmosphere, thus itself contributing to climate change (Tubiello 2007). Clearing and management of land for food and livestock production over the past century were responsible for cumulative carbon emissions of about 150 GT C, compared to 300 GT C from fossil fuels (LULUCF, 2000). At present, agriculture and associated land use changes emit about a third of the worldwide greenhouse gas emissions.

Both the magnitude of the emissions and the relative importance of different sources vary widely among world regions and are shown for direct and indirect GHG in Figure 8 and for CO<sub>2</sub> in Figure 9. In 2005, the group of five regions mostly consisting of non-Annex I countries (i.e. 154 in total, see: [http://unfccc.int/parties\\_and\\_observers/parties/non\\_annex\\_i/items/2833.php](http://unfccc.int/parties_and_observers/parties/non_annex_i/items/2833.php)) was responsible for 74% of total agricultural emissions.

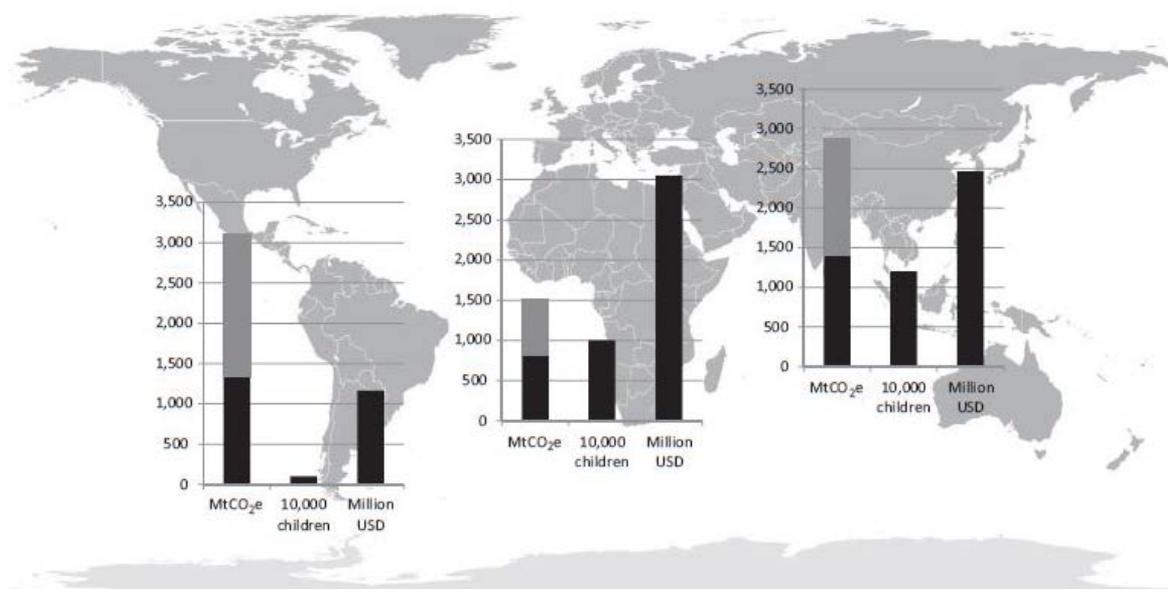


Figure 8. Regional differences in estimated direct GHG emissions from agricultural production (black) and indirect GHG emissions from agricultural-driven land-use change (gray) for the year 2005, and adaptation cost to prevent malnourishment children ([www.annualreviews.org](http://www.annualreviews.org))

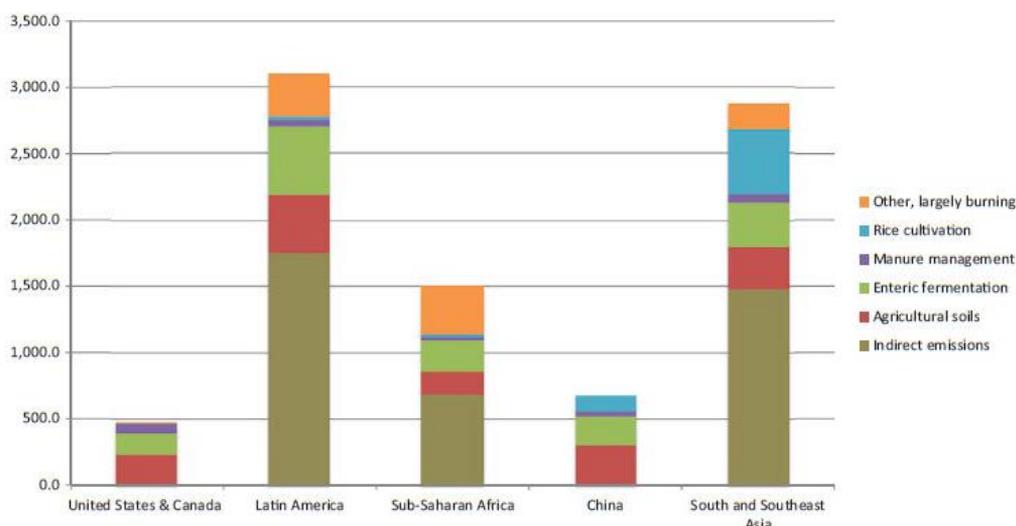


Figure 9. Regional differences in the composition of direct and indirect emissions from agricultural production for the year 2005 in Mt of CO<sub>2</sub>-eq ([www.annualreviews.org](http://www.annualreviews.org))

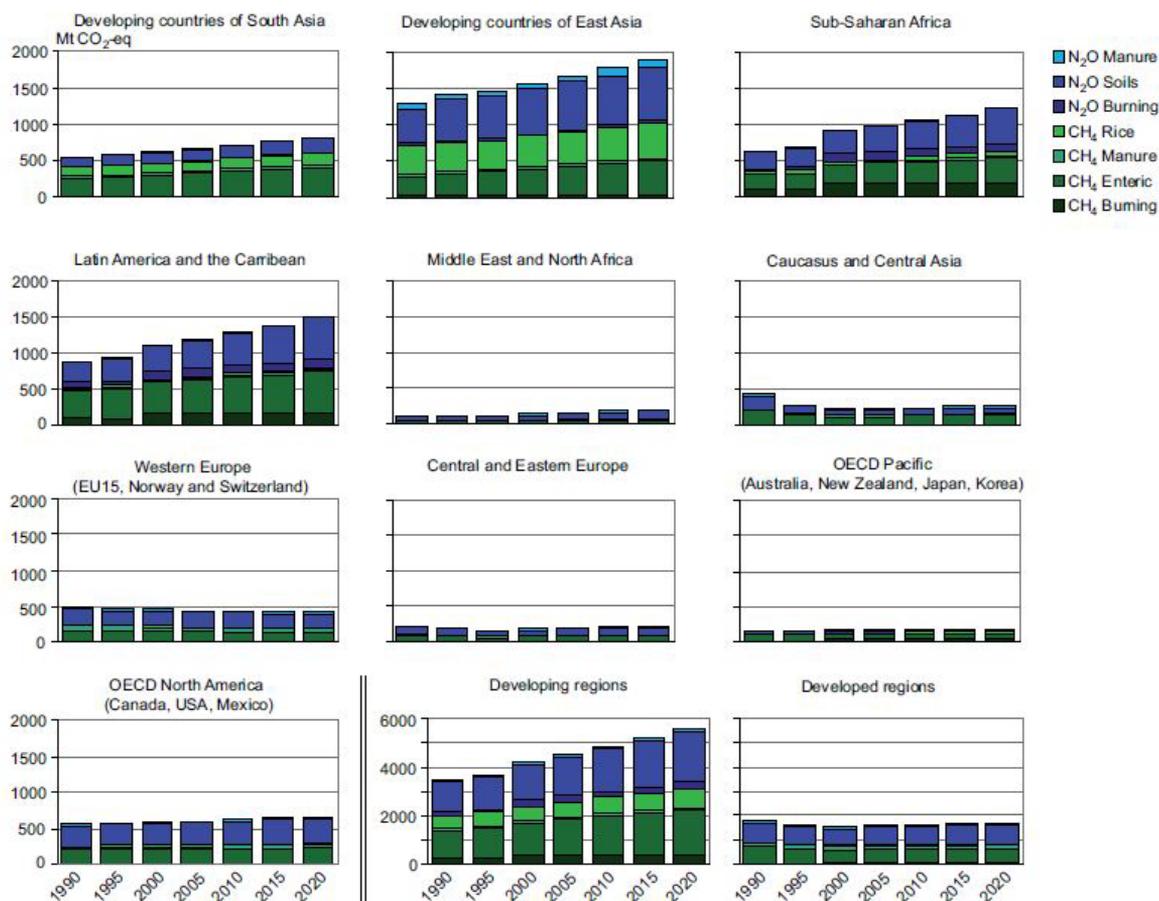


Figure 10. Estimated historical and projected CH<sub>4</sub> and N<sub>2</sub>O emissions in the agricultural sector of the ten world regions during the period 1990-2020. (Source: Adapted from USEPA, 2006)

Tubiello (2007) mentions that agriculture and land use change emit a quarter of the CO<sub>2</sub> emission (through deforestation and soil organic carbon depletion, machine and fertilizer use), half of the methane (via livestock and rice cultivation), and three-fourths of the nitrous oxide annually released into the atmosphere by human activities. Figure 10 shows the main regions, responsible for the CH<sub>4</sub> and N<sub>2</sub>O emissions. In seven of the ten regions, N<sub>2</sub>O from soils was the main source of GHGs in the agricultural sector in 2005, mainly associated with N fertilizers and manure applied to soils.

### 3.1 Emissions from potato cultivation

Total greenhouse gas emissions from potato production worldwide are difficult to assess in detail. However, Evert *et al.* (2013) identified hotspots in the potato cultivation regions worldwide having a potentially significant environmental or social impact' using a quick-scan approach. In addition, they calculated GHG emission per ton of fresh potato yield by summing:

- (1) emissions due to seed production, biocides, and diesel use for operations on the farm,
- (2) emissions from N fertilizer production and use,
- (3) emissions related to diesel use for irrigation, and
- (4) (in)direct soil emissions from N in potato residues which are left in the field.

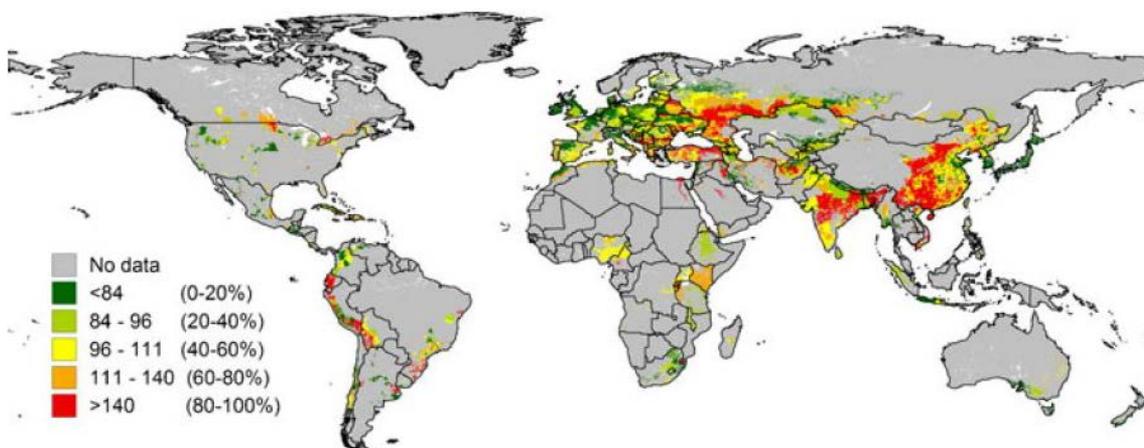


Figure 11. GHG emission per ton fresh potato yield (kg CO<sub>2</sub>-eq t<sup>-1</sup>)

For the evaluation of the GHG emissions and to define an indicator value for a carbon footprint on acceptable environmental impact, Evert *et al.* (2013) used the 80th percentile of the GHG emissions of all potato producing grid cells (with a value of 140 kg CO<sub>2</sub>-eq t<sup>-1</sup>) as a threshold. Figure 11 shows that the GHG emissions of potato production exceed this threshold in the Andes, in southern Russia, in India, and in most of China. In order to work on improving the sustainability of an agricultural production system, one does not need to know what thresholds to aim for. For example, it is certainly not the case that a potato producer with GHG emissions of less than 140 kg CO<sub>2</sub>-eq t<sup>-1</sup> (the 80<sup>th</sup> percentile) should feel free to neglect opportunities to reduce his or her carbon footprint.

### 3.2 Sources of emissions from cultivation

Most important sources of GHG emissions from crop cultivation are emissions from the field (mainly N<sub>2</sub>O), energy used for nitrogen fertilizer production and diesel fuel burned.(CO<sub>2</sub>) On top of that are the minor emissions from the production of other fertilizer compounds, biocides and gasoline. In Figure 12 sources of GHG emissions from a potato cultivation are shown quantitatively (in grams of CO<sub>2</sub> equivalent).

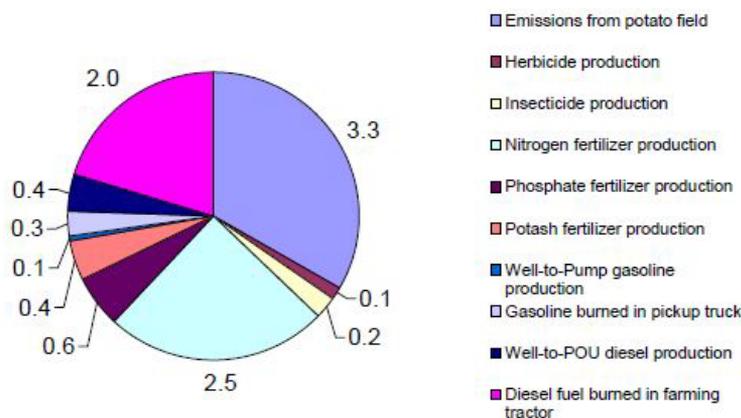


Figure 12. Sources of GHG emissions from a potato cultivation (source: Morgan *et al.*, 2007)

The management style of individual potato farmers and their efficiency also play an important role. Khoshnevisan (2013) analysed data obtained from an inventory in the province of Esfahan in Iran. Khoshnevisan concluded that 13% of the overall input energies (i.e. 11506.63 MJ ha<sup>-1</sup>) could be saved if the performance of inefficient farms could be risen to a higher level. He also concluded that, by energy optimization the total GHG emission could be reduced to the value of 2075.21 kg CO<sub>2</sub>eq in this region.

## 4. Impact of Climate Change on potato cultivation

Like many crops in agriculture, potato stands to be affected by climate change, although not all factors result in negative effects. Factors which have a major impact on crop growth and development are: increase of CO<sub>2</sub> and temperature, water stress (either drought or water logging), salinization, solar radiation and ozone, and accompanied with these factors an increased pressure of pests and diseases.

### 4.1 Increase CO<sub>2</sub>

A potato crop will benefit more from climate change than f.e. wheat or rice, especially from increased CO<sub>2</sub> levels due to increased yields and reduced crop water use if planting can be done at appropriate times of the year. Studies in open-top chambers (Schapendonk, 1995, 2000) showed that potato yields increased on average by 36% when CO<sub>2</sub> concentration was doubled from 350 to 700 ppm CO<sub>2</sub>, representing a yield increase of 0.11% per ppm increase in CO<sub>2</sub> concentration of the atmosphere. The yield response differed between years and among varieties, with late cultivars benefiting more (i.e. 49%) from increased CO<sub>2</sub> levels than early varieties (i.e. 23%). The authors hypothesized that, under higher CO<sub>2</sub> concentration, more assimilates become available in the leaves, enhancing the production and benefiting the activity of the sink organs (tubers), thus resulting in a substantial enhancement of final yield. The late variety may have benefited more because of a relatively earlier tuber formation. These data were used by (Wolf, 2003) to simulate potato yields in southern and northern Europe. He concluded that "Climate change gave increases in irrigated yields of 2,000 – 4,000 kg.ha<sup>-1</sup> dry matter in most regions of the EU." Higher yields will also lead to higher uptake of, e.g. nitrogen, so a higher nitrogen use efficiency of the available nitrogen. An increased atmospheric CO<sub>2</sub> concentration leads to a smaller stomatal aperture and reduced water losses through transpiration from individual leaves, which could possibly lead to greater water use efficiency (Schapendonk, 2000). In the trial by (Magliulo, 2003), water use of potato decreased by 11% when CO<sub>2</sub> increased from 370 to 550 ppm.

Relative crop yield response to elevated CO<sub>2</sub> is greater in rain-fed than in irrigated crops, due to a combination of increased water-use efficiency and root water-uptake capacity (Tubiello, 2007). Low fertilizer N applications tend to depress crop responses to elevated CO<sub>2</sub> (Kimball and Idso, 1983; Kimball *et al.*, 2002).

### 4.2 Temperature rise and heat stress

Higher temperatures promote foliar development, delay tuberization and influence potato quality characteristics such as higher numbers of smaller tubers per plant, and lower specific gravity which is indicative of lower dry matter contents (Haverkort, 1988). However, the possible negative effects of future raising temperatures and reduced availability of water will be more than compensated for by the positive effect of increased CO<sub>2</sub> on potential water use efficiency and crop productivity. The importance of potato as a climate change robust crop for food security is, therefore, likely to increase in the decennia to come.

Supit *et al.* (2012) concluded that "Crops planted in spring (potato, sugar beet) initially benefit from the CO<sub>2</sub> increase, however, as time progresses, increasing temperatures reduce these positive effects. By the end of the century, yields decline in southern Europe and production may only be possible if enough irrigation water is available. In northern Europe, depending on the temperature and CO<sub>2</sub> concentration increases, yields either stagnate or decline. However, in some of the cooler

regions, yield increase is still possible.” The negative aspects of climate change that these authors expect toward the end of the century are due to expected reduction of precipitation. This aspect of climate change, however, is surrounded with the greatest degree of uncertainty (Ruane *et al.*, 2013) and depending on the sort of interactions as for instance (Hijmans and Spooner, 2001) mention that yield may increase between 2010 and 2050 due to atmospheric CO<sub>2</sub> increase (+30% yield) and lengthening of the growing season (+20% yield) totaling some 50% are calculated for the rainy summer crops and lower in dry winter crops (+10%) due to higher temperatures that reduce the length of the wintercropping season. Water use efficiency in most systems will improve between 10% and 40% over this period. When the crop is grown in hot periods of the year these benefits are counteracted by an increased incidence of heat stress causing reduced tuber yield, second growth phenomena (Lugt, 1960; Vreugdenhil, 2007) and higher evapotranspiration, often leading to lower yields and water use efficiencies. (Hijmans, 2003) assessed the effect of climate change on global potato production using a simulation model linking temperature and solar radiation datasets (with plant performance based on radiation use efficiency (RUE) algorithms). In general, the strongest negative impacts to potato production were predicted for the tropical and subtropical lowlands though these impacts could be ameliorated by the development of heattolerant cultivars (Hijmans, 2003).

### 4.3 Water stress

Potato shows a high sensitivity to drought stress (dependent on cultivar rooting depth) along with preferences for tuberizing under short-day conditions and best performances in cool temperate climates (Haverkort, 1990). In addition, water stresses (i.e., either waterlogging or drought conditions) occur to varying degrees dependent on site-specific heterogeneity of soils, complexity of field-scale topography, soil resource management by the farmer, and availability of water for irrigation. Drought events occurring early in the growing season reduce the number of tubers per plant (Haverkort *et al.*, 1990). Furthermore, a single, short-term drought event during tuber bulking can inhibit future bulking of those potatoes set and result in initiation of new tubers; these plant responses not only decrease potato grade (i.e. tuber size and quality) but lower overall yield. High soil moisture conditions prior to harvest are known to negatively affect tuber specific gravity, whereas other in season stressors influence the development of disorders such as internal heat necrosis and hollow heart (Hiller, 1985).

### 4.4 Salinity

Potato has been classified as moderately sensitive to salinity up to EC-values in order of magnitude of 7 dS/m when no extreme weather conditions, like heat waves occur (Bustan *et al.*, 2004).

Salinity retards plant emergence, reduces growth of both haulms (shoots) and tubers, and hastens maturity (Levy 1992; Nadler and Heuer, 1995).

Potato leaves are very sensitive to saline water and are severely damaged by overhead irrigation with saline water (Levy and Veilleux, 2007), especially at the beginning of tuber formation (Bruns and Caesar, 1990).

During the period of bud initiation the crop is even more sensitive to salinity. In this growth stage, salinity reduces the proportion of extra-large tubers in favor of smaller, more commercially acceptable tubers. However, dry matter yield of large tubers will increase resulting from a preferential supply of assimilates (Bernstein *et al.*, 1951; Paliwal and Yadav, 1980; Nadler and Heuer, 1995). As a result, total yield of the tubers is hardly affected until EC 6, as depicted in Figure 13.

#	Treatment	Water applied (mm)
1	Non-saline, 1.5 dS m <sup>-1</sup>	480
2	Saline, 3.0 dS m <sup>-1</sup>	480
3	Saline, 6.0 dS m <sup>-1</sup>	480
4	Non-saline, 60% of water applied	288
5	Non-saline, irrigation withheld between days 57 and 74 after planting	442

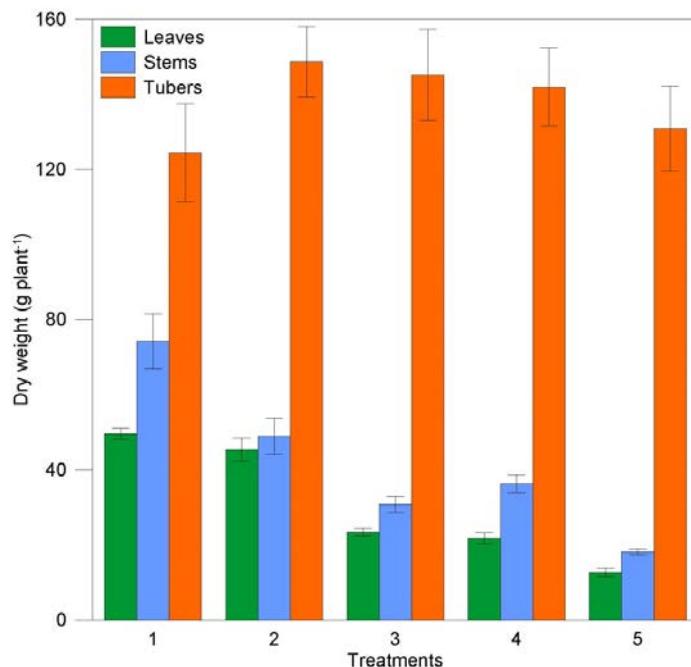


Figure 13. The effect of salt stress or water stress on the accumulation of dry weight in potato plants (reproduced after Heuer & Nadler, 1995)

Cultivar differences in salt tolerance of potato have also been well documented (Levy, 1992), but the relationship between tolerance and physiological or morphological characters has not been made and a consistent relationship between maturation time and salt tolerance has not been shown either. Levy (Levy, 1992) suggests that salt tolerance may be partly attributed to earlier maturity (salinity escape) as long as earliness is not associated with yield decline. This speculation is also consistent with general observations that higher growth rates allow a plant to dilute the effects of ions that accumulate in the tissues as a result of high salinity.

### 4.5 Pests and diseases

Climate change may have a secondary effect on the increase of the amount of pests and diseases with a concomitant effect on crop growth performances and in return plant defense mechanisms in which stress hormones ABA and HSPs (Figure 14) are involved.

Nowadays, pests and diseases already represent a serious, on-going threat to potato production, requiring considerable pesticide inputs for those diseases that can be controlled. Such chemical

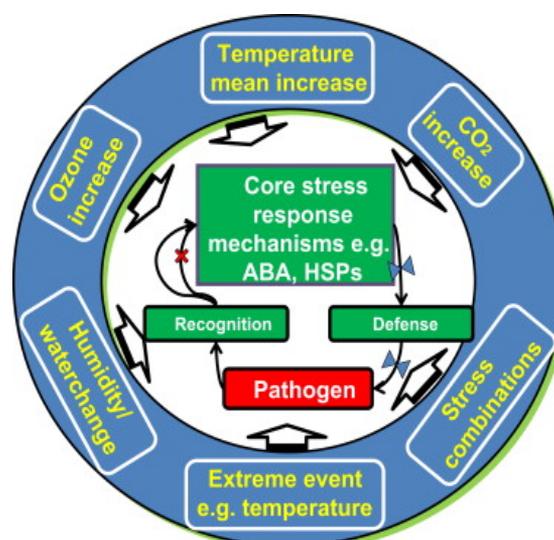


Figure 14. Schedule on the potential impact of climatic variables on host plant – pathogen interactions (From: Newton, 2012)

control is increasing in the world as potato production intensifies. Effects of climate change will also increase the pressure and challenge potato production even further.

Major global diseases that threaten the potato crop are following (Birch *et al.*, 2012):

- Late blight. This disease is caused by the oomycete pathogen *Phytophthora infestans*. *P. infestans* infects the foliage and stems of the potato crop. It is the most widespread and economically significant threat to potato production. An estimate of the chemical control costs and yield losses associated with late blight exceeds € 6.7 Million (Haverkort *et al.*, 2009). In many parts of the world fungicide application is the only means to prevent disease.
- Nematodes. They attack plants, including potato, using a variety of feeding strategies. The nematodes themselves can cause stunted or deformed roots (Riga and Neilson, 2005) but their major effect on potato is due to their ability to transmit a variety of damaging plant viruses such as Tobacco Rattle Virus (TRV) (e.g. Ploeg *et al.*, 1992). The most important nematode pathogens threatening potato production are *Trichodorus*, *Paratrichodorus*, *Meloidogyne* species and *Globodera* species. If left uncontrolled, some sorts of nematodes may cause a 75 % loss in potato yields (Seinhorst, 1982).
- Bacterial threats cause disease mainly in tropical and subtropical regions and affects around 3 million growers, on 1.5 million Ha of land in 80 countries worldwide, with losses estimated at over \$950 million annually (Walker and Collion, 1998). The most seriously affected nations include China, Bangladesh, Bolivia and Uganda, with yield loss in some regions as high as 90 % in the field and 98 % in storage (Lopez *et al.*, 1999). In many countries it is considered to be in the top 5–6 most damaging pathogens of potato, and in Peru and Bolivia is second only to late blight. Chemical controls are hardly available and soil fumigants or the use of antibiotics have proved ineffective (Murakoshi and Takahashi, 1984; Farag *et al.*, 1982; 1986) and limited success has been achieved using biocontrol with antagonistic bacteria. Intercropping with maize or bean showed some disease reduction (Autrique and Potts, 1987), as did the adjustment of soil pH by controlled soil amendments (Michel and Mew 1998).
- Virus threats. Approximately 37 viruses naturally infect potato but only about one third of them cause economically important diseases (Jeffries, 1998), like Potato leafroll virus, Potato virus X and Potato virus Y, and commonly occur in potato production systems Worldwide. Viruses cause curling, yellowing or mosaic symptoms on leaves, stunting of plants, and some affect tuber quality, inducing brown or necrotic marks and lines on tubers. Viruses seldom cause complete destruction of the crop but they rise to small, deformed tubers. Virus diseases accumulate over several growing seasons and they are the main cause of 'degeneration' of seed tubers resulting in significant yield depression.
- Insect threats, from which there are many insect pests of potato throughout the world with each geographic region having its own suite of pests. The most notorious insect threat comes from the Colorado potato beetle, which is now established in many parts of the world, but its range is still restricted by temperature, and it is absent in colder regions. The beetle and its larvae feed on potato leaves and an uncontrolled infestation can severely damage crop yield. It has traditionally been controlled with insecticides, but it has adapted insensitivity to some chemicals (Alyokhin *et al.*, 2008).

## 4.6 Extreme events

Schaap *et al.* (2011) explored the risks of a number of climate factors including extremes and the emergence and abundance of pests and diseases for the northern region of the Netherlands. For a number of cash crops they developed an Agro Climate Calender (ACC). This ACC describes climate factors, meteorological description of the climate factor, type of operational management if applicable, the impact on the seed potato crop, the potentially vulnerable period, and the estimated

range of crop losses expressed as percentage of the market value. The ACC provides an overview of potential yield and quality losses in relation to changes in climate factors, as shown for seed potato in Table 1. It also offers entry points for adaptation measures (Schaap *et al.*, 2013).

Table 1. Agro climate calendar for seed potato (description: see text).

Climate factor	Vulnerable period	Meteorological description	Farm management	Impact on crop	Weight of economic loss (%)
Wet field	Oct–Apr	Period of 21 days of more than 0.5 mm rainfall on 75% of the days	Plowing and preparation of planting bed	Delayed planting date	–
High-intensity rainfall	May–Sep	Daily precipitation of at least 45 mm or at least 60 mm in 3 days	–	Rotting of the tubers	25–75
Heat wave	Jul–Sep	Heat wave (at least 3 days with more than 30°C in a period of at least 5 days above 25°C)	–	Second growth	25–75
Warm and wet	Jul–Sep	At least 14 consecutive days with a maximum temperature above 20°C and for 50% of the days at least 0.5 mm precipitation	–	<i>Pectobacterium</i> (previously <i>Erwinia</i> ) <i>carotovorum</i> causes soft rot and black leg	10–50
Sustained wet weather	Jun–Sep	A period of at least 21 days with more than 0.5 mm precipitation on 75% of the days	Spraying	Not possible to spray against <i>Phytophthora infestans</i>	50–100
Wet field	Aug–Oct	Period of 21 days of more than 0.5 mm rainfall on 75% of the days	Harvest	Damage to tubers	N.A.
Warm winter	Dec–Mar	Period of at least 14 days with a maximum temperature above 10°C	Storage	More rotting of tubers and early sprouting in March	25–75

In a cost-benefit analysis, Schaap *et al.* (2013) calculated that changes in extremes, including pests and diseases, are important for the economic success of farming systems. They identified several viable adaptation options (Figure 15) from literature, expert judgement and in workshops with farmers.

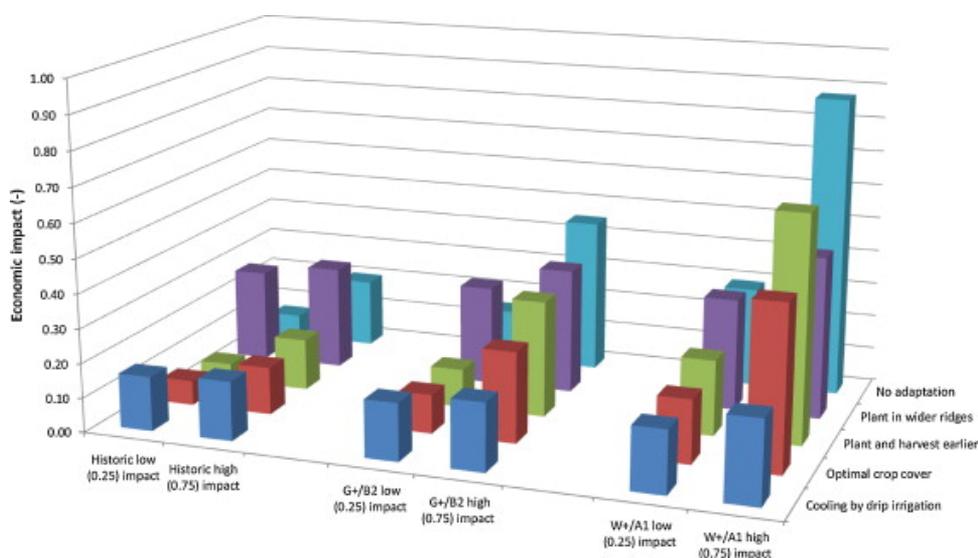


Figure 15. The economic impact of the climate factor per adaptation measure and without adaptation (as a fraction of the standard gross margin) for the climate factor heat wave that causes second-growth in seed potato and ware potato; the economic impacts considering costs and benefits of adaptation are shown per average year in historic (1976–2005), G+/B2 and W+/A1 2050 (2036–2065) scenarios.

## 5. Farm management strategies

Although annual GHG emissions from agriculture are expected to increase in the coming decades, improved management practices and emerging technologies may permit a reduction in emissions per unit of food (or of protein) produced. To determine which management practices could be effective in this context, it is worthwhile to identify the main trends in the agricultural (potato) sector with implications for GHG emissions or removals first. To summarize:

- Growth in land productivity is expected to continue, due to decreasing returns from further technological progress, and greater use of marginal land with lower productivity. Use of these marginal lands increases the risk of soil erosion and degradation, with highly uncertain consequences for CO<sub>2</sub> emissions (Lal 2004a, 2004b; Van Oost, 2004).
- Conservation tillage and zero-tillage are increasingly being adopted, thus reducing the use of energy and often increasing carbon storage in soils. According to (FAO, 2001), the worldwide area under zero-tillage in 1999 was approximately 50 Mha, representing 3.5% of total arable land. However, such practices are frequently combined with periodical tillage, thus making the assessment of the GHG balance highly uncertain.
- Further improvements in productivity will require higher use of irrigation and fertilizer, increasing the energy demand (for moving water and manufacturing fertilizer; (Schlesinger, 1999). Also, irrigation and N fertilization can increase GHG emissions (Mosier, 2001).
- Changes in policies (e.g., subsidies), and regional patterns of production and demand are causing an increase in international trade of agricultural products. This is expected to increase CO<sub>2</sub> emissions, due to greater use of energy for transportation.

### 5.1 Mitigation technologies and practices

Opportunities for mitigating GHGs fall into three broad categories:

- a. Reducing emissions of CO<sub>2</sub>, CH<sub>4</sub>, or N<sub>2</sub>O (Cole *et al.*, 1997; IPCC, 2001a; Paustian *et al.*, 2004) by more efficient management of carbon and nitrogen flows in agricultural ecosystems, like practices that deliver added N more efficiently to crops (Bouwman, 2001).
- b. Enhancing removals. Agricultural ecosystems hold large carbon reserves (IPCC, 2001a), but some of this carbon can be recovered through improved management, thereby withdrawing atmospheric CO<sub>2</sub>. Any practice that increases the photosynthetic input of carbon and/or slows the return of stored carbon to CO<sub>2</sub> via respiration, fire or erosion will increase carbon reserves, thereby 'sequestering' carbon or building carbon 'sinks'.
- c. Avoiding (or displacing) emissions by using crops and residues used as a source of fuel, either directly or after conversion to fuels such as ethanol or diesel (Schneider and McCarl, 2003; Cannell, 2003). The impacts of the mitigation options considered are summarized qualitatively in Table 2 (derived from Smith *et al.*, 2008).

### 5.2 Cropland management

Mitigation practices in cropland management, mentioned in Table 2, include following:

- a. Agronomy. Agronomic practices that increase yields and generate higher soil carbon storage (Follett, 2001) include: using improved crop varieties; extending crop rotations, notably those with perennial crops that allocate more carbon below ground; and avoiding or reducing use of bare (unplanted) fallow (West and Post, 2002; Lal *et al.*, 2003; Lal, 2004a, 2004b; Freibauer *et al.*, 2004).

Table 2. Proposed measures for mitigating GHG emissions from agriculture and their apparent effects on reducing emissions of individual gases where adopted.

Measure	Examples	Mitigative effects <sup>a</sup>			Net mitigation <sup>b</sup> (confidence)	
		CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	Agreement	Evidence
Cropland management	Agronomy	+		+/-	***	**
	Nutrient management	+		+	***	**
	Tillage/residue management	+		+/-	**	**
	Water management (irrigation, drainage)	+/-		+	*	*
	Rice management	+/-	+	+/-	**	**
	Agro-forestry	+		+/-	***	*
	Set-aside, land-use change	+	+	+	***	***
Grazing land management/ pasture improvement	Grazing intensity	+/-	+/-	+/-	*	*
	Increased productivity (e.g., fertilization)	+		+/-	**	*
	Nutrient management	+		+/-	**	**
	Fire management	+	+	+/-	*	*
	Species introduction (including legumes)	+		+/-	*	**
Management of organic soils	Avoid drainage of wetlands	+	-	+/-	**	**
Restoration of degraded lands	Erosion control, organic amendments, nutrient amendments	+		+/-	***	**
Livestock management	Improved feeding practices		+	+	***	***
	Specific agents and dietary additives		+		**	***
	Longer term structural and management changes and animal breeding		+	+	**	*
Manure/biosolid management	Improved storage and handling		+	+/-	***	**
	Anaerobic digestion		+	+/-	***	*
	More efficient use as nutrient source	+		+	***	**
Bio-energy	Energy crops, solid, liquid, biogas, residues	+	+/-	+/-	***	**

Another interesting agronomic practice is the introduction of temporary vegetative cover between successive agricultural crops, or between rows as these 'catch' or 'cover' crops add carbon to soils (Barthès *et al.*, 2004; Freibauer *et al.*, 2004) and may also extract plantavailable N unused by the preceding crop, thereby reducing N<sub>2</sub>O emissions.

- b. Nutrient management. Nitrogen applied in fertilizers, and other N sources at a surplus is particularly susceptible to emission of N<sub>2</sub>O (McSwiney and Robertson, 2005). Improving N use efficiency by reducing leaching and volatile losses, improved efficiency of N use can also reduce off-site N<sub>2</sub>O emissions. Practices that improve N use efficiency include: precision farming, using slow- or controlled-release fertilizer forms or nitrification inhibitors, Improved timing of N application (prior to plant uptake or placing N more precisely into the soil to make it more accessible to crops roots (Dalal *et al.*, 2003; Monteny *et al.*, 2006). Adding more nutrients, when deficient, can also promote soil carbon gains (Alvarez, 2005), but the benefits from N fertilizer can be offset by higher N<sub>2</sub>O emissions from soils and CO<sub>2</sub> from fertilizer manufacture (Schlesinger, 1999; Gregorich *et al.*, 2005). Emissions per hectare can also be reduced by adopting cropping systems with reduced reliance on fertilizers, like rotations with legume crops (West and Post, 2002; Izaurralde *et al.*, 2001).
- c. Tillage/residue management. Advances in weed control methods and farm machinery now allow many crops to be grown with minimal tillage (reduced tillage) or without tillage (no-till) to avoid soil carbon losses due to soil disturbance and reduce CO<sub>2</sub> emissions from energy use. Reduced-or no-till may also affect N<sub>2</sub>O, emissions but the net effects are inconsistent and not well-quantified globally (Smith and Conen, 2004; Helgason *et al.*, 2005; Cassman *et al.*, 2003).
- d. Water management. About 18% of the world's croplands now receive supplementary water through irrigation (Millennium Ecosystem Assessment, 2005). Expanding this area (where water reserves allow) or using more effective irrigation measures can enhance carbon storage in soils through enhanced yields and residue returns (Follett, 2001; Lal, 2004a, 2004b). Drainage of croplands lands in humid regions can promote productivity (and hence soil carbon) and perhaps also suppress N<sub>2</sub>O emissions by improving aeration (Monteny *et al.*, 2006).

Figure 16 presents global technical mitigation potential. About 89% is from soil carbon sequestration, about 9% from mitigation of methane and about 2% from mitigation of soil N<sub>2</sub>O emissions. The total mitigation potential per region is presented in Figure 17. However, the most appropriate mitigation response will vary among regions, and different portfolios of strategies will be developed in different regions, and in countries within a region.

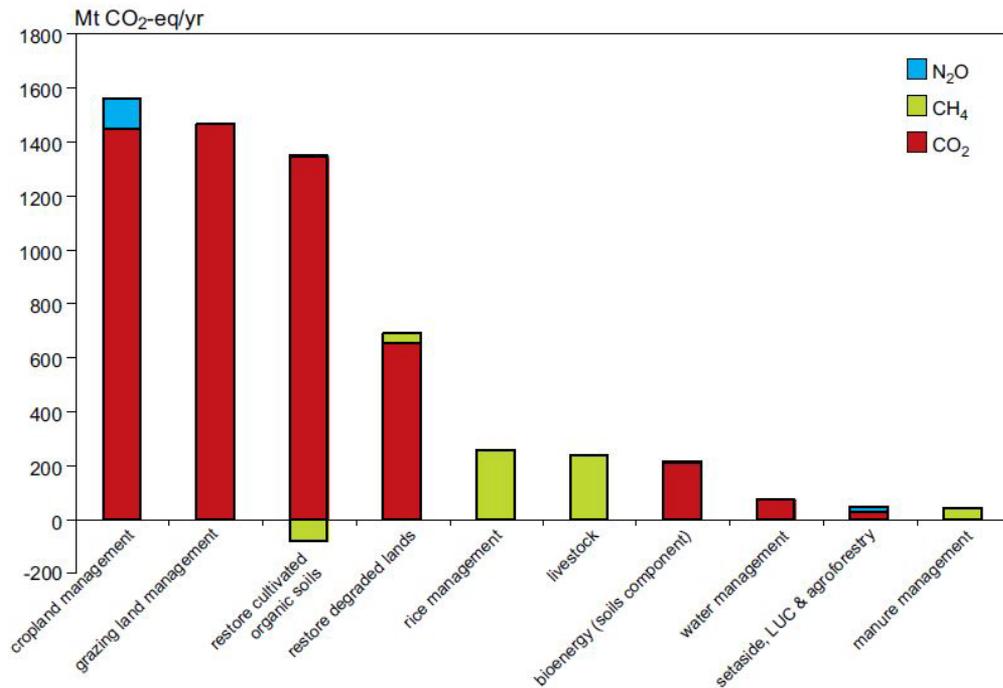


Figure 16. Global technical mitigation potential by 2030 of each management practice showing the impacts on GHG (From Smith *et al.*, 2007)

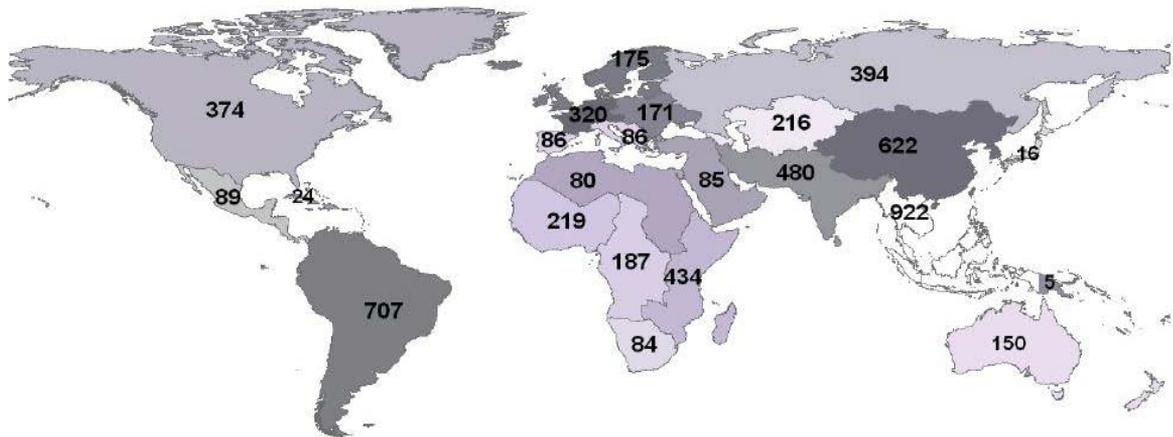


Figure 17. Total technical mitigation potentials (all practices, all GHGs: Mt CO<sub>2</sub>-eq/yr) worldwide (From Smith *et al.*, 2007)

An inventory of the factors responsible for GHG emissions hands possibilities to identify possibilities for reduction. Table 3 provides some examples of opportunities to reduce emissions from potato production.

Table 3. Examples of reduction opportunities for potato production sector.

Type	How Emissions are Reduced	Examples
Land and Crop Management	<ul style="list-style-type: none"> <li>Adjusting the methods for managing land and growing potato crops.</li> </ul>	<ul style="list-style-type: none"> <li>Fertilizing crops with the precise amount of nitrogen required (precision farming by DSS), since less efficient nitrogen application can lead to higher N<sub>2</sub>O emissions.</li> </ul>
Manure Management	<ul style="list-style-type: none"> <li>Controlling the way in which manure decomposes to reduce N<sub>2</sub>O and CH<sub>4</sub> emissions.</li> <li>Capturing CH<sub>4</sub> from manure decomposition to produce renewable energy.</li> </ul>	<ul style="list-style-type: none"> <li>Handling manure as a solid or depositing it on pasture rather than storing it in a liquid-based system such as a lagoon. This would likely reduce CH<sub>4</sub> emissions but may increase N<sub>2</sub>O emissions.</li> <li>Storing manure in anaerobic containment areas to maximize CH<sub>4</sub> production and then capturing the CH<sub>4</sub> to use as an energy substitute for fossil fuels.</li> </ul>

Changes in soil management can increase the equilibrium soil carbon pool by increasing C inputs into the soil or by slowing decay rates of soil organic matter (Schlesinger, 1999). Efforts to improve soil quality and raise SOC levels can be applied by crop management and conservation tillage and include so-called “best practice” agricultural techniques, such as use of cover crops and/or nitrogen fixers in rotation cycles; judicious use of fertilizers and organic amendments; soil water management improvements to irrigation and drainage; and improved varieties with high biomass production.

Table 4. Estimated carbon sequestration rates for different ‘good practice’ management practices (From: LULUCF, 2000, IPCC, 2000)

Practice	Country/region	C gain (T C ha <sup>-1</sup> yr <sup>-1</sup> )	Time (years)
Improved crop production and erosion control	Global	0.05–0.76	25
Partial elimination of bare fallow	Canada	0.17–0.76	15–25
	USA	0.25–0.37	8
Irrigation	USA	0.1–0.3	
Fertilization	USA	0.1–0.3	
Yield increase, reduced bare fallow	China	0.02	10
Amendments	Europe	0.2–1.0	50–100
Forages in rotation	Norway	0.3	37
Ley-arable farming	Europe	0.54	100

Tables 4 and 5 summarize potentials for C-sequestration for a variety of agronomic field techniques. Table 6 shows that, over the next 40 years, best practice and conservation tillage alone could store about 8 GT C in agricultural soils. Larger amounts could be sequestered over the same period by increasing C inputs into land, for instance by establishing agro-forestry practices in marginal lands (20 GT C), or by reducing disturbance, such as by conversion of excess agricultural land to grassland (3 GT C). The total gain from multiple mitigation approaches over existing agricultural land would thus be roughly 10 GT C (and up to 30 GT C with the inclusion of marginal land conversion for agro-forestry), an amount lower than the 50 GT C lost historically.

Table 5. Estimated carbon sequestration rates under reduced or no tillage practices, as reported in various countries (From: LULUCF, 2000, IPCC, 2000)

Country/region	C gain (T C ha <sup>-1</sup> yr <sup>-1</sup> )	Time (years)
Global	0.1–1.3	25
UK	0.15	5–10
Australia	0.3	10–13
USA	0.3	6–20
Canada	0.2	8–12
USA and Canada	0.2–0.4	20
Europe	0.34	50–100
Southern USA	0.5	10

Table 6. Estimated carbon sequestration over the next 40 years as a function of land use management of existing cultivated and marginal land (From LULUCF, 2000, IPCC, 2000)

Sector	Total Gt C sequestered
“Best Practice” Crop management	8
Agroforestry improvements	1.6
Cropland conversion to agroforestry	19.5
Cropland conversion to grassland	2.4
Total arable land	31.5

### 5.3 On-farm reduction of greenhouse gas emissions

In general, the direct benefits of carbon sequestration in reduced tillage systems are limited in time, typically 20–40 years, while those arising from reduced C emissions will last as long as the relative management changes are maintained. In the majority of current agricultural areas several mitigation practices may positively reinforce land mitigation potentials under specific conditions. For example, increased irrigation and fertilization that are necessary to maintain production in marginal semi-arid regions under climate change conditions, may greatly enhance the ability of soils in those areas to sequester carbon, especially in sub-Saharan Africa, where small improvements in efficiency of irrigation can have very large effects on biomass production of crops (Solomon *et al.* 2000). Efficient agronomic and water management and shifting cultivation to new and suitable agroclimatic zones can significantly arrest the decline in the production.

Franke *et al.* (2013) studied four potato production systems in South Africa which are exposed to different climates and also relevant for other potato-producing regions worldwide: a continental climate over the interior with dry winters and rainy summers and a Mediterranean climate in the south-western coastal areas, with dry warm summers and rainy winters. They conclude from their study that in all agro-ecosystems, potato growers are likely to respond to climate change by: advancing planting dates to avoid heat stress in late spring and summer. Changing lengths of the

growing season could further affect crop performance, if varieties with suitable growing durations are available. In warmer areas with cold winters, a further benefit of climate change is a reduction in the risk of frost. The authors also assume that growers will introduce and use varieties with an earliness or lateness such that their growth cycle matches that of the shortened (winter) or lengthened (summer) seasons.

## 5.4 Possibilities to cope with salinity in potato cultivation

In case of salinity different strategies are possible to optimize potato crop growth: 1) irrigation practices, 2) soil coverage by mulching, 3) intercropping or mixed cropping and 4) possible integration with aquaculture.

### 5.4.1 Irrigation practices

Under saline conditions, the irrigation regime in a row crop is important. Common methods for potato are furrow and sprinkler irrigation and precision farming. Yield response to frequent irrigation is considerable because the crop has a shallow root system and requires a low soil water depletion. Irrigation with brackish or saline water will cause accumulation of salt near the root zone with a profile depending on the forms of the ridges and the irrigation practice. Figure 18 shows different salt accumulation patterns under furrow irrigation with different bed forms and different irrigation regimes. A symmetric furrow irrigation pattern may result in an unfavourable salt accumulation within the root zone. Surface drip irrigation has the advantages that water can well be saved and depending on the drip schedule salt ions can permanently be leached from the root zone.

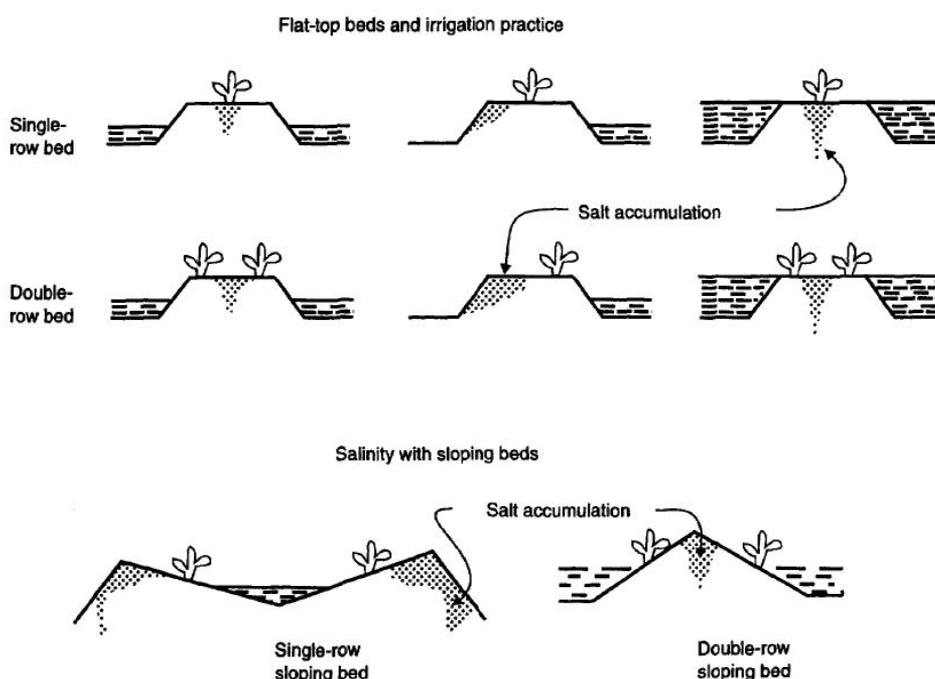


Figure 18. Salt accumulation patterns in potato growth under furrow irrigation (Hillel, 2000)

A more sophisticated irrigation regime can be considered in which plants are forced to adapt and to increase their salt tolerance. An example is the Alternate partial Root Drying irrigation management (ARD, (Jacobsen *et al.* 2012). For potato such an intermediate saline-fresh drip

irrigation with intermediate salinity in the root zone has indeed been shown to result in smaller yield losses than with continuous saline drip irrigation (Levy 1992). However, it appeared that the type of soil is important. Ahmadi *et al.* (2010) showed that water saving irrigation in potato was not recommended on a loamy sand soil due to considerable yield losses, but sandy loam or coarse sand soils showed high water productivity.

### 5.4.2 Mulching

Application of a soil coverage or mulching treatments may also improve crop performance under saline conditions. Positive effects of straw mulch (Figure 19) have been reported for potato cultivation with the grass species *Setaria* in Rwanda (Devaux and Haverkort, 1987), with chopped grass in the Czech Republic (Dvorak *et al.*, 2012) or with rice straw in India (Kar and Kumar, 2007). The studies reported significantly higher leaf area index, water use efficiency, intercepted photosynthetically active radiation (IPAR) and finally tuber yields in the mulched plots compared to the non-mulched plots under the same irrigation treatment due to a reduction in soil temperature by 4–6 °C and preservation of soil humidity.



Figure 19. Winter potatoes covered by rice straw in India (Anderson, 2010)

### 5.4.3 Intercropping

Intercropping, i.e., growing two or more crops at the same time on a single field, is an ancient practice still used in much of the developing world. This type of farming with a combination of moderately salt tolerant, like broccoli, and salt tolerant crops, like barley (see Table 1) can especially be practiced on slopes as a way to reuse drain water.

A combination of crops is an alternative farming system which can be very well practiced, when the growing calendars of the different annual crops are in one line. An example is the cultivation of potato which has a crop calendar from November until May in combination with f.e. beet or the extreme salt tolerant quinoa (Sun 2013), which has a crop calendar from March until September.

### 5.4.4 Integrated aqua – agriculture

Integration of aquaculture with agriculture is a perspective combination to reuse the effluent from the cultivation of fish for the cultivation of cash crops. Roest *et al.* (2013) investigated the feasibility of real-life integrated, brackish groundwater - aqua-agriculture farming for potato in the Egyptian desert environment (Figure 20).

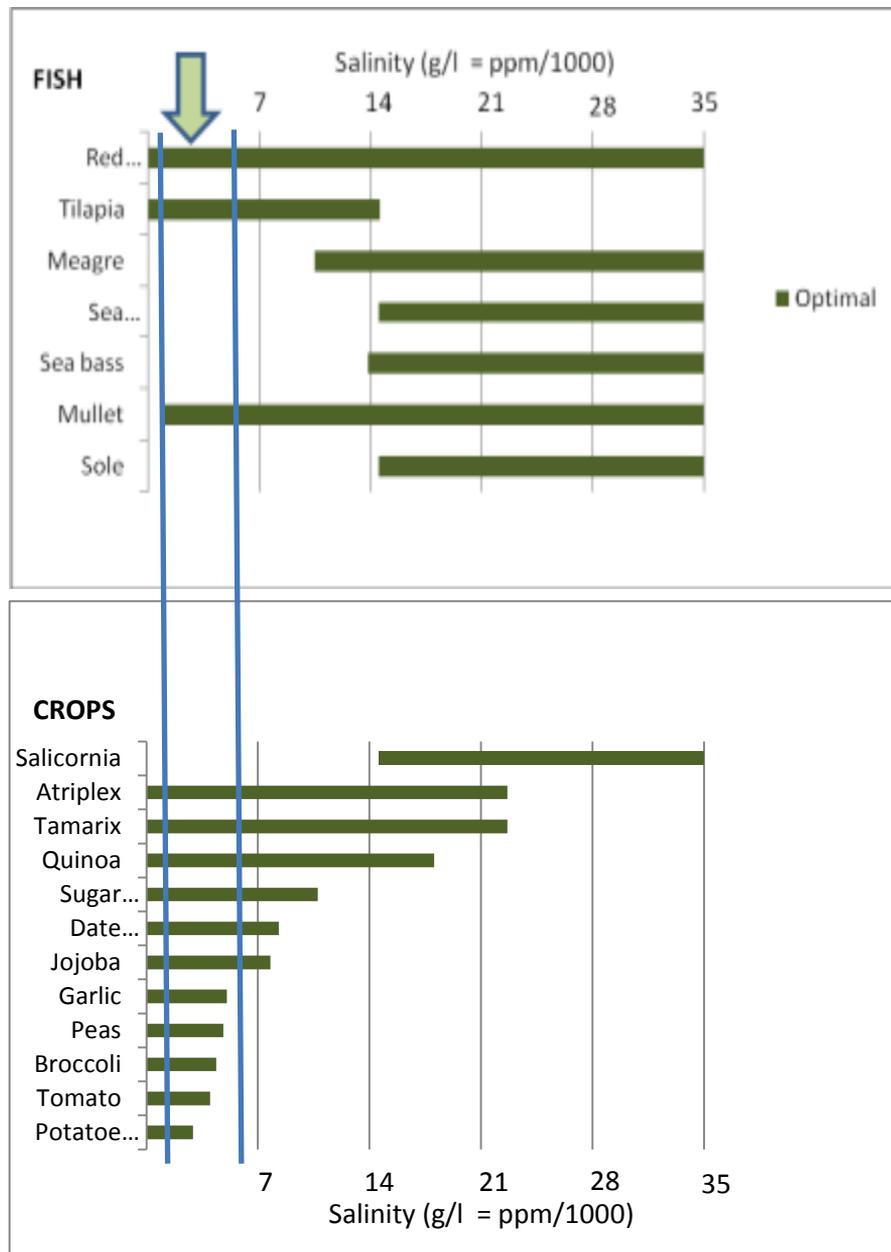


Figure 20. Combination of aquaculture and agriculture. The EC trajectory between the blue lines represents EC values becoming common in brackish environments (Roest *et al.*, 2013)

## 6. Running initiatives, research questions and cooperation within GRA-net

Potato production has been already subject of research for a long time. Climate change and its impact on potato growth is also an important theme. Table 7 shows examples of currently running initiatives in international potato research and development.

Table 7. Examples of currently running initiatives in potato research and development

Country / lead institute	project	Category	Theme	Start - end	partners
Germany Max planck	Trost - Improvement of drought tolerance in starch potato by marker assisted selection in potato breeding	Adaptation	Drought	2011	Potato breeders, JKI, LMU, LWK Niedersachsen and four MPI groups; Karin Köhl (coordinator).
Peru CGIAR	Intern. Program on dryland systems	Adaptation & Mitigation	Drought, Mitigation vulnerability, resilience	continuously	Icrisat, IWMI, ICARDA (Leader), CIP, ILRI, World agroforestry Centre
Switzerland, ETH Zurich	IDP bridges project	Adaptation	drought		
USA, Nelson Institute SAGE, Uni wisconsin	Impacts of potato management and climate change on groundwater recharge across the Central Sands –	Adaptation	hydrology	2012	Kucharik and graduate student Mallika Nocco
The Netherlands, Wageningen UR,	Disease-resistant cropping landscapes (using spatial models). Focus on late blight	Adaptation	Pests, diseases	2013	Contact: E. Lammerts van Bueren
The Netherlands, Wageningen UR	Umbrellaplan Plant health	Adaptation		2006	Contact: P Boonekamp
UVA, TBS van Leeuwen	Sustainable tools to control emerging mite pests	Adaptation	pests and diseases	2015	

Research can expand the knowledge required to develop sustainable solutions by integration of current advances in the molecular sciences, in biotechnology and in plant and pest ecology with a more fundamental understanding of plant and animal production in the context of optimizing soil, water and nutrient use efficiencies and synergies, *et cetera*. Especially the development of sustainable hands-on solutions to save the environment for future generations should be emphasized. As a way forward, Table 8 hands an expert judgement of the authors on the regional risks and actions or research priorities needed.

Tabel 8. Expert judgement of the authors on regional risks distribution, actions and research priorities.

<b>Risk category</b>	<b>Region</b>	<b>Farm/sector level actions</b>	<b>Research needs</b>
GHG	Europe (east, south), India, China	Precision Agriculture C & N flows, reuse residuals	Optimisation precision agriculture (nutrient management)
High daily Temperatures	Mid Africa, India, China (South)	Cultivar selection	Breeding
Water			
Lack of water (drought)	Arid zone: Turkey, China (North), India, Pakistan, Afghanistan, VS	Irrigation, Breeding, Integrated farming systems, extension	Breeding, valorisation secondary metabolites crops, optimisation of water use
Excess of water	China, Mid America, Mid Africa	Insurance	Risk analysis
Extremes			
Drought	Arabian peninsula, South-east Asia, North-west Africa	Integration different farming systems	Enhance water use efficiency
Excess of water	Highly populated delta zones in south Asia and North west Europe	Water management	Protection strategies by vegetation cover
Erosion	China, Chile, Peru, Europe (south), Afghanistan, Mid Africa	Plantings, Water Management, Contour Plowing	Protection strategies by vegetation cover
Erosion in combination with water excess	China, East Africa, Brazil	Plantings, Water Management, Contour Plowing	Protection strategies by vegetation cover
Pests and diseases (late blight)	Europe, China	Integrated pest management, biodiversity and crop selection	Scenario/Risk analysis, breeding
Nitrogen surplus	Europe, Turkey, India, Pakistan Afghanistan, China (East), VS	Precision Agriculture	Precision agriculture
Low land use efficiency	China, India, Pakistan, Afghanistan, Mid and East Europe, Africa	Integrated crop management, integrated farm management	Understanding landscapes, remote sensing
Salinity			
Lack of water	Arabian peninsula, South-east Asia, North-west Africa	Irrigation strategies, salt tolerant crop selection, cultivar selection	Valorisation secondary metabolites crops, dynamics physiological responses, breeding
Excess of water	Highly populated delta zones in south Asia and North west Europe	Plantings, anaerobia and salt tolerant crop selection	Integration aquaculture-agriculture-ecosystems, breeding

## 7. Key messages

There is much scope for technological developments to reduce GHG emissions in the agricultural sector as an increase in crop yields will reduce emissions per unit of production. Such increases in crop productivity will be implemented through improved management techniques, such as better management, genetically modified crops, improved cultivars, fertilizer recommendation systems and precision agriculture. All of these depend to some extent on technological developments.

Although technological improvement may have very significant effects, transfer of these technologies is a key requirement for these mitigations to be realized. For example, the efficiency of N use has improved over the last two decades in developed countries, but continues to decline in many developing countries due to barriers to technology transfer (International Fertilizer Industry Association, 2007). This suggests that technological improvement will be a key factor in GHG mitigation in the future.

As mitigation practices can affect more than one GHG, it is important to consider the impact of mitigation options on all GHGs (Robertson *et al.*, 2000; Smith *et al.*, 2001; Gregorich *et al.*, 2005). Mitigation potentials for CO<sub>2</sub> represent the *net* change in soil carbon pools, reflecting the accumulated difference between carbon inputs to the soil after CO<sub>2</sub> uptake by plants, and release of CO<sub>2</sub> by decomposition in soil. Mitigation potentials for N<sub>2</sub>O and CH<sub>4</sub> depend solely on emission reductions.

Adaptation priorities and research agendas are tailored to regional or local needs but some common ground is found in themes as drought stress, pest and diseases and saline conditions.

For all adaptation measures it is clear that production stabilization or increase via increasing efficiencies in soil and crop management, i.e. doing things better, is the preferred way to move forward. By linking to local priorities and systems adaptation then becomes integrated into the workflow of farmers. This approach also offers opportunities to combine adaptation and mitigation for example by improving fertilizer and water management.

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