Climate Change and Crop Protection

Anything can happen

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Statement of the Publisher

PAN AP supports solutions to climate change based on the principles of food sovereignty, gender and climate justice.

Climate change adversely affects food production, deepens food shortages and exacerbates rural poverty, joblessness and misery, as people face crop losses through droughts, floods and climatic disasters. The hardest impact will be felt by women, indigenous people, farmers, agricultural workers, fisherfolk, Dalits, ethnic minorities, and the world's poor and disadvantaged. Therefore, ecological viable solutions to climate change must be developed and driven by grassroots and affected communities.

PAN AP endorses the People's Protocol on Climate Change as a framework to people's demands for climate justice based on the principles of social justice, sovereignty, respect for the environment, gender justice, and responsibility, and calls for an economic system that is sovereign, socially just, democratic and ecologically sustainable.

Corporations including agrochemical and agribusiness companies are continuing their unsustainable forms of production that are devastating human health and the environment and this is further perpetuated through "carbon trading" schemes. They have seized the opportunity to profit in so-called carbon emissions reduction technologies and projects that are using public funds. Adaptation and mitigation technologies are not the final solutions to the climate crisis. The final solution is through people-oriented ecological development.

PAN AP is in the global struggle to advance and strengthen food sovereignty, gender and climate justice, and people's resilience to climate change. Together we can fully resist corporate monopoly control over food and agriculture.

"Our vision is a society that is truly democratic, equal, just, culturally diverse, and based on food sovereignty, gender justice and environmental sustainability."

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1. Abstract

Agriculture is affected by climate change, with particularly adverse effects in developing countries. Climate change also influences the ecology of weeds, pests and disease, with possible implications for crop protection and pesticide use. Elevated atmospheric carbon dioxide (CO_2) influences plant growth and the nutritional quality of most plant species, with potential bottom up effects. Increased temperature causes migration of species northwards and into higher latitudes, while in the tropics higher temperatures might adversely affect specific pest species. However, an agro-ecosystem consists of more than the crops and the pests, natural enemies play a critical role in crop protection, and so far climate change research has largely neglected them.

This paper reviews existing scientific literature about the ecological consequences of climate change and elevated atmospheric carbon dioxide on weeds, pests (insects, mites, slugs and nematodes), diseases and their natural enemies (parasitoids, pathogens and predators). The objective was to investigate if there is any observable trend that could imply that pressure from weeds, pests and diseases might increase due to climate change and elevated carbon dioxide (CO_2).

The results show a clear research bias towards elevated carbon dioxide and insect herbivory in temperate regions, therefore, available information applies mostly to these areas. Although increased temperature might outweight some effects of elevated CO_2, experiments combining both parameters have been rare. Little research has been conducted on weeds and plant diseases under climate change. When it comes to natural enemies, it seems climate change ecology research still remains in the 1980s, where scientists never looked beyond the second trophic level. The conclusion regarding crop protection is that anything can happen. However, crop protection has always been dynamic and climate change might increase the speed of changes. Farmers can cope with these changes when considering five basic measures. When it comes to pesticide use, climate as influencing factor plays a minor role, economy, policy, education and agronomy are the main drivers of pesticide use.

2. Acknowledgements

3. Introduction

Agriculture provides human society with food, fiber and energy, and for many people in developing countries it is the main source of income. Agriculture usually takes place under the open sky and while human beings have gained a certain control over agricultural production, unexpected climatic changes and changes in weather events could always endanger a harvest. With climate change agriculture will change. The Intergovernmental Panel on Climate Change (IPCC) stated in its Fourth Assessment Report: *"At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1 to 2°C), which would increase the risk of hunger"* (IPCC 2007 pg. 48). Fischer et al. (2005) projected the most significant negative changes for developing countries in Asia, where agricultural production declines of about -4% to -10% are anticipated under different socio-economic and climate change scenarios.

However, agriculture production is not only affected by climatic change. Agricultural production itself contributes significantly to greenhouse gas emissions (GHG) (IPCC 2007; Bellarby 2008), but has also large potential to mitigate emissions (IPCC 2007 pg. 59-60). Furthermore, conventional industrial agriculture is associated with high inputs of agro-chemicals, particularly fertilizers and pesticides. Pesticide use, especially in developing countries, presents a major health risk to agricultural workers, farmers, their families and the environment. Furthermore dependence on agro-chemicals can lead to an economic catastrophe, when loans for them cannot be paid back due to crop or market failure.

Pesticide use is influenced by many factors: farmer's financial resources, expected yields and commodity prices, industry's (often aggressive) marketing, availability, farmer's education, crop management (see Box on page 24) and last but not least presence of weeds, diseases, pests and their natural enemies. The latter factors are influenced by the weather, and in the midterm by climatic changes (Goudriaan & Zadoks 1995). Climate change might therefore have an influence on pesticide use but so far no global surveys or possible future scenarios exist, which explore this subject further. Tilman et al. (2001) foresee a 2.4 to 2.7-fold increase in pesticide use by 2050 related to population growth and conversion of natural ecosystems to agriculture, but the effects of climate change is not considered by the

authors. Chen and McCarl (2001) investigated the relationship of temperature, precipitation and pesticide costs for several crops in the USA and concluded that increases in rainfall leads to increases in average pesticide costs for corn, cotton, potatoes, soybeans, and wheat; while hotter weather increases pesticide costs for corn, cotton, potatoes, and soybeans but decreases the cost for wheat. A simulation by the same authors applying different climate change scenarios showed uniform increases in average pesticide costs for corn, soybeans, cotton, and potatoes and mixed results for wheat (ibid.). Patterson et al. (1999) looked at numerous specific insect pests, weeds and crop diseases and their ecology under climate change conditions and concluded that some insect pests species, weed species and crop diseases may ecologically benefit from climate change, while others may be reduced. The authors finally state that climate change will increase the challenges from pests.

Many people believe that global warming as predicted would increase pressure from weeds, pests and diseases, and for Asia[1] the IPCC scientists seem to listen to that kind of intuition and make a rather simplistic generalization for Asian's temperate regions based on one study done for the USA and citing no other sources: *"(...) higher temperatures and longer growing seasons could result in increased pest populations in temperate regions of Asia. (...) Warmer winter temperatures would reduce winter kill, favouring the increase of insect populations. Overall temperature increases may influence crop pathogen interactions by speeding up pathogen growth rates which increases reproductive generations per crop cycle, by decreasing pathogen mortality due to warmer winter temperatures, and by making the crop more vulnerable"* (Cruz et al. 2007).

With this simplistic statement the IPCC omits a number of important facts:

- while temperature is considered to be the dominant abiotic factor for insect pests (Bale et al. 2002) it must not be positively correlated (Deutsch et al. 2008). The yellow stem borer (*Scirpophaga incertulas* [Walker]) for example, a dominant rice pest in Bangladesh, experiences high mortality above a temperature of 34°C and lower humidity (Catling & Islam 1995). Patterson et al. (1999)

GHG: Greenhouse gas emissions. Major greenhouse gases are: Carbon dioxide (CO_2), methan (CH_4) and nitrous oxide (N_2O).

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1 This article is an edited version of a publication for Pesticide Action Network Asia & the Pacific and refers therefore often to Asia and the situation in developing countries.

Pathogen:
Disease causing organism.

Entomopatho-gens:
Disease which infect insects.

Abiotic:
Nonliving

Diapause:
A temporary pause in the growth and development of an organism due to adverse environmental conditions.

Parasitoids:
Organism that is parasitic during part of its life cycle, especially one that eventually kills its host.

Overwinter:
Passing through or waiting out the winter season.

show a number of temperature thresholds. Finally, tropical insects which enter thermally induced summer-diapauses actually avoid seasons with higher temperatures;

- evidence of decreased winter kill due to warmer winter temperature is scarce (Kiritani 2007) and would not allow for a generalization. This is especially true for organisms which overwinter in the soil since fungal entomopathogens might have a much stronger affect on the early stages of insects life in a wetter and warmer winter climate; furthermore mild winters may be detrimental for some insects species because activated larvae consume more energy through the winter and thus reduce their reproductive output as adults (Irwin & Lee 2000);

- it has long been known that elevation of atmospheric CO_2 (carbon dioxide) reduces the nitrogen/protein concentrations in most plants, (Lincoln et al. 1986; Lincoln 1993) which does not only have a potential impact on human nutrition (Loladze 2002, Lieffering et al. 2004), but can also affect herbivores (Mattson 1980) such as mites (Joutei et al. 2000), insects (Lincoln et al. 1986; Fajer 1989)and slugs (Peters 2000);

- an agro-ecosystem consists of more than a crop and its pests/diseases. Why should climate change arbitrarily affect pests, but not their enemies? When pests migrate due to climate change is it likely that none of its natural enemies will follow? Populations of parasitoids, predators and pathogens of pests commonly develop synchronistically with their hosts/prey and would they not also adapt to changed pest levels?

So far no study has been conducted to look more comprehensively at the impact of climate change on pests, weeds and diseases and their natural enemies. This is especially true for regions outside the temperate climate zones. Most science related to impacts of climate change on agricultural crops have taken place in industrialized countries (Leakey 2009) and focused on species in the global North.

This report will present information on possible effects of climate change on weeds, diseases, pests, and their natural enemies. In order to get an impression of climate change and agriculture, the first chapter is dedicated to climate change and agriculture. This chapter is followed by an analysis of the possible effects of climate change on weeds, pests and diseases as well as their natural enemies. Finally, conclusions and recommendations for farmers are made.

4.   Methodology and Limitations

The subject is truly interdisciplinary and falls into many scientific areas: climate science, agricultural science and biology/ecology. This report is based upon literature research. The literature search was journal and topic specific. Journals with a specific focus like: 'Crop Protection', 'Biological Control', 'Annual Review of Entomology', 'Journal of Insect Physiology' and 'Journal of Arachnology' were searched using keywords like 'climate change', 'elevated CO2', 'elevated carbon dioxide' etc.; while in journals focusing on global/climate change such as 'Global Change Biology', 'Climatic Change' and 'Global Environmental Change' were searched using keywords like 'pesticide', 'pest', 'pathogen', 'disease', 'rust', 'mildew' etc.

Interactions between crops, diseases/pests and their enemies are basically ecological topics therefore journals like 'Oecologica', 'Journal of Experimental Botany', 'Ecology', 'TRENDS in Ecology & Evolution' and 'Agriculture, Ecosystems and Environment' were searched using keywords like 'climate change', 'elevated CO2', 'elevated carbon dioxide' etc..

Furthermore the reference list of useful articles was used to identify other relevant literature. Some online publishers offer the possibility of finding articles related to other articles, or articles by the same author(s), this function was extensively used. In some cases, volumes of specific journals focussed on one topic and these volumes were more closely investigated. Finally, because some of the authors are specialists in certain areas, their publications were searched through more intensively. This was also undertaken with publications which made references to them.

While a wealth of information was found, there were certain limits to this methodology:

These limitations were of two types:

1. Limited resources and capacity and 2. the scientific basis.

1. Limited resources and capacity: There is a vast amount of literature. A literature database created by Jones and Curtis (2000) alone lists some 3,000 articles on the effect of elevated CO_2 on plants in the time span 1990-1999. The dominant scientific publishers SpringerLink, Wiley-Blackwell and Elsevier (ScienceDirect) hold about 13 million articles

in thousands of journals. While the most relevant articles were identified, some articles may have been missed. Two problems could not be solved: the whole research was limited to English and German literature, and many articles are not freely available and a budget to buy copies was not available.

The scientific basis: Most of the articles found can be roughly divided into four categories:

a.) description of certain experiments and their results,
b.) reviews of the current science and conclusions,
c.) meta-analysis of published results from experiments and
d.) descriptions of models and their application/results.

Each of these categories has advantages and disadvantages. The subject is of such complexity that no experiment or model can ever reflect it comprehensively. Experimental designs such as free air CO_2 enrichment (FACE) facilities or climate chambers have inherent limitations (Hendrey & Miglietta 2006). A review and/meta-analysis of many experiments can try to deduce trends and scenarios. However, ecology is neither linear nor logical. Evolution for example happens by accidental mutations and further selection. It can hardly be foreseen. In addition, published science is biased – when an experiment does not show statistically significant results it might not lead to a publication. In this particular subject, science is rather biased toward northern latitudes. Most FACE facilities for example are located in industrialized countries[1]. While there are some good reasons for this (cooler latitudes will be more affected ecologically especially through northward migration of organisms), there is no justification for the lack of scientific research regarding the ecological impact of climate change in developing countries. Furthermore, many FACE experiments focus on forest species and grassland, not a single orchard was investigated[1].

5. Impacts of Climate Change on Agriculture

Climate change has already had an effect on agriculture. Lobell and Field (2007) estimate that in the time span 1981-2001, changes in precipitation and increased temperatures have already resulted in annual combined losses of wheat, maize and barley of roughly 40 million tons per year. While the scientists consider these losses relatively small in comparison to the technological yield gains over the same period, the results demonstrate the negative impacts of climate change already occurring on crop yields at a global scale (ibid.).

In order to analyze future trends in agriculture and food production many factors besides climate change must be considered. These include technological progress, population growth, land use change (especially reduction of arable land, land degradation), and consumer demands. Parry et al. (2004) who are strongly involved in the IPCC, computed future yields for wheat, rice, maize and soybean under different emissions and socio-economic scenarios until 2080. The results show that, in general, crop yields decrease in developing countries and yields increase in developed countries. On a global scale, the production of the four crops would be sufficient to feed the world under all scenarios. However, this is only possible if food distribution from the industrialized countries in the North to the less developed countries in the South takes place (ibid).

There are a number of uncertainties regarding the results derived by Parry et al. (2004).

1. The authors themselves state that the positive effect of increased CO_2 on crop growth plays a very critical role in their model outcomes, and this might not translate into field level impacts (ibid.). Indeed, it seems to be very difficult to extrapolate results from experiments under optimal controlled conditions to 'suboptimal' conditions in farmers' fields. In addition, Leakey (2009) suggests that for maize, a C4[2] plant, the assumption of enhanced growth under higher CO_2 levels are likely to be overly optimistic,

2. The IPCC assumes a further increase of surface ozone (O_3) until the end of the century (Vinzargan 2004) which may lead to considerable crop losses at least until 2030,

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1 See: Global List of FACE Experiments http://public.ornl.gov/face/global_face.shtml

2 Explanation see box page 11.

especially in China (van Deningen 2009). However, the crop model of Parry et al. 2004 looked at temperature and precipitation, and neglected crop losses due to phytotoxic (toxic to plants) surface Ozone (O_3).

3. The UN lists land degradation and decline of arable land due to population growth as the number one cause of the current food security crisis (UN Special 2009), and Wassmann et al. (2009) consider the rise in sea-levels and tropical cyclones as major threats to rice production in the Asian mega-deltas especially in Vietnam, Bangladesh and Myanmar. The socio-economic model of Parry et al. (2004) does assume that increased cereal prices will lead to a reclamation of additional arable land, but it seems the parallel land loss as well as increasing extreme weather events were not appropriately addressed,

4. Parry et al. (2004) assume a linear progression in agricultural technology and do not discuss how this converges with climate change mitigation. Agriculture contributes to approximately 30% to the global GHG emissions (IPCC 2007, Bellarby 2008) – a linear progression of industrial agriculture and its extension to all developing countries is a contradiction to climate protection.

Finally, looking at crop yields alone might be too narrow – the nutritional value of the future crops might counteract some of the yield gains (see Box 'Hidden Hunger?').

However, if the scenarios developed by Parry et al. (2004) and considered by the IPCC partly resemble future development, regional food sovereignty will be endangered and global justice will be even more distorted, when the victims of climate change are dependent of food 'aid' from those countries which largely caused climate change.

6. Crops, weeds, pests and diseases in a changing world

The agro-ecosystem must be understood as a multitrophic system with human interference. For the farmer, the crop is the centre of this ecosystem, and for ecologists the plant is the food basis or primary producer for an entire food web (Price 2002).

Crop plants live in a very complex ecosystem. They live in competition with neighboring plants including weeds. Both are supported and/or attacked by viruses, bacteria, fungi, insects, mites, spiders, amphibia, birds, mammals etc. All of these species interact with each other. Pimentel (2009) estimates that globally 70,000 pest species, including 9,000 insect and mites, 50,000 plant pathogens and 8,000 species of weed exist. About 10% of these 70,000 are considered major pests.

Each insect pest usually has numerous natural enemies (CPC 2007), which also have enemies again (Hunter 2009). A plant affected by an insect might produce volatiles which attracts natural enemies of this particular insect (Takabayashi et al. 2006; Khan et al. 2008, Schnee et al. 2006, Degenhardt 2009), but the same chemicals may also attract more pests (e.g. Unsicker et al. 2009).

In addition, each ecosystem also depends on its non-living (abiotic) environment like soil, water, climate, and micro-climate. Small changes might have large impacts for the individual plant/animal, which are not seen or understood by us. Why, for example, is one plant infested by aphids, but not the neighboring plant?

Climate change will have an impact on our ecosystems, which we will never fully comprehend. Pimm (2009) says: '*There is likely no hope of ever predicting the detailed consequences of climate disruption to a particular species any more than we can predict the outcome of tossed dice.*'

The ability of current science to make predictions about the impact of global changes on ecosystem interactions is limited, because models that include multiple interactive effects of global change are still relatively rare (Emmerson et al. 2004). Furthermore, viruses, micro-organisms, plants and animals undergo evolution, and are sometimes able to adapt to new situations very quickly (Harmon et al. 2009). Ecological reality may not respect computational convenience (Pimm 2008).

Ecosystems are very complex and our society changes many parameters (land use, land management, climate, air quality) at the same time. We need to be very cautious when making predictions for the real world by basing our findings on laboratory experiments and computer models. However, science is of course not useless, it shows trends and directions, and good science always discusses limitations and results.

As such, the following chapter will provide some information about the different groups of weeds, pests and diseases which commonly affect crop plants.

6. 1 Weeds

Weeds compete with crops over nutrients, water and light and can considerably reduce yields and crop quality. In some cases weeds can pose a human health problem (poisonous plants, allergens) or inhibit harvest. Elevated CO_2, changes in temperature and precipitation patterns may affect weeds as much as crops. Higher CO_2 will stimulate photosynthesis and growth in C3 weeds and C3 crops[1], and reduce transpiration and increase water use efficiency in both C3 and

Multitrophic: involving several food chain levels, with plants, herbivores, and carnivores constituting the first three levels.

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1   C4 plants account for a small fraction of the total number of plant species (fewer than 1.000 out of 250.000) (Elmore & Paul 1983).

Hidden Hunger?

Most plants obtain carbon, their major constituent, via photosynthesis from atmospheric carbon dioxide (CO_2) and more CO_2 usually benefits plant growth. Before industrialization, around the year 1750, levels of CO_2 in the air were at 280 ppm; in 2005 it reached 380 ppm, and a level of 560 ppm can be expected by the end of the 21st century (IPCC 2007).

Computer models, which calculate future yields under climate change usually incorporate increasing atmospheric CO_2 as the 'fertilization effect'. Experiments with elevated CO_2 indeed show increased biomass production and crop yields for most plants (Kimball et al. 2002). However, higher yields in tons per hectare might be useless, when the nutritional value of the harvest is much lower.

Cotrufo et al. (1998) evaluated 75 studies on nitrogen/ protein content under elevated CO_2 and found that nitrogen concentrations were reduced by an average of 9% (below-ground tissues) to a 14% average reduction for above-ground tissues. While Cotrufo et al. evaluated studies of all kind of plants, Loladze (2002) looked more specifically at food crops. His results show an average nitrogen reduction of 15-20% as well as substantial reductions of other important micro-nutrients such as zinc and iron. A meta-analysis of 228 experimental observations (elevated CO_2 compared to ambient CO_2) of barley, rice, wheat, soybean and potato showed a reduction of grain protein concentration of 10–15% in wheat, barley and rice. The reduction in potato tuber protein concentration was 14%. For soybean, there was a much smaller reduction of protein concentration of 1.4% (Taub et al. 2008). Yang et al. (2008) confirmed the general trend of nitrogen reduction for rice. Their results showed a 6% reduction in nitrogen, but no significant reduction of zinc and iron.

In response to Loladze, other researchers investigated the experimental settings of enriched CO_2 experiments and analyzed rice grain samples from an open field experiment. Quite opposite to Loladze, the analysis showed increased micro-nutrient content in rice grains from the field with elevated CO_2 (Lieffering et al. 2004). They argue that the reduction of micro-nutrients observed in other experiments is likely due to reduced nutrient availability in experimental soils and/or in limited root growth in pots (ibid.).

In 2008, Högy and Fangmeier published an article on the analysis of numerous studies on the grain quality of wheat under elevated CO_2. They confirmed the lower protein levels and suggest that protein concentrations in wheat grains may decrease to values below the minimum quality standard for bread-making. They also detected significantly lower concentrations of amino acids, zinc, iron and other nutrients, but these reductions were observed only in chamber experiments (Högy & Fangmeier 2008), which was criticized by Lieffering et al. (2004).

However, while it is not clear if higher CO_2 levels decrease the content of micro-nutrients, it seems very clear that the protein content is significantly reduced in most crop plants. Therefore results of computer models which calculate yields in metric tons must be interpreted with caution, with regards to food security. It would be much more useful to have results in energy units (Calory or Joule) instead of tons/ha.

C4 weeds and crops[1]. Higher temperatures can possibly offset some of the benefits of elevated CO_2 for both, weeds and crops. High temperatures sometimes limit reproductive development and global warming may decrease reproductive output in such situations despite an increase in CO_2. It is unclear whether this is more likely to occur in C3 than C4 species, but if it were, it could alter weed community compositions and affect crop/weed interactions (Bunce & Ziska 2000).

This would imply that weed and crops both benefit or lose on the same scale. However, weeds are usually already very competitive due to greater genetic variation and physiological plasticity, otherwise they would not cause yield losses. Hence they may gain more advantages from climate change than crops (ibid.).

Phenology: Studies and describes the periods of plant and animal life cycle events related to climate.

In temperate regions, global warming will affect the growth and marginally affect phenology, and influence the geographical distribution of weeds. Weed species of tropical and subtropical origins, currently restricted to the southern regions, may expand northward (Patterson 1995).

However, since climatic change, especially increased CO_2 affects C3 and C4 plants differently, and different combinations must be investigated separately:

- C4 weeds in C3 crops,
- C3 weed in C3 crops,
- C3 weeds in C4 crops and,
- C4 weeds in C4 crops.

When solely looking at the benefit of elevated CO_2 it would be possible to argue that C4 weeds such as barnyard grass (*Echinocloa crus-galli*) and redroot pigweed (*Amaranthus retroflexus*), which do not react to elevated CO_2 with more biomass production would be less competitive than C3 crops which grow better under increased CO_2. And *vice versa*: in C4 crops like millets, sorghum, maize and sugarcane C4 weeds may become less competitive than C3 weeds.

6. 1. 1 C4 weeds in C3 crops

According to Holm et al. (1977) 14 of the world's worst weeds are C4 plants, while around 76% of the harvested crop area in 2000 were grown

with C3 crops (Monfreda et al. 2008). If the hypothesis is right that C3 crops would benefit more from elevated CO_2 than C4 weeds, losses due to C4 weeds might decrease. In the early 1980s, experiments were conducted to prove this kind of hypotheses (e.g. Patterson & Flints 1980) and basically the hypothesis was supported (Coleman & Bazzaz 1992, Ziska 2003). However, more research has been done manipulating CO_2 concentrations alone. Temperature increase or drought in combination with elevated CO_2 was less investigated (Fuhrer 2003, Bunce & Ziska 2000). When including temperature increase, trends are not clear, and will depend on the local conditions. Optimal temperatures for growth in C4 plants are generally higher than optimal temperatures for C3 plants (Flint & Patterson 1983), but with higher CO_2 the optimum temperature of many C3 plants also increases (Bunce & Ziska 2000).

However, looking at photosynthesis and temperature alone might be insufficient. Tang et al. (2009) recently showed that barnyard grass (Echinocloa crus-galli) in combination with a mycorrhiza also benefits from elevated CO_2 levels. In drought situations C4 weeds might also have advantages over C3 crops under elevated CO_2 (Ward et al. 1999).

6. 1. 2 C3 weeds in C4 crops

The benefit of elevated CO_2 under sufficient water condition will lead to higher C3 weed competitiveness in C4 crops. An experiment with Sorghum, and a C3 and C4 weed showed what the potential implications increased CO_2 level may have on the crops. Under ambient CO_2 the presence of the C3 velvetleaf (Abutilon theophrasti [Medicus]) had no significant effect on either sorghum seed yield or total above ground biomass; however, at elevated CO_2, yield and biomass losses were significant. The additional loss in sorghum yield and biomass was associated with a threefold increase in velvetleaf biomass in response to increasing CO_2 (Ziska 2003).

Elevated CO_2 alone might not only lead to an increase of pure biomass of C3 weeds. McPeek & Wang (2007) showed that dandelion (Taraxacum officinale) produced more fertile seeds and eventually larger seedlings.

However, C4 crops might out-compete better growing C3 weed in drought situations, and at higher temperatures utilizing mycorrhiza (Tang et al. 2009).

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1 There is a number of species mostly cacti, but also pineapple which use a third type of photosynthesis, the crassulacea acid metabolism (CAM). See text box next page. CAM plants will not be considered here.

6. 1. 3 C3 weeds in C3 crops

Logic would imply that the same type of plants (with regards to photosynthesis) in the same ecosystem would react to changes in a similar way. This is only partly true, while C3 crops and C3 weeds, both benefit from elevated CO_2 it seems that the magnitude varies. Stimulation of biomass accumulation from CO_2 doubling was estimated by one research team to be +31% in wheat, +30% in barley, +27% in rice, +39% in soybean, +57% in alfalfa, and +84% in cotton. In contrast, a survey of experimental results on 27 non-crop C3 species revealed that biomass accumulation increased from 79% to 272% compared to ambient CO_2 (Patterson 1995). An experiment, which investigated seven C3 crop and three C3 weeds at 350ppm and 700ppm CO_2 showed similar growth rates and mass of C3 crops and C3 weeds (Bunce 1997).

6. 1. 4 C4 weeds in C4 crops

Since all C4 plants (weeds and crops) have the same photosynthesis path they may react to changes in the same ecosystem in a similar way. However, research on impact of climate change in this combination has not been done.

Three types of photosynthesis – a short introduction

Plants derive energy from sunlight and create organic matter. This process is called photosynthesis. Sunlight plus carbon dioxide (CO_2) and water as key ingredients are converted to sugar (Glucose) – the primary carbon compound, on which all life is based and oxygen (O_2)- precondition for respiration (Larcher 2001). Terrestrial plants open their stomata to take in CO_2, to release O_2 and for transpiration. Every time a plant opens its stomata to take in CO_2, it will also transpire and lose water. In order not to lose water, every plant keeps the stomata closed in dry times as much as it can, but this has the disadvantage of reduced photosynthesis and thus growth. In hotter and dryer regions, plants therefore developed different types of photosynthesis to utilize CO_2 without opening the stomata too often. These plants are classified by their photosynthetic metabolism into C4 plants (named according to the number of carbon molecules in the first photosynthesis product) and CAM (Crassulacean Acid Metabolism) plants, while the 'normal' and most common plants, which developed under cooler, wetter climates are called C3 plants. Common C4 crops are: maize (*Zea mays* L.), sorghum (*Sorghum bicolor* [L.] Moench), millets (mainly *Pennisetum glaucum* [L.] R. Br., *Setaria italica* [L.] P. Beauvois, *Panicum miliaceum* L., *Eleusine coracana* L.) and sugar cane (*Saccharum officinarum* [L.] (Leakey 2009). CAM crops are: pineapple (*Ananas comosu*), Agave, Aloe and Opuntia (Prickly Pear Cactus) (Black & Osmond 2003).

Due to their different types of photosynthesis C4 and CAM plants react very differently to elevated atmospheric CO_2. Basically elevated CO_2 does not directly stimulate C4 photosynthesis and growth. Nonetheless, drought stress can be ameliorated at elevated CO_2 as a result of even lower stomatal conductance. Therefore, unlike C3 crops for which there is a direct enhancement of photosynthesis by elevated CO_2, C4 crops will only benefit from elevated CO_2 in times and places of drought stress (Leakey 2009). Figure 1 shows the different response of C3 in comparison to C4 plants to CO_2 increase. CAM plants react to elevated CO_2 similar to C3 plants with enhances growth, if water supply is sufficient. If not they will respond like C4 plants (Isreal & Nobel 1994).
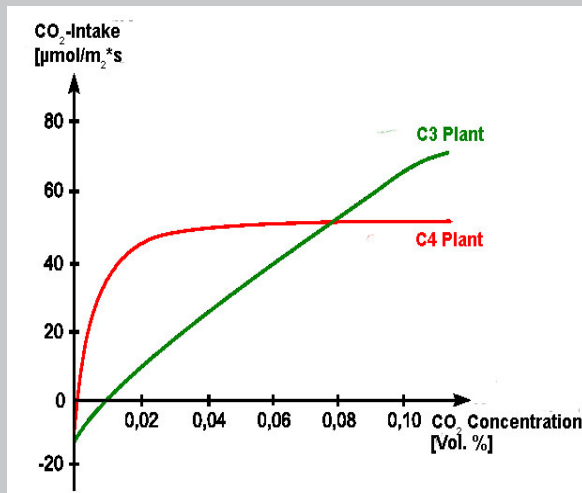

Figure 1: Comparison of CO_2 Intake of C3 and C4 Plants in relation to atmospheric CO_2 Concentrations. At current CO_2 levels (0,038% or 380 ppm) CO_2 saturation in C4 plants is achieved. Image taken from http://de.wikipedia.org/wiki/Photosynthese and translated.

6. 2 *Herbivore*

Herbivorous species are animals which eat mainly living plant tissue. Elephants, deer, many slugs, leaf chewing and sap sucking insects and mites – these are all more or less herbivores[1]. Climate change might affect them directly, but since they live from plant tissue, anything that affects plants will affect them as well.

Most ecological research on climate change and herbivorous species have focused on elevated CO_2 and its impacts on insect species. Other groups of animals have largely been neglected (Bezemer & Knight 2001) and much less research has been done on increased temperature combined with elevated CO_2 (Whittaker 1999; Flynn et al. 2006; Zvevera & Kozlov 2006; Hoover & Newman 2004), which would resemble more realistic future scenarios. The underlying idea of the focus on CO_2 is that elevated CO_2 reduces the nutritious quality of the primary producers (C3 plants), with impact on the foodweb (Fajer 1989, Emmerson et al. 2004). When it comes to specific pests like snails, slugs or nematodes the scientific base becomes even thinner. The few studies on these animal groups mostly did not focus on major pests. However, the

following sub chapter will look at selected pest groups: insects, snails and slugs, and nematodes.

6. 2. 1 *Insects herbivores*

Damage by insects pests is usually caused by chewing on plant tissues or sucking the plant sap (e.g. aphids). In many cases insect pests also transmit viruses, which then affect the plant. Price (2002) estimated that globally there are 360,000 insects species, which mainly live from plant material.

Climate change is associated with warming, elevated CO_2 and regionally changed precipitation. Currano et al. (2009) investigated fossil leaves from a historic time period with abrupt warming and increasing CO_2 levels, similar to what climate change might cause in the future. The authors conclude that global warming will in the long-term increase insect herbivory. In contrast, Fajer (1989) argues that an enriched CO_2 atmosphere alone, leading to low plant quality, will reduce herbivore densities and increase the probability of extinction. Regarding the tropical regions Deutsch et al. (2008) suggest that many insect species may become extinct, because tropical insects are already living at environmental temperatures close to their optimum and any increase will have adverse affects - and it is very likely (> 90%

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1 The classification of herbivore is not absolute. Many animals are partly or at different stages omnivore. (see Hunter (2009)
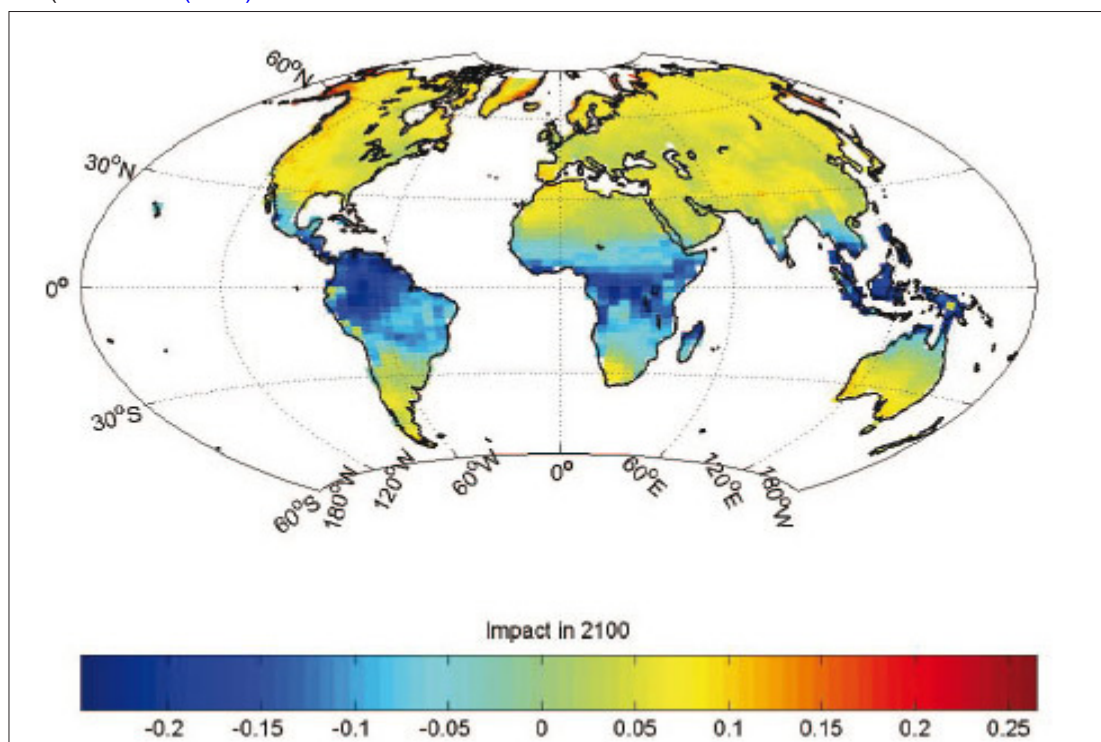

Figure 2: Predicted impact of global warming by 2100 on insect species as calculated by Deutsch et al. (2008). Positive impacts (positive values) are displayed yellow to red, while negative impacts (negative values) are shown in blue. Image used with written permission by Joshua J. Tewksbury.

chance) that, be the end of the century, a large proportion of tropical and subtropical Asia and Africa will experience unprecedented seasonal average temperatures (Battisti & Naylor 2009). Figure 2 illustrates the predicted impact of global warming by 2100 on insect species as calculated by Deutsch et al. (2008).

However, Currano et al. (2008), Fajer (1989) or Deutsch et al. (2008) do not refer specifically to agricultural insect pests, which are a special issue, since farmers provide 'food' and a fertilised habitat for insects globally.

Insects are ectothermic, they are very sensitive to temperature, and they cannot sustain living below and above certain thresholds. Each insect species and even each population might have a different optimum temperature for surviving and reproduction. In colder regions (higher latitudes) with distinctive seasons insects have broader thermal tolerance and are living in climates that are currently cooler than their optima (Deutsch et al. 2008). Global warming might therefore benefit many insect species in the temperate regions. A warmer climate in these regions may result in changes in geographical distribution, increased overwintering (i.e. more insects survive the winter), changes in population growth rates,

increases in the number of generations, extension of the development season, changes in crop-pest synchrony, changes in interspecific interactions and increased risk of invasion by migrant pests (Porter et al. 1991; Bale et al. 2002). Musolin (2007), for example, observed that in Japan, warmer climate led to the northward migration of the green stinkbug (*Nezara viridula*) a major agricultural pest damaging soybean, rice, cotton and many other crops. From his literature review of true bugs (Heteroptera) he concludes in line with Porter et al. (1991) that warming in temperate regions may have manifold effects on bugs. Table 1 shows the responses on bugs (Heteroptera) to slight and substantial temperature increases compiled by Musolin (2007).

Reduced winter mortality of two insects pests was observed in Japan, when mean temperature in January was above 4°C (Kiritani 2007). Kiritani (2007) suggests some general trends for different types of insects in Japan. Species which already develop at low temperatures and need a smaller number of warm days will benefit from increasing average temperatures, and produce more generations and appear early when spring temperatures are high. Species which require higher temperature in the time before they lay their eggs tend to have increased reproductive

Ectothermic: Refers to organisms that control body temperature through external means. As a result, organisms are dependent on environmental heat sources.

Abundance: The relative representation of a species in a community.

Voltinism: Indicates the number of generations of an organism per year.

Univoltine: Refers to organisms having one generation per year.

Bivoltine: Refers to organisms having two generations per year.

Multivoltine: Refers to organisms having more than two generations per year.

Table 1: Expected responses of Heteroptera species and communities under two scenarios of further climate change

Categories of responses	Slight temperature increase (<2°C)	Substantial temperature increase (>2°C)
Distribution range	Likely to shift in some species, especially those capable of long-distance flights and associated with ornamental plants and/or urban habitats	Likely to shift in many species
Abundance	Likely to increase in multivoltine species with flexible life cycles	Likely to change, depending on the community response
Phenology	Slight to moderate advance of early-season events	Substantial advance of early-season and some delay of late-season events
Voltinism	An additional generation in some multivoltine species with flexible life cycles	One or more additional generation(s) in some multivoltine and univoltine species (with facultative diapause)
Physiology and behaviour	Slight/ undetectable changes	Evident/detectable changes (e.g. in parameters of photoperiodic responses)
Community structure	Similar to currently observed	Increased species richness; substantial changes in structure
Musolin (2007)		

activity. However, since crops must be, a) present and b) in a vulnerable stage, a high pest density in the breeding habitats would not necessarily lead to crop damage (ibid.).

Direct effects of higher CO_2 concentrations on insects are basically not investigated. It seems that insects can detect CO_2 sources such as plants and elevated levels might affect the insect's CO_2-sensing system (Guerenstein & Hildebrand 2008).

However, there is a general agreement between scientists that the reduced nutrient quality of C3 plants might lead to a compensation by increased feeding of many, but not all, herbivorous species (Lincoln et al. 1986, Whittaker 1999, Emmerson et al. 2004, DeLucia 2008, Barbehenn et al. 2004). Whittaker (1999) concluded from its review of studies on insects and elevated CO_2 that so far, population densities of chewing insects are unaffected or decrease, but do not increase while sap sucker (phloem feeder) population densities might increase.

However, the results from experiments with aphids (phloem feeders) feeding on plants grown under elevated CO_2, and/or at elevated temperature have not shown consistent results (for review see Holopainen 2002). Annex I shows results of numerous experiments with aphids mostly on wild plants, but also on some agricultural plants. In some cases aphid performance was not (significantly) influenced by either elevated temperature and/or elevated CO_2 (e.g. Salt et al 1996; Diaz et al. 1998; Flynn et al. 2006), in one research trial two species responded very differently under same conditions (e.g. *Brevicoryne brassicae* vs. *Myzus persicae* on *Brassice napus ssp. oleifera*, Himanen et al. 2008). Increased aphid infestation (Hughes & Bazzaz 2001; Bezemer et al. 1998) as well as reduced infestation (Thompson et al 1993; Hughes & Bazzaz 2001; Newman et al. 1999) in response to elevated CO_2 have been observed. Experiments by Awmack & Harrington (2000) showed significant effects through aphids on the peas (shoot, root weight, flower number) at elevated CO_2, although the aphid density was unaffected.

A meta-analysis of studies on elevated temperature and elevated CO_2 suggests that insect herbivore performance is adversely affected by elevated CO_2, favoured by elevated temperature, and not modified when both parameters (temperature and CO_2 combined) were elevated (Zvevera & Kozlov 2006). However, only 10 of the 41 scientific papers analyzed by Zvevera & Kozlov (2006) dealt altogether with six agricultural crops and none

of the plant-herbivore interaction investigated was related to agricultural crops/pests (ibid.). Moreover, only two of the investigated studies were on C4 plants, both did not include herbivore interaction.

It seems that current knowledge does not allow a generalization regarding the impact of climate change in herbivorous insects, especially not for the tropics. Even the trend of a northward shift of insects must not coercively translate into a pest problem – ecosystems are not that simple and human influence is quite strong. Basically, it would be necessary to investigate at least over three trophic levels with several generations of plants, herbivores, predators/parasites, under elevated temperature and elevated CO_2.

A few pest species/groups have been investigated more thoroughly and the cotton bollworn/pod borer (*Helicoverpa armigera*) a widely occurring lepidopteran pest (see Figure 2) might give some idea what impact climate change might have on this species. Larvae of *Helicoverpa armigera* feed on many vegetables, cotton and cereals (CPC 2007). The adult moth lays eggs on the plant and after the eggs are hatched, the caterpillars feed. The duration of larval development depends on the temperature (to a maximum of 35°C in South- and Southeast Asia) and on the quality of the host food. On completion of growth the fully fed larva enters the soil to pupate. The pupal diapause is induced by short day lengths (11-14 hours/day) and low temperatures (15-23°C) experienced as a larva (ibid.). After a number of days, depending on the environmental conditions, the butterfly will emerge from the pupae and the cycle begins again.

A Chinese research team has conducted several studies on *Helicoverpa armigera* and CO_2. Chen et al. (2005) reared larvae of *Helicoverpa armigera* on milky grains of spring wheat grown in ambient CO_2 concentrations, at 550 ppm and at 750 ppm. The results show that the larvae developed quite similarly under all CO_2 concentrations, even though the larvae under elevated CO_2 consumed much more than those under ambient CO_2. Quite interesting is the fact that the adult moth raised under elevated CO_2 lived longer, but laid significantly less eggs.

Research with three generations of *Helicoverpa armigera* reared on milky grains of spring wheat grown in ambient CO_2 concentrations at 750 ppm showed again that bollworm fecundity was

significantly decreased for the second and third generations under elevated CO_2 levels. While the consumption per larva and relative consumption rate significantly increased in elevated CO_2, the potential population consumption was significantly reduced by elevated CO_2 in the second and third generations. Therefore the researcher suggests that net damage of cotton bollworm on wheat will be less under elevated atmospheric CO_2 levels because increased consumption is offset by slower development and reduced fertility (Wu et al. 2006).

In a similar experiment (larvae reared on milky wheat grain under 750 ppm CO_2) the researcher included a parasitoid wasp (*Microplitis mediator*) widely used as bio-control agent of *Helicoverpa armigera*. The researcher found no significant changes in wheat consumption by *H. armigera* population under elevated CO_2 or in the parasitic rate of M. mediator. The results indicate that the population relationship between H. armigera and M. mediator is unlikely to vary due to future elevated atmospheric CO_2 concentrations (Yin et al. 2009).

A multiple generation experiment compared consumption, growth and performance of *Helicoverpa armigera* feeding on transgenic Bt-Cotton versus conventional cotton grown under elevated CO_2 (750ppm) versus ambient CO_2 (375 ppm). The results suggest that on the one hand damage caused by the cotton bollworm might be higher under elevated CO_2 conditions, regardless of the cotton variety. On the other hand population abundance might be lower under elevated CO_2 compared to that under ambient CO_2 (Chen et al. 2007). The researcher explain both observation with nutritional changes under elevated CO_2 (e.g. compensatory feeding), but did not determine the nutrient content of the different experimental cotton groups.

An experiment of Coll & Hughes (2008) investigated the effects of elevated CO_2 on *H. armigera* and an omnivorous bug, which feeds on plants but also preys on the bollworm. Bollworm larvae feeding on elevated CO_2-grown pea plants (*Pisum sativum* at 700 ppm) were significantly smaller than those grown on ambient-grown plants. The omnivorous bug required prey to complete its development, and performed best on a mixed plant-prey diet, regardless of CO_2 level. The bugs performed best when fed larvae from the elevated-CO_2 treatment apparently because these prey were smaller and thus easier to overcome. Taken together, results indicate that elevated CO_2

may benefit generalist predators through increased prey vulnerability, which would put pest species under higher risk of predation.

However, none of the four experiments were conducted under increased temperatures, which might level off adverse effects of elevated CO_2 (Zvevera & Kozlov 2006) on *H. armigera*.

6. 2. 2 Spider Mites

Spider mites are not insects. They belong to the class of Arachnida, and some of them are among the most important plant pests worldwide. They feed on leaves of over 150 plant species including field crops, vegetables, and fruits. A common member of the group is *Tetranychus urticae* (the glasshouse red spider mite, or two-spotted spider mite), which is common in tropical and warm temperate zones, and in glasshouses in temperate zones. Past research on spider mites and climate change is limited to a few studies with elevated CO_2. In one study two-spotted spider mites (*Tetranychus urticae*) were raised on common beans grown at 600 and 700ppm CO_2. A significant decrease in the number of the offspring in the first and second generations (34% and 49%) respectively was observed compared to ambient CO_2 (Jotei et al. 2000). A similar experiment was conducted, where two-spotted spider mites (*Tetranychus urticae*) were raised on clover (*Trifolium repens*) grown at different CO_2 levels (395-748 ppm). The results showed a quite opposite effect: under elevated CO_2 spider mite reproduction increased significantly compared to lower CO_2 (Heagle et al. 2002). They noted that slight temperature differences could cause significantly different reproduction rates (ibid.).

6. 2. 3 Soil Nematodes

Soil nematodes are very small (0.3–5.0mm long as adults) worm-like animals which occur in millions per square meter soil. Nematodes feed on a wide range of soil organisms (bacteria, fungi, slug eggs, insect larvae) as well as plant roots. Herbivorous nematodes can cause crop losses especially in root crops like potatoes and beets grown mostly in Europe, but also in soy bean grown in Asia (CPC 2007). Many nematodes species work as natural enemies of insect larvae and slugs (Georgis et al. 2006).

Soil nematodes are dependent on the continuity of soil water films for movement. Their activities are largely controlled by soil biological and physical

Bt-Cotton:
Genetically modified cotton, which produced the toxin of *Bacillus thuringiensis* (Bt.) against Lepidoptera larvae.

Omnivore:
Species eating a mixed diet of plant and animal tissue as primary food source.

conditions (Yeates & Bongers 1999).

Scientific research on climate change and its impact on herbivorous nematodes is very limited. However, based upon their environmental requirements some assumptions are possible. Severe droughts resulting in a reduction of soil water will most likely negatively affect soil nematodes. Higher average temperatures will probably have little effect, since thermal conductivity of soils is low (Larcher 2001).

Similar to other organisms which feed on plants, increased CO_2 levels are believed to have an impact on herbivorous nematodes (Ayres 2008) and several studies have been conducted, where the above ground plant community was exposed to elevated CO_2. Almost all of these studies were done in different grasslands and forests, and thus results have been variable and contradictory. Research results regarding nematodes, from experiments conducted on agricultural crops in arable soils, are very limited. Basically, all kinds of results were determined: increase, decrease and no change of nematodes populations (Sticht et al. 2009). A recent publication presents results of a long term agricultural experiment conducted in winter wheat and sugar beets in Germany. Winter wheat and sugar beet were grown in rotation under 550 ppm atmospheric CO_2 compared to ambient (380ppm) atmospheric CO_2. The number of herbivore, bacterivore and fungivore nematodes was significantly higher under wheat and sugar beets grown under elevated CO_2, while the number of carnivore was not changed. The total numbers of herbivore, bacterivore and fungivore nematodes were higher under elevated CO_2 wheat than under elevated CO_2 sugar beet, most likely due to the very different root system of both plant

species (ibid). However impacts on yield were not determined.

Apparently, a prediction of how climate change will affect herbivorous soil nematodes and thus yields cannot be made. There is some evidence that population dynamics may change, but so far no trend is clear. Basically, and most likely true for all ecological research, the impacts of climate change are specific to crop/plant, region and interacting species.

6. 2. 4 Snails and Slugs

In general, many snails and slugs are omnivorous, as they consume living plants, litter, animal carcasses and/or eggs of other (smaller) animals. However, their appetite for living plants can be considerable and some snails such as the Golden Apple Snail (*Pomacea canaliculata*) in Asian rice systems are considered a major pest. Activity of snails and slugs depends on surface moisture. During drier times or on drought land, snails and slugs usually hide in the soil or other places.

Some research has been done to investigate effects of climate change on (mostly European) snails and slugs. Bezemer & Knight (2001) investigated the isolated and combined effects of elevated CO_2 and warming on the garden snail (*Helix aspersa*) over several generations. Elevated temperature (+ 2°C) alone reduced appearance of young snails, while elevated CO_2 (+200ppm above ambient) alone did not show any effect. In the combined run, significantly more juveniles were found, and appeared about 70 days earlier than in the trial with increased temperature.

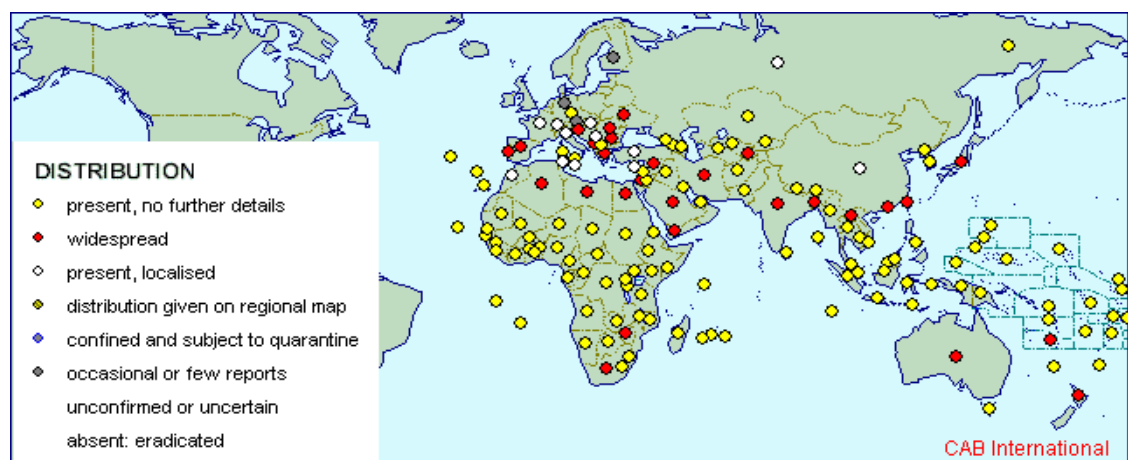Most other experiments were feeding studies

Figure 3: Global Distribution of cotton bollworn/pod borer *Helicoverpa armigera*. **No occurrences are reported in South-, Latin- or North America. Reproduced from the Crop Protection Compendium, 2007 Edition. © CAB International, Wallingford, UK, 2007. Legend added by L. Neumeister.**

conducted with elevated CO_2 alone. Increased consumption by the Burgundy/ Roman snail (*Helix pomatia*) was observed, while food consumption of *H. aspersa* was not influenced by CO_2 concentration. No shift of preference towards different foods was observed on garden snail (*Helix aspersa*) and Burgundy/ Roman snail (*Helix pomatia*) (Diaz et al. 1998, Ledergerber et al.1998).

6. 3 *Plant Diseases*

Crops can be damaged by diseases caused by fungi (rust, blight, mildew, rot), bacteria/phytoplasma (wilt) and viruses. The occurrence of plant fungal and bacterial pests depends on climate and weather, but are also strongly influenced by agricultural practices. Viruses and phytoplasma are often transferred via vectors, often insects (Weintraub & Beanland 2006). Temperature, rainfall, humidity, radiation or dew can affect the growth and spread of fungi and bacteria (Patterson et al. 1999). Other important factors influencing plant diseases are air pollution, particularly ozone and UV-B radiation (Manning & von Tiedemann 1995) as well as nutrient (especially nitrogen) availability (Thompson et al. 1993).

Agronomic practices (tillage system, crop rotation), fungicide use, but also herbicide use strongly influence disease pressure. Fernandez et al. 2009 showed for example, that in Canadian cereal cultures, previous use of glyphosate, the most extensively used herbicide globally, was consistently associated with higher Fusarium Head Blight pressure.

Since plant diseases depend on host plants, impacts of climate change will influence diseases. Direct effects have also been observed. Manning and von Tiedemann (1995) for example, compiled

Figure 4: Burgundy or Roman snail (*Helix pomatia* [L.] a largely herbivorous snail.

results of studies where the bacteria and fungi cultures were directly exposed to increased CO_2. They showed that direct exposure of high CO_2 concentrations often inhibits bacteria and fungi growth.

So far research in the effects of climate change on plant disease continues to be limited (ibid.; Garrett et al. 2006), but it is likely that climate change will have positive, negative or neutral impacts on specific host–pathogen systems (Coakley et al. 1999, Chakraborty et al. 2000).

In general, climate change has the potential to modify host physiology and resistance, and to alter stages and rates of development of the pathogen (Coakley et al. 1999). Elevated CO_2 may increase C3 plant canopy size and density, resulting in a greater biomass with a much higher microclimate relative humidity. This is likely to promote plant diseases such as rusts, powdery mildews, leaf spots and blights (Manning and von Tiedemann 1995). However, Kobayashi et al. (2006) conclude from literature reviews that it is not clear whether the disease severity is enhanced or diminished by a higher CO_2 level. Research on rice leaf blast and rice sheath blight in the temperate climes of Japan showed that elevated CO_2 increased the potential risks for infection from leaf blast and epidemics of sheath blight (ibid.). A simulation modeled rice leaf blast epidemics in Japan, China, Thailand South Korea and the Philippines under increasing temperature and ultraviolet B (UV-B) radiation. Elevated CO_2 was not considered. The simulation showed that in the cooler regions of Japan and northern China a temperature increase might lead to more severe blast epidemics, while in humid tropics and warm humid tropics this risk might decrease. The authors concluded that in these regions blast development is inhibited by high temperatures. UV-B radiation will enhance the severity of blast, but more in cooler, than in warmer regions (Luo et al. 1995).

In soybeans, elevated CO_2 alone or in combination with ozone (O_3) significantly reduced downy mildew (*Peronospora manshurica*) disease severity by 39–66% across a 3 year study. In contrast, elevated CO_2 alone or in combination with O_3 significantly increased brown spot (*Septoria glycines*) severity, but the increase was small in magnitude (Eastburn et al. 2009).

In wheat, grown at elevated atmospheric CO_2 (700 ppm) and under different fertilization and water regimes, the host water content, the plant N content and the infection rate with powdery mildew were investigated.

Phytoplasma: Specialised bacteria, parasiting the phloem of a plant.

In all fertilisation regimes, the mean per cent leaf area infected with mildew was significantly reduced under elevated atmospheric CO_2, compared to ambient CO_2.

In a moderate water supply treatment (3.6 mm/day), the plants grown in elevated atmospheric CO_2 concentrations had significantly reduced N contents (9.9%) and significantly increased water content (4%), the amount of mildew infection was unchanged. At higher water supply (5.4 mm/day) host water content at elevated CO_2 was similar to that of ambient CO_2, but N content was significantly reduced. As a consequence severity of powdery mildew caused by *Erysiphe graminis* infection was significantly reduced, compared to ambient CO_2. At lower water supply (1.8 mm/day) the results were quite different. Host water content at elevated CO_2 was higher compared to that of ambient CO_2, but N content showed no difference. As a consequence severity of powdery mildew infection was significantly increased, compared to ambient CO_2. It seems that severity of mildew infection is more sensitive to host water content than to host nitrogen content (Thompson et al. 1993).

Astonishing results were gained in an experiment on oat (*Avena sativa*) grown under elevated CO_2 (700 ppm) and infected by barley yellow dwarf virus (BYDV). Root mass of virus infected plants increased by 37–60% with CO_2 enrichment, but was largely unaffected in healthy plants. CO_2 enrichment increased photosynthesis and water use efficiency by 34 and 93% in healthy plants and by 48 and 174% in infected plants – basically the infected plant performed better under elevated CO_2 than at ambient CO_2 (Malmström & Field 1997).

In conclusion, global climate change will affect plant diseases in concert with other global change phenomena. (Garret et al. 2006), but so far there are no indications if disease pressure increases or not. Solid regional models considering agricultural practises, and including precipitation patters are needed.

7. Natural enemies the underrated friends

The term 'natural enemy' describes naturally occurring organisms[1] which reduce weed, pest or disease pressure in a specific ecosystem or an urban setting. Natural enemies belong to the same groups of organisms as the pests and disease causing fungi, bacteria, viruses etc. However, natural enemies usually belong to a higher trophic level than pests, with the exception of omnivore species which feed on plants and animals as well as weed controlling organisms,

This is a very important point, since natural enemies (except omnivores with a mixed plant-animal diet) are not directly affected by the quality of the plant tissue.

Depending on the agro-ecosystem the types of natural enemies can vary. In orchards, higher animals such birds (Mols & Visser 2002), bats and shrews (*Soricidae*) might considerably reduce pests. In palm oil plantations in Malaysia, for example, nest boxes for barn owls attracted enough owls to effectively control rats. In rice paddy fields frogs, toads and fishes might play a role in controlling certain pests. Even fungi such as grape powdery mildew have a mite as a natural enemy, which suppresses powdery mildew density (English-Loeb et al. 2005, Norton et al. 2000).

In China, researchers found that when spiders moved into an area of planthopper infestation, they reduced the pest predator ratio from 9:1 to 1.5:1 within 10 days in one study area and from 5:1 to 0.03:1 within 5 days in another. When implementing conservation practices that fostered spider density increases, including limited frequency of pesticide application, the need for chemical plant protection decreased as much as 80% with no measurable loss in rice yield (Riechert 1999). Some scientists estimated that natural pest control is worth $4.5 billion annually (Losey & Vaughan 2006) and consequently any reduction in this 'service' also implies monetary costs.

In general, each common pests has numerous natural enemies – a look at the Crop Protection Compendium (CPC) shows that for the cotton bollworm (*Helicoverpa armigera*) there are 216

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1 Viruses are not organisms and since they do not have a metabolism they do not belong to any trophy level. It might be misleading to call them 'natural enemies', but here and in the CPC they are classified as pathogens.

known natural enemies which can be divided into 25 pathogens, 121 parasitoids and 70 predators (CPC 2007 accessed 12.08.09). This example shows the large diversity of natural enemies. Price (2002) estimated that globally, the 310,000 herbivorous insects species are confronted with 400,000 carnivorous insect species.

Natural enemies can be divided roughly into three functional groups: pathogens, parasites/parasitoids and predators. This classification serves a more pragmatic approach as drawing the line is not possible; principally a fungi (a pathogen) which affects a pupae or larvae could also be classified as a parasite. But for simplification, microorganisms (fungi, bacteria, microsporidia) and viruses which affect and live from animal tissue are here defined as pathogens. Another important distinction has to be made between specialist and generalists. A specialist usually affects/ parasites/ preys on one (or very few) specific species, while a generalist has a broader spectrum (for example, a spider web does not select). Again, there is no absolute line to draw – under certain circumstances a specialist may change its specificity, while a generalist may specialize.

Considering the tremendous economic importance of natural enemies in agro-ecosystems, surprisingly little research has been done on the effects of climate change on them. Basically, very few experiments[1], two under elevated CO_2 (but no temperature increase) was conducted involving three trophic levels: plant-herbivore-natural enemy (Coll & Hughes 2008; Yin et al. 2009), and another (Bezemer at al. 1998) under elevated CO_2 and increased temperature separately. Some more experiments looked at impacts of temperature on specific groups of natural enemies. For some groups of natural enemies mathematical models were applied to predict their response to climatic changes (e.g. Stireman et al. 2005, Guiterrez et al. 2008).

One publication reviewing and summarizing effects of climate change on the natural enemies of agricultural pests was published by Thomson et al. (2009) but this paper focuses very much on insect parasitoids and completely neglects entomopathogens (fungi, bacteria, microsporidia, viruses). Predators are also underrepresented.

However, ecologists argue that the tritrophic interactions between plants, herbivorous insects, and their natural enemies (predators, parasitoids

and pathogens) result from a long co-evolutionary process specific to a particular environment and relatively stable climatic conditions. (Hance et al. 2007). Abrupt environmental changes as induced by current climatic change and elevated CO_2 may influence the biology of each component of a system differently, provoking a destabilization in their population dynamics that may lead to the extinction of part of the system (Fajer 1989). Specialists, for example many host specific parasitoids, which evolved under rather stable conditions might be especially endangered (van der Putten 2004).

In order to give an impression on the implications of climate change, the next subchapters will take a closer look at the three groups of natural enemies and their ecology.

7. 1 Pathogens

Fungi, bacteria, microsporidia and viruses can successfully affect rodents, insect pest, mites and plant pathogens. They are widely used in biological control (for an overview see Hajek et al. 2007 and Roy et al. 2009), with the bacteria *Bacillus thuringiensis* and the fungi *Beauveria bassiana* being prominent examples.

Effects of climate change on the efficiency of pathogens depends on the environment they live in. In general fungi and bacteria benefit from warm and moist environments, therefore mild and wetter winters as predicted in temperate zones will benefit them, especially those living in the soil (e.g. *Beauveria bassiana*). Since many larvae or pupae of pests also overwinter (pass through or wait out the winter season) in soils, fungi and bacteria might affect them more strongly.

Guiterrez et al. (2008) found out that during the normally wet Northern California winter, the fungal pathogen (*Pandora neoaphidis*) causes catastrophic mortality to pea aphid (*Acyrthosiphon pisum*), but during hot dry periods, the impact of the pathogen declines.

Most entomopathogenic fungi have optimal growth temperatures between 25 and 35°C. *Beauveria bassiana* grows at a wide temperature range (from 8 to 35°C) with a maximum thermal threshold for growth at 37°C (Fernandes et al. 2008). Higher temperatures, low humidity as well as direct exposure to UV radiation reduces efficiency of pathogens.

However, each pathogen responds to temperatures differently and behavior of the host in response

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1 Please note that only peer reviewed scientific English/German publications are considered.

to temperature is important as well (Blanford & Thomas 1999). Manning and von Tiedemann (1995) compiled results of studies, where the bacteria and fungi cultures were directly exposed to high levels of CO_2. They showed that direct exposure of high CO_2 concentrations often inhibits bacteria and fungi growth.

Some pathogens, which always live in the host body might not be affected directly by climatic changes, they basically follow the development of their hosts. The author's own research on effects of higher temperature on the impact of the microsporidia *Nosema lymantriae* on the gipsy moth (*Lymatria dispar*) clearly showed a much higher and earlier mortality of gipsy moth larvae at higher temperatures. Research with a very similar experimental design by Pollan (2009) achieved similar result.

Pathogens, especially viruses, become more deadly if the vector/host is weakened, therefore environmental stress such as high or low temperature might lead to higher mortality. Considering that herbivorous pests are potentially weakened by the lower nutritional quality of (C3) plants grown under elevated CO_2 (see previous chapter) it could be assumed that mortality of pests feeding on C3 crops increases when infected with pathogens (with potentially serious consequences also for some natural ecosystems). However, it seems that no one has investigated this kind of interactions so far. According to Prof. Hajek (pers. comm.[1]) virtually no studies of the effects of climate change on entomopathogens exist.

7. 2 Parasitoids

Parasitoids are organisms which need to live parts of their life in or on another organism (the host). Some parasitoids paralyze or kill their host quickly, while others need to develop with their host. It was suggested that among all natural enemies parasitoids have the strongest impacts on herbivore species (Hawkins et al. 1997). In biological pest control parasitoids, especially wasps of the genus Trichogramma[2], are widely used, and some estimates suggest that 10% to 20% of all insects may be parasitoid wasps (Pennacchio & Strand 2006).

Parasitoids which live on crop pests belong to the third trophic level. Thus they are indirectly or directly affected by any changes of the first (plant) and second level (herbivore). It is not at all clear what happens to herbivores under climate change (see previous chapters), therefore conclusions for parasitoids are speculative. However, there are some ecological 'laws' which imply certain scenarios. If a herbivore reproduces less, because of low nutritional value, less potential hosts are available for the parasitoid. If the host changes it seasonal appearance or behavior due to climatic changes the parasitoid might not be able to locate the host. Finally parasitoids might be adversely affected, if the host dies too early due to additional environmental stress. However, in temperate zones milder winters might enhance survival of parasitoids. Legrand et al. (2004) have shown that parasitoids of cereal aphids are active in winter and this winter activity can considerably reduce spring aphid populations.

No experiments have been conducted to investigate changes of all three trophic levels together (plant-herbivore-parasitoid) under climate change (elevated CO_2 and temperature). Bezemer et al. (1998) conducted an experiment involving several plant species, aphids and parasitoids under elevated CO_2 (+200ppm of ambient concentrations), and showed that elevated CO_2 did

Figure 5: A spider web does not select. This yellow spider caught numerous hover flies, which are considered natural enemies of aphids.

1 Personal communication with Prof. Ann E. Hajek, Department of Entomology. Cornell University. USA

2 For more information see: http://en.wikipedia.org/wiki/Trichogramma

not influence parasitism. Elevated temperature (+ 2°C of ambient temperature) increased parasitism about 300% on average, but due to high variation between the replicates no significance could be detected.

Hoover & Newman (2004) developed a mathematical model that predicts responses of grasses, cereal aphids and parasitoids to combined effects of elevated CO_2 and elevated temperature. Their results suggest that aphid and parasitoid populations will develop more similar to current ambient conditions than expected from the individual effects of CO_2 or temperature increases.

In one experiment with cotton bollworm larvae reared on milky wheat grain under 750 ppm CO_2, researchers included a parasitoid wasp *(Microplitis mediator)* widely used as bio-control agent of the cotton bollworm (*Helicoverpa armigera*). The researchers found no significant changes in wheat consumption by *H. armigera* population under elevated CO_2 or in the parasitic rate of *M. mediator*. The researchers concluded that the population relationship between *H. armigera* and *M. mediator* is unlikely to vary due to future elevated atmospheric CO_2 concentrations (Yin et al. 2009).

The development of a parasitoid wasp (*Glyptapanteles liparidis*) of gypsy moth (*Lymantria dispar*) feeding on three different tree species fumigated with 540±20ppm CO_2 was not adversely affected by changes in food quality when compared to ambient CO_2 (Schafellner & Schopf 2008). However, it must be taken into account that the effects of elevated CO_2 on mature trees as investigated by Schafellner & Schopf (2008) might not be comparable to annual plants or tree seedlings.

Stireman et al. (2005) looked at frequency of parasitism in 15 Lepidoptera (Butterfly) rearing programs from a broad spectrum of climatic regimes and locations, from the region between southern Canada and central Brazil. They conducted a statistical analysis and found that the precipitation variability seems to be a key factor influencing parasitism. A higher variability led to a decrease in parasitism. These findings basically support the theory that interaction, which evolved due to stable conditions, are weakened when frequent changes occur.

In general, host-specific parasitoids should be more sensitive to variations in host emergence time or developmental rate when compared to generalists.

Specialist parasitoids may miss narrow windows of vulnerability of their particular hosts. In contrast, because generalists exploit a variety of hosts that might individually respond to climatic cues in different ways, they should be less susceptible to the host population's lags and asynchronies associated with climatic unpredictability (ibid.)

7. 3 *Predators*

Predators are basically all organisms which prey on/hunt pest organisms. The range stretches from predatory nematodes, to spiders, to eagles. Predators not only reduce pest population by feeding on them, their simple presence causes pests to cease feeding, to forage at less favorable sites, and to drop off host plants altogether in an escape response. The resulting effect is usually a slowing of prey population growth, which delays the outbreak phase. However, dropping from a plant or field crop floor may result in mortality as well due to desiccation and predation by generalist predators (Riechert 1999, Nelson et al. 2004). Preisser et al. 2005 even suggest that intimidation by predators has a stronger impact on prey than consumption.

Like parasitoids, predators which prey on crop pests belong to the third trophic level[1]. Thus they are indirectly or directly affected by any changes of the first (plant) and second level (herbivore).

Atmospheric CO_2 levels may affect the performance of natural enemies and/or

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1 Predators can also belong to the fourth tropic level, if they, for example, feed on parasitoids or pests containing a parasitoid.

Figure 6: Seven-spot ladybirds (*Cocinella septempunctata*). Ladybirds are predators and probably the most famous natural enemies of aphids.

susceptibility of prey via a variety of indirect effects. Some of these impacts, which potentially make prey more susceptible to their enemies, include:

- herbivores that feed on poor host plants under elevated CO_2 conditions often spend more time in the more vulnerable, early stages of development, and thus may suffer greater mortality from natural enemies;

- herbivores may be physically weakened while feeding on poor hosts under elevated CO_2 conditions, and are thus less able to defend themselves against predators and parasitoids; and enriched CO_2 may alter enemy-avoidance behavior; some aphids, for example, show reduced responses to alarm pheromones under elevated CO_2, potentially making them more susceptible to enemy attack (Awmack et al. 1997).

Such effects would increase the susceptibility of herbivores to natural enemies, reducing herbivore population size under elevated CO_2 conditions (Coll & Hughes 2008).

Elevated temperature basically favors adult hunting insects and spiders, and it seems that the lethal temperature of many spiders is much above the temperature expected by climate change (Hanna & Cobb 2007). Skirvin et al. (1997) modeled the interaction of ladybird (*Coccinella septempunctata*) with aphid populations (*Sitobion avenae*) and predict that in hot summers coccinellids reduce aphids more strongly than in moderate summers.

8.   Anything can happen

This report looks at recent scientific (English language) literature. The objective was to investigate if there is any observable trend that could imply that pressure from weeds, pests and diseases might increase due to Climate Change. The conclusion is: Anything can happen. Only one thing is clear: climate change will change crop protection challenges. In cooler latitudes, global warming brings new species but others may disappear. Whether or not new species translate into a pest problem is uncertain. Invasive species are often brought to other places by global trade of food and goods (Hulme 2009). Their sudden appearance relates not necessarily to climate change. Agro-ecosystems are managed systems, and pest problems have always changed (Way & van Emden 2000). Maybe Andrew & Huges (2004) are right, when they state: '*(...) we might expect that under a warmer climate, broad patterns in insect community structure and rates of herbivory may remain similar to that at present, even though species composition may change substantially*.'

What do we know for certain? We know that elevated CO_2 increases biomass production in C3 plants but at the same time, the protein concentration decreases. Basically, this could mean that organisms that live off plants (herbivores) simply need to eat more plant material. This is frequently observed for some species, but not for others. The low quality food seems to have an impact on the fecundity of later generations for some species. Much research has been conducted on wild, forest and grassland species by changing a single parameter, either CO_2 *OR* temperature. Experiments with crops and their pests are rare – and an extrapolation from natural or semi-natural habitats to agriculture is very difficult. With farming, nutritious 'food' is provided for all kinds of herbivores. On the other hand, chemical pest management usually kills competitors as well as natural enemies, with possible major consequences for some (resistant) species/populations. Policy, land management and farming practices including pest management, tillage and fertilization might have a stronger influence on weeds, pests, diseases, than climate change (see Box '*Increasing pesticide use through climate change?*' and Annex II).

When it comes to natural enemies and climate change, knowledge becomes even scarcer. There is the hypothesis that adverse effects on the first and second trophic level might lead to even worse effects on the third and fourth level. While this is

somewhat logical–empirical evidence is missing. Climate change ecology research still remains in the 1980s, where scientists never looked beyond the second trophic level (van der Putten et al. 2001). There is not a single publication about an experiment simulating 'real' climate change in an agro-ecosystem: C3 and C4 crops/weed-herbivore pest-natural enemies under elevated CO_2 and increased temperature (see also Hoover & Newman 2004). There are more biases in science. Tropical pests might be of special interest, because they already live at optimum temperature. Lower food quality (due to lower protein) and temperature above their optimum might affect them twofold.

In the past, climate was quite stable, however, at present climate is changing and this trend will continue. Farmers need to be supported, so they can be prepared to cope with climate change and its impact on agriculture.

Our economic activities cause rapid changes: on top of all the current fast changes like population growth, air pollution, urbanization, land degradation, loss of biodiversity etc., human society is going to change the climate and the nutritional properties of most primary producers (C3 plants).

Regarding crop protection there are certain measures which can be applied regardless of what kind of changes will come (see also Table 1 in Zehnder et al. 2007):

Measure 1: Observe your fields and orchards. Not every insect is your enemy. Learn about the old pests/diseases and new. Keep yourself informed. Visit and or initiate a farmer field school (FFS)[1], where you can learn more about pests and their enemies and their management. Thorough knowledge of the pest life cycle, the ecological and behavioral interactions with the environment and natural controlling factors are the basic foundation for successful management strategies (Conlong & Rutherford 2009).

Measure 2: Tolerate and increase biodiversity. Natural pest control by the enemies of your enemies comes for free! A diverse fauna of enemy species can successfully suppress pests (Cardinale et al. 2003). Intercropping can attract natural enemies (pull) and repel pests (push) (Khan et al. 2007; Cook et al.

2007), partial weediness (as long as weeds are not host to pathogens or problematic pests), mulching and reduced tillage for example increases spider abundance (Sunderland & Samu 2000). If you spray pesticides to control weeds and pests, you usually kill your 'friends' and/or you destroy their homes. As a consequence an increase in the pest population may occur (resurgence) and you need to spray more frequently, and resistant pests might emerge (Shetty & Sabitha 2009).

Measure 3: Do not depend on one 'high input variety', or one breed of crop variety. Mix and change your breeds. A broad genetic variability serves as a foundation for robust crops (Zhu et al. 2000; Mundt 2000). In addition, it seems more recent traditional breeding has not selected for CO_2 responsiveness, which simply means newer breeds do not benefit from elevated CO_2 as much as older breeds (Ainsworth et al. 2008).

Measure 4: Do crop rotation, it increases biodiversity. Noxious pests, and weeds establish slower (e.g. grassy weeds in cereals), because specific relationships between pests and host plants are interrupted (Dhawan & Peshin 2009). Furthermore, crop residues are often host of pathogens and alternating crops will prevent the infection from the residues to the host crop (Sharma & Bambawale 2009).

Measure 5: Take care of your soil and spare mineral fertilizers. Ecologically based pest management (EBPM) considers belowground and aboveground habitat management equally important. A 'healthy' soil, with optimal physical, chemical, biological properties increases plant resistance to insect and diseases (Altieri et al. 2005). Excess of nitrogen can increase the severity of certain diseases (Sharma & Bambawale 2009) and make a crop more susceptible to pests (Altieri et al. 2005).

Resurgence: Abnormal increase in pest populations often exceeding the economic threshold level, following the insecticide application (Shetty & Sabitha 2009).

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1 More information: http://en.wikipedia.org/wiki/Farmer_Field_School and http://www.farmerfield-school.info/

Anything can happen

Increasing pesticide use through climate change?

The underlying questions of this review was, if climate change causes an increase in agricultural pesticide usage.

There is no evidence that elevated CO_2 and elevated (mean) temperature as projected by the IPCC for the next 50 years will cause tremendous new pest problems, especially if farmers respect the fives rules (see Chapter 7). In general, pesticide use is largely decoupled from climate and even from biotic factors. Certainly, there are weeds, pests and diseases, but the scale of the problem is anthropogenic. Otherwise farming without the use of pesticide as in the past or on organic farms would not be possible. Education, agronomy, economy and policy are the main drivers of pesticide use.

Pretty et al. (2006) for example showed how education influences pesticide use. The researchers investigated 61 Integrated Pest Management (IPM) projects in 21 developing countries. In five projects, pesticide use was be cut by 93.3% (±6,7%), but yields declined only by 4.2% (±5%), in 47 projects pesticide use declined by 70.8% (±3.9) and yields increased by 41.6% (±10.5). In 10 projects, mainly zero-tillage and conservation agriculture projects, pesticide use as well as yields increased. In those IPM projects, where pesticide use was considerably reduced, pests, weeds and diseases did not simply disappear, but the management changed from a pesticide based to a knowledge based system, making many pesticide applications redundant.

Zhu et al. 2000 showed on large scale, that simple agronomic measures such as mixing varieties reduced rice blast severity by 94% and increased yield by 89%.

Conversion to cost-cuttting zero-tillage, which is very popular in the USA and Europe often leads to increasing pesticide use, especially when crop rotation is very limited. Weeds in such systems are usually controlled with herbicides, since tillage as a weed control tool is reduced or abandoned. In addition, pressure from certain fungi, such as Fusarium can increase significantly (Johal & Huber 2009; Fernandez 2009; Dill-Macky & Jones 2000). A new quality of decoupling emerged through the introduction of genetically engineered crops. In particular, herbicide-resistant crops such as corn, cotton, soybeans and rape seed are now grown extensively throughout the world. This has increased the usage and intensity of specific herbicides and lead to the development of resistant 'superweeds', which are controlled with additional herbicides (Johnson et al 2009; Benbrook 2009; Johal & Huber 2009).

Figure 7 shows insecticide sales in Norway and the temperature deviation in Norway from the 1961-1990 average (State of the Environment Norway 2010; Mattilsynet 2009). The data show that between 2000-2008 temperatures were, except for 2001, always higher than in the previous decade, but insecticide sales dropped sharply. When calculating the correlation coeffizient (r) with SPSS, it turns out that temperature is – against any logic – negatively correlated with insecticides sales (r = -0.49; p<0.05), which implies that increasing temperature reduces insecticides sales. A similar trend can be observed in Denmark (see Annex II). What happened?

In 1991, Norway introduced a pesticide tax as one instrument of a pesticide reduction programme. In 2000, the tax rate was increased (Sæthre et al. 1999; NFSA 2005) and sales dropped considerably. Pesticide sales data may not be the best indicator for pesticide use, but better Norwegian data, such as the treatment frequency are not available (pers. comm. with NFSA[1]). It is very likely that the large reduction in sales after 2000 translated in a use reduction. Considering that the Norwegian tax rate is bound to the toxicity (higher rates for more toxic pesticides), a replacement of high dosage-low toxicity insecticides with low dosage-high toxicity insecticide is not a possible explanation for the reduction.

In highly managed eco-systems esp. annual crops, climate may create 'background noise', but pesticide use is mainly decoupled from the natural environment and the climate.
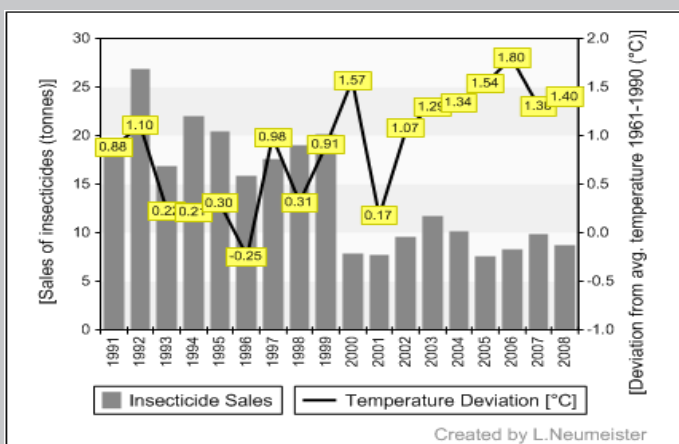

Figure 7: Insecticide sales in Norway 1991-2008 and deviation from average temperature 1961-1990

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1 personal communication with Erlend Spikkerund (Senior Scientific Officer / Ecotoxicologist of the Norwegian Food Safety Authority (NFSA), 29.02.2010 via e-mail.

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Annex I - Experiments with aphids feeding on herbaceous plants grown at elevated CO_2 and/or elevated temperature

Aphid/ Host(s)	Experimental Design	Results	Source
Myzus persicae/ transgenic Bt Brassice napus ssp. oleifera compared to non-transgenic Brassica napus ssp. oleifera	Chamber, different combinations of elevated CO_2 (720ppm) and/or elevated temperature (24/20°C [day/night]) compared to ambient CO_2 and lower temperature 20/16°C [day/night])	Final weight of adults was not affected by the plant type, but it was significantly reduced in elevated temperature compared with lower temperature. Elevated CO_2 lowered adult weight compared with aphids on plants grown in ambient CO_2 level. Mean weight of nymphs was reduced on plants grown in elevated temperature, elevated CO_2 or plant type had no significant effect on progeny weight. The cumulative fecundity was increased by elevated temperature and reduced by elevated CO_2. Total number of progeny produced by was highest in plants grown under ambient CO_2 and elevated temperature, followed by elevated CO2 combined with elevated temperature, thereafter in the ambient CO_2 and lower temperature and finally lowest in plants grown in elevated CO_2 under lower temperature. Rate of reproduction in Bt-transgenic and nontransgenic plant was equal.	Himanen et al. 2008
Brevicoryne brassicae/ transgenic Bt Brassica napus ssp. oleifera compared to non-transgenic Brassica napus ssp. oleifera	Chamber, different combinations of elevated CO_2 (720ppm) and/or elevated temperature (24/20°C [day/night]) compared to ambient CO_2 and lower temperature 20/16°C [day/night])	The developmental time, total number of progeny and final weights of adults of Brevicoryne brassicae was not affected by plant type, elevated CO_2 or temperature. Cumulative fecundity was not affected by plant type, elevated CO_2 or elevated temperature Mean progeny weights were marginally increased by elevated CO_2 and reduced by elevated temperature.	Himanen et al. 2008

Aphid/ Host(s)	Experimental Design	Results	Source
Acyrthosiphon pisum/ Vicia faba	Chamber, 350 ppm CO2 ('ambient') and 700 ppm ('elevated'); Constant 23°C	Populations of A. pisum were reduced by over 60% at elevated CO_2.	Hughes & Bazzaz 2001
Aphis nerii/ Asclepias syriaca	Chamber, 350 ppm CO_2 ('ambient') and 700 ppm ('elevated'); Constant 23°C	No significant effect through elevated CO_2.	Hughes & Bazzaz 2001
Aphis oenotherae/ Oenothera biennis	Glasshouse, 350 ppm CO_2 ('ambient') and 700 ppm ('elevated'); 25°C (day), 20°C (night)	No significant effect through elevated CO_2.	Hughes & Bazzaz 2001
Aulacorthum solani/ Nicotiana sylvestris	Chamber, 350 ppm CO_2 ('ambient') and 700 ppm ('elevated'); Constant 24°C	No significant effect through elevated CO_2.	Hughes & Bazzaz 2001
Myzus persicae/ Solanum dulcamara	Chamber, 350 ppm CO_2 ('ambient') and 700 ppm ('elevated'); Constant 24°C	Populations of M. persicae increased by 120% at elevated CO_2.	Hughes & Bazzaz 2001
Macrosiphum euphorbiae/ Solanum dulcamara	Chamber 350 ppm CO_2 ('ambient') and 750 ppm ('elevated'); different day/night temperatures: 20/15°C, 23/18°C, 26/21°C.	Aphid populations were unaffected by any temperature or CO_2 treatment, however under elevated CO_2 aphid numbers tended to increase, but this increase was not significant. Total aphid weight also remained unaffected by temperature or CO_2.	Flynn et al. 2006
Aulacorthum solani/ Vicia faba	Chamber, 350 ppm CO_2 ('ambient') and 700 ppm ('elevated'); Constant 18+-5°C	Decreased shoot and root weights (20 and 18% resp.) and flower number (60%). Aphid density was unaffected by elevated CO_2.	Awmack & Harrington (2000)
Acyrthosiphon pisum/ Vicia faba	Chamber, 350 ppm CO2 ('ambient') and 700 ppm ('elevated'); Constant 18+-5°C	Decreased shoot and root weights by 27 and 34% and flower number decreased by 73% compared to ambient CO2. Aphid density was unaffected by elevated CO_2.	Awmack & Harrington (2000)
Rhopalosiphum padi/ Festuca arundinacea	Open-Top Chamber ambient CO2 and 700 ppm (elevated); natural summer temperature (USA, Illinois)	322% fewer aphids on plants grown at elevated CO_2 compared to ambient CO_2.	Newman et al. 1999
Sitobion avenae/ Poa annua; Poa trivialis; Festuca ovina; Helicotrichon pratense	Chamber mesocosm, 350 ppm CO_2 ('ambient') and 700 ppm ('elevated'); fertilised and non-fertilised	Elevated CO_2 did not have a significant impact on aphid fitness.	Diaz et al. 1998

Aphid/ Host(s)	Experimental Design	Results	Source
Myzus persicae/ Brassica oleracea (Brussel sprout)	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	Lower nitrogen level in eCO_2 plants (not significant). Enhanced number of offspring at elevated CO_2 (not significant).	Bezemer et al. 1999
Brevicoryne brassicae/ Brassica oleracea (Brussel sprout)	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	Significantly lower nitrogen level in eCO_2 plants. Significantly less offspring at elevated CO_2.	Bezemer et al. 1999
Myzus persicae/ Senecio vulgaris	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	Lower nitrogen level in eCO_2 plants (not significant). Significantly enhanced number of offspring at elevated CO_2.	Bezemer et al. 1999
Brevicoryne brassicae/ Senecio vulgaris	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	Lower nitrogen level in eCO_2 plants (not significant).	Bezemer et al. 1999
Myzus persicae/ Cardamine hirsuta	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	No significant difference in poulation size between elevated and ambient CO_2.	Bezemer et al. 1999
Myzus persicae/ Brassica pekinensis	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	No significant difference in poulation size between elevated and ambient CO_2.	Bezemer et al. 1999
Myzus persicae/ Brassica oleracea (Brussel sprout)	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	No significant difference in poulation size between elevated and ambient CO_2.	Bezemer et al. 1999
Myzus persicae/ Poa annua	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	Population size >90% larger on plants grown at elevated CO_2 (not significant).	Bezemer et al. 1999
Brevicoryne brassicae/ Brassica oleracea (Brussel sprout)	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	No significant difference in poulation size between elevated and ambient CO_2.	Bezemer et al. 1999
Brevicoryne brassicae Cardamine hirsuta	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	No significant difference in poulation size between elevated and ambient CO_2.	Bezemer et al. 1999
Brevicoryne brassicae/ Brassica pekinensis	Ecotron, 360-400ppm CO_2 ('ambient') and plus 200 ppm ('elevated'); 20°C (day), 12°C (night)	No significant difference in poulation size between elevated and ambient CO_2.	Bezemer et al. 1999
Myzus persicae/ Poa annua; Cardamine hirsuta; Senecio vulgaris; Spergula arvensis	Chamber mesocosm, 350-400 ppm CO_2 ('ambient') and 550-600 ppm ('elevated'); 20°C (day), 12°C (night); introduction of parasitoid *Aphidius matricariae*	Elevated CO_2 caused no change in N or C content of the plants, but aphid densitiy was 300% greater compared to ambient CO_2. Parasitoid efficiency was not affected by CO_2 treament.	Bezemer et al. 1998

Aphid/ Host(s)	Experimental Design	Results	Source
Myzus persicae/ Poa annua; Cardamine hirsuta; Senecio vulgaris; Spergula arvensis	Chamber mesocosm, 22°C (day), 14°C (night); introduction of parasitoid *Aphidius matricariaee*	Significant higher foliar N content at elevated T, but no changes in C content. Higher aphid population on Poa annua; Cardamine hirsuta; Senecio vulgaris at elevated T, but also avg. 300% higher parasitism rate. High variance in parasitism between groups - signifcance of effects could not be determined.	Bezemer et al. 1998
Aulacorthum solani/ Vicia faba	Chamber, 350 ppm CO_2 ('ambient') and 700 ppm ('elevated').	Daily rate of production of nymphs was increased by 16% a eCO_2. No difference in development time.	Awmack et al. 1997
Aulacorthum solani/ Tanacetum vulgare	Chamber, 350 ppm CO_2 ('ambient') and 700 ppm ('elevated')	Development time was 10% shorter at elevated CO_2, but the rate of production of nymphs was not affected.	Awmack et al. 1997
Aphis fabae fabae (shoot feeding) & *Pemphigus populitransversus* (root feeding)/ *Cardamine pratensis*	Glasshouse (Solardome), ca. 350 ppm CO_2 ('ambient') and ca. 600 ppm ('elevated')	No significant effects of elevated CO_2 on population size of the shoot or root-feeding species.	Salt et al. 1996
no defined Aphid species/*Triticum aestivum*	Glasshouse, 350 ppm CO_2 ('ambient') and 700 ppm ('elevated'); ca. 20°C (day), 15°C (night); different N treatments	The aphid infestation and N contents of the wheat leaves were significantly reduced at elevated atmospheric CO_2.	Thompson et al. 1993

Annex II - Correlation between annual temperature and precipitation and pesticide use in Denmark

Denmark introduced a pesticide reduction program in 1986. In 1997 and 2003 the program was revised and elaborated (Nielson 2007). In 1996, the Danish government introduced an ad valorem tax (VAT) on pesticides. The tax rates were increased in 1998. Insecticides are taxed with 53.85%, and herbicides and fungicides are taxed with 33.33% of the retail price (DEPA 1999). The following figures show that the tax introduction had an large impact on insecticide sales and the frequency of insecticide treatments, while an impact on the amount insecticides used per ha is less pronounced (Statistics Denmark (2010a, 2010b). Paradoxically, the Danish pesticide policy seems to decouple insecticide use from annual average temperatures. The correlation (expressed as correlation coefficient: r) is either negative or close to zero, and the linear regression analyses show that increasing temperatures lead to decreasing insecticide use resp. have no influence. Looking at fungicide use, the picture appears similar. While the impact of the tax is less visible, there is a continuous decline in fungicide use in Denmark (Statistics Denmark 2010a, 2010b). It seems there is no correlation between precipitation and fungicide use. The regression analyses shows rather a trend towards decreased fungicide use at higher precipitation.

The data from Denmark and Norway (see Box on pg. 24) are illogical, higher annual temperatures lead to less insecticide use and higher annual precipitation has no effect on fungicide use – it seems that policy (pesticide reduction programs and taxes) largely overlays the influence of the climate, at least at the current scale of changes.

Figure 1-A: Insecticide sales (tonnes active ingredients) and deviation from the average annual temperature (1961-1990) in Denmark
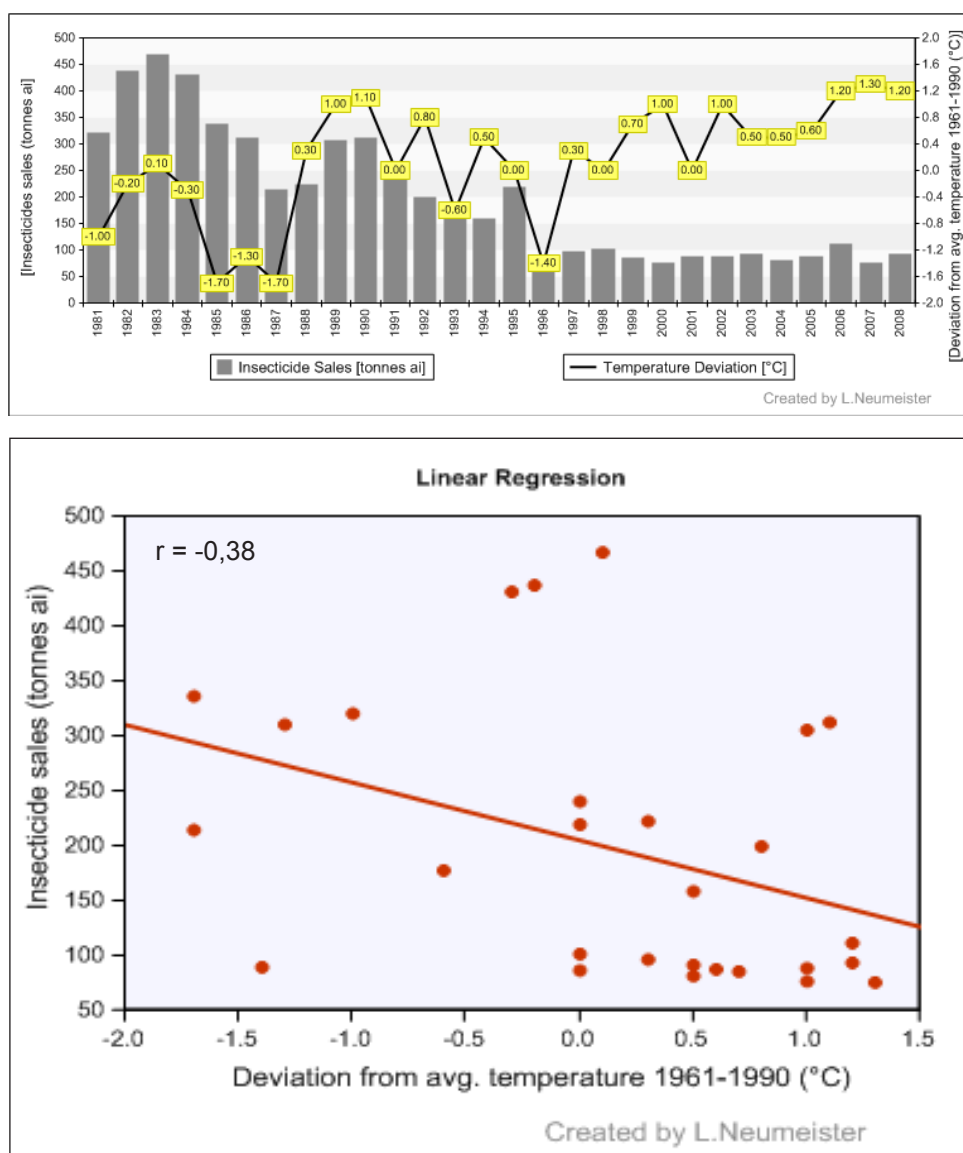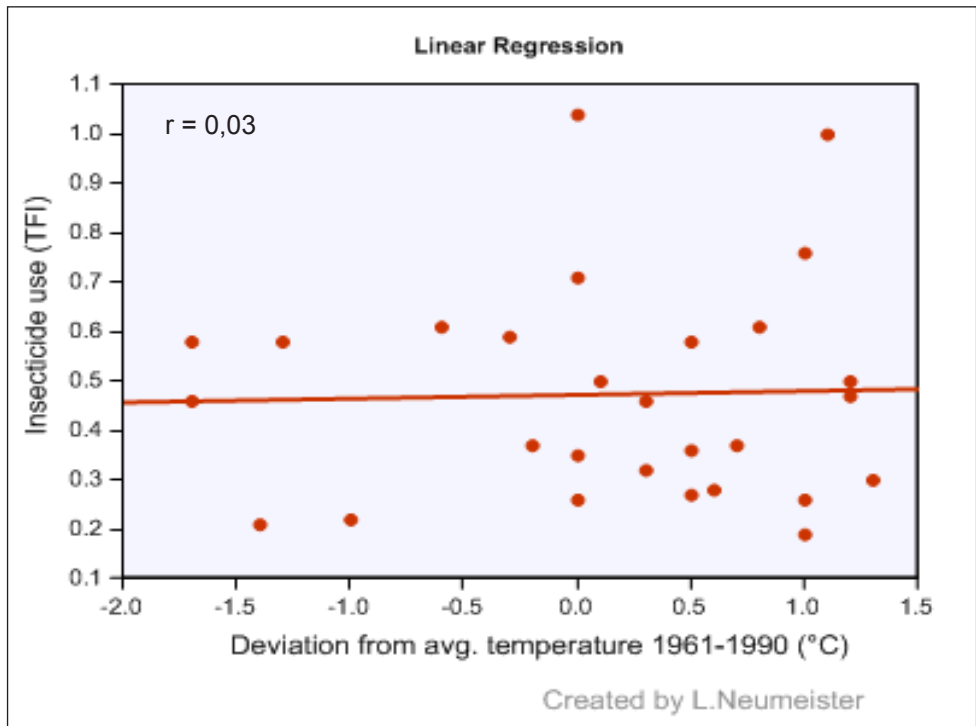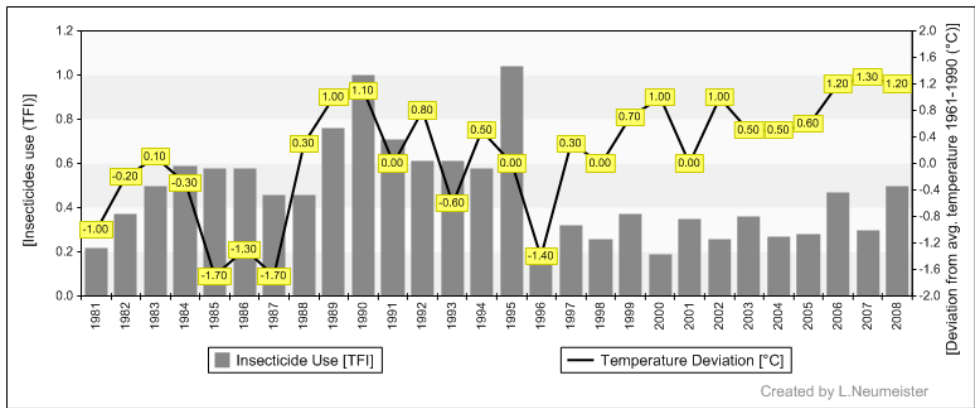
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Figure 2-A: Treatment frequency of insecticides expressed as Treatment Frequency Index (TFI) and deviation from the average annual temperature (1961-1990) in Denmark

Figure 3-A: Insecticide use in kg active ingredient [ai]/ha and deviation from the annual average temperature (1961-1990) in Denmark
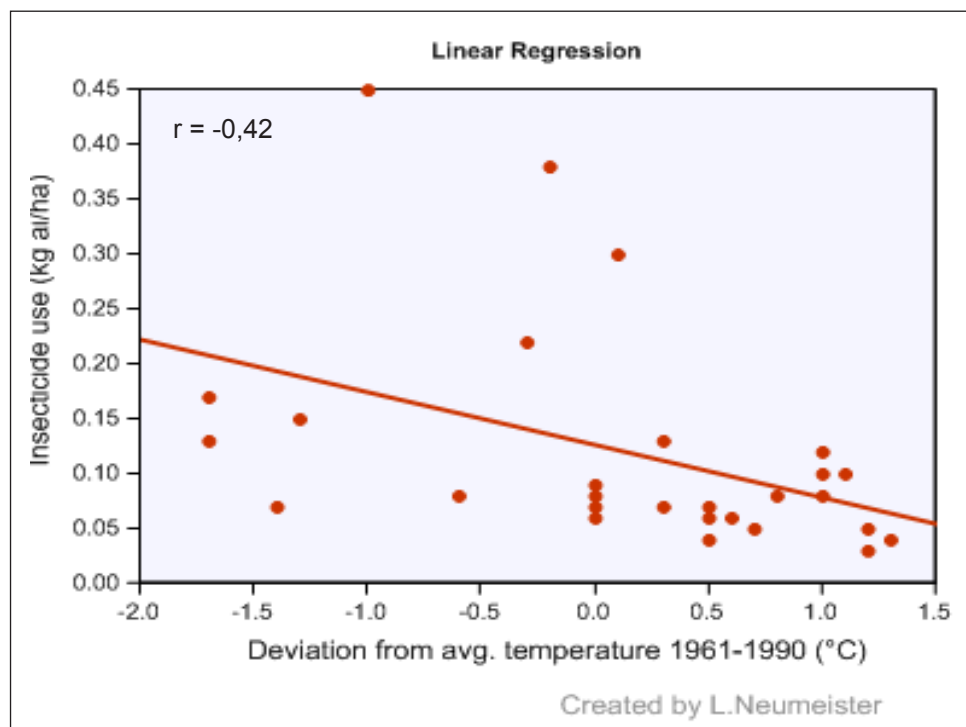
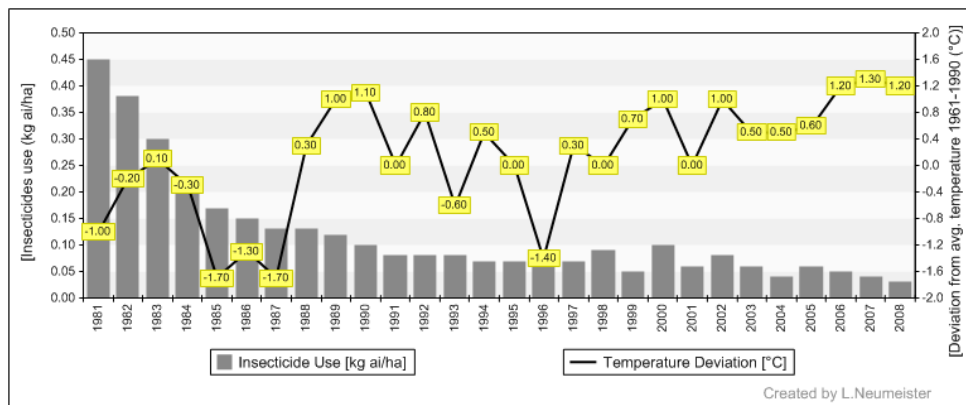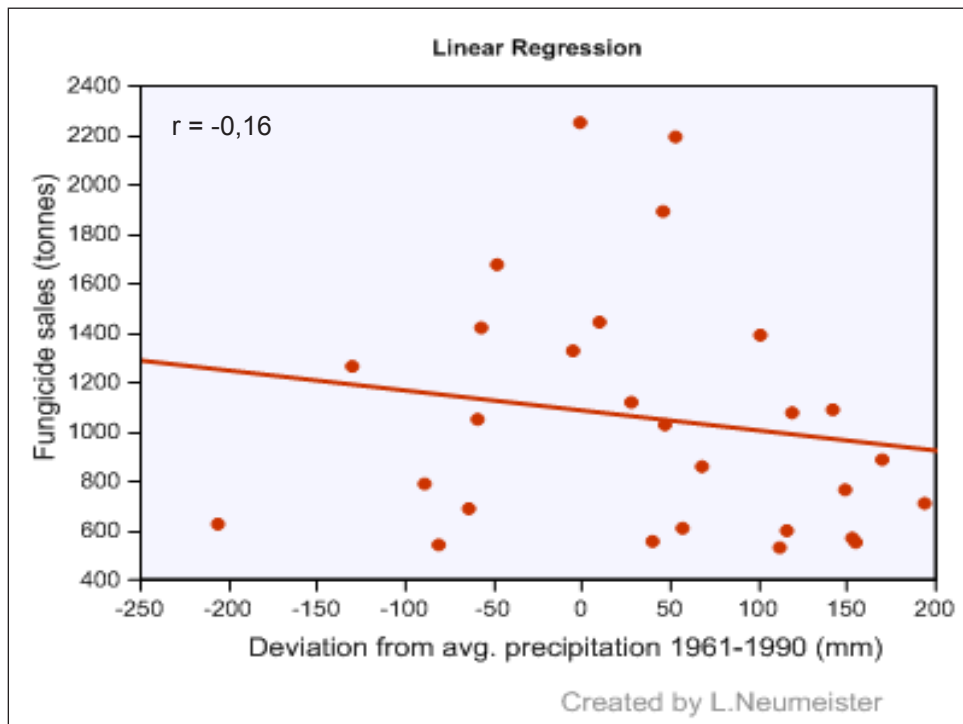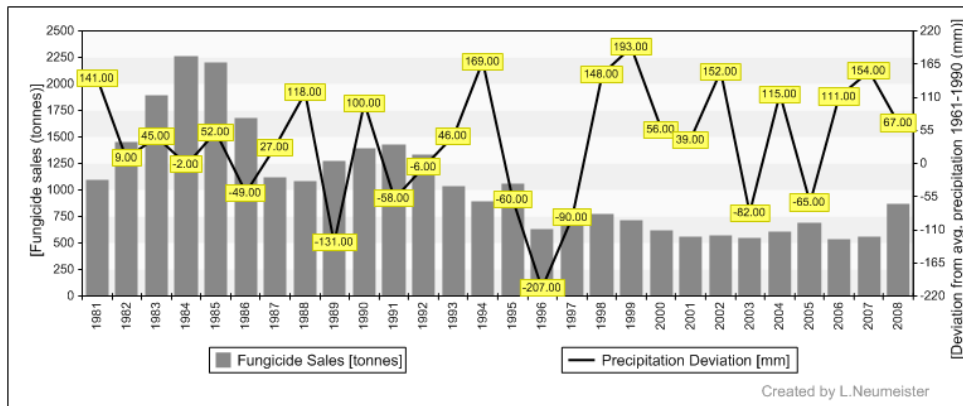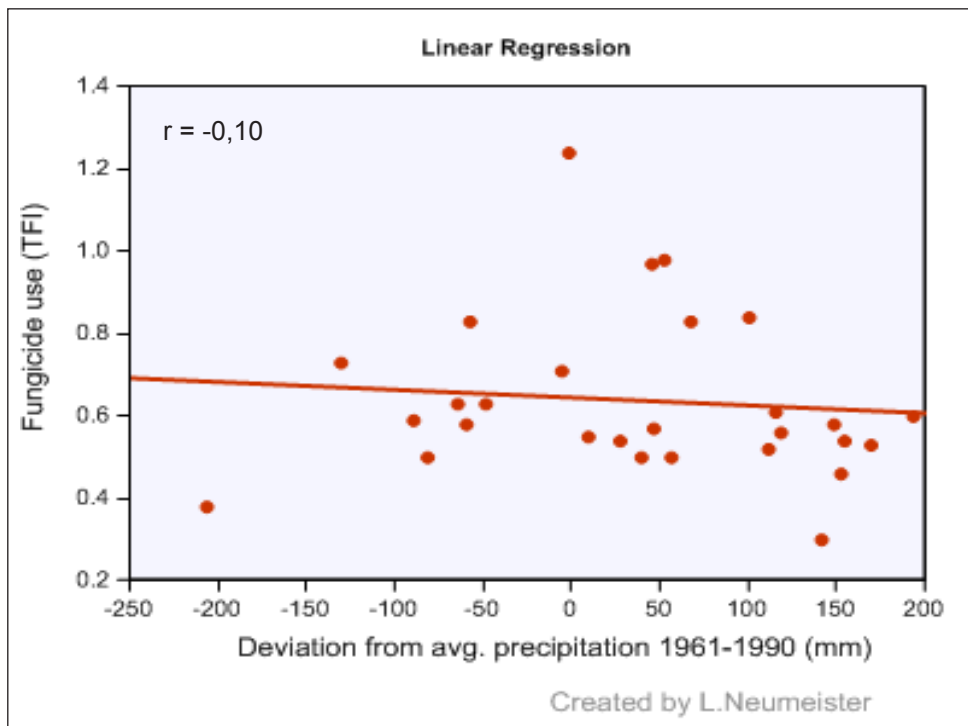*Climate Change and Crop Protection*

Figure 4-A: Fungicide sales (tonnes active ingredients) and deviation from the average annual precipitation (1961-1990) in Denmark

Figure 5-A: Treatment frequency of fungicides expressed as Treatment Frequency Index (TFI) and deviation from the average annual precipitation (1961-1990) in Denmark
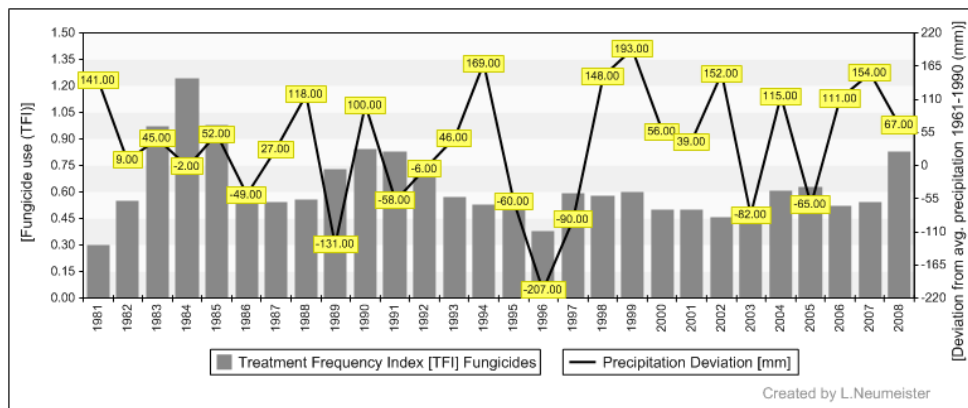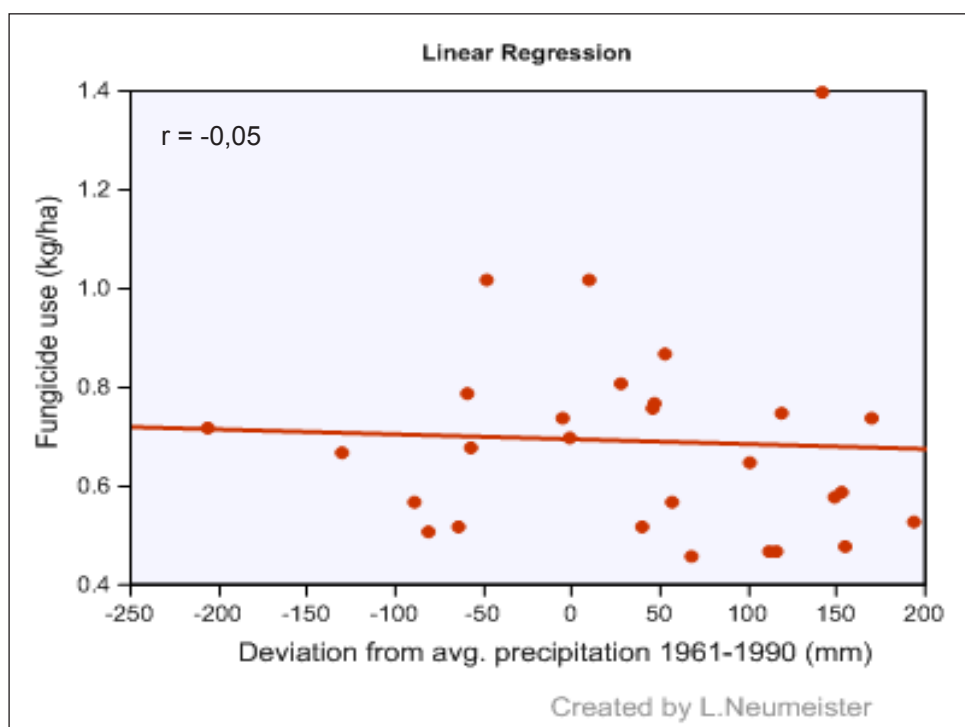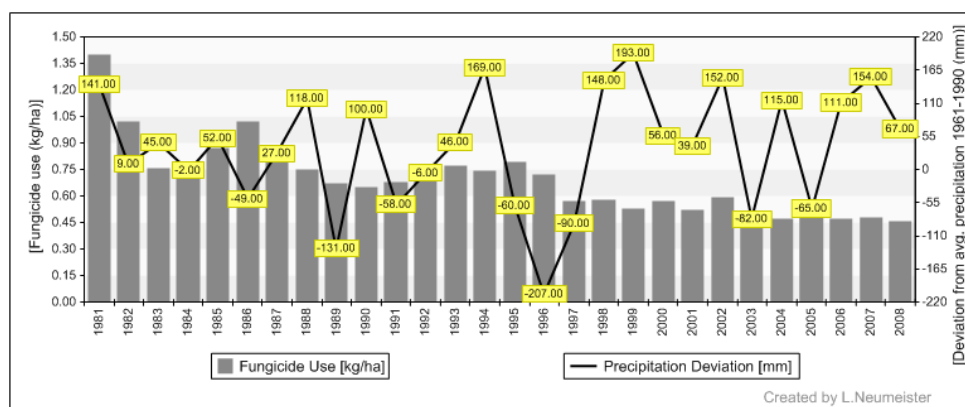

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Figure 6-A: Fungicide use in kg active ingredients [ai]/ha and deviation from the average annual precipitation (1961-1990) in Denmark

Sources:

[1]   Cappelen J (2010): DMI Annual Climate Data Collection 1873-2009, Denmark, The Faroe Islands and Greenland - with graphics and Danish summary. Technical Report 10-04. Danish Meteorological Institute (DMI), Ministry of Climate and Energy. Copenhagen.

[2]   Statistics Denmark (2010a): PEST1: Sales of pesticides used in the agriculature and treatment frequency divided by group of pesticide and unit of measurement. StatBank Denmark, Agriculture and Fishery. http://www.statbank.dk

[3]   Statistics Denmark (2010b): PEST2: Total pesticides sale by type of pesticide and unit of measurement. StatBank Denmark, Agriculture and Fishery. http://www.statbank.dk

[4]   DEPA (1999): Economic Instruments in Environmental Protection in Demark. Danish Environmental Protection Agency (DEPA). Ministry of Environment and Energy. Available at: http://www.mst.dk/Udgivelser/Publications/2000/07/87-7909-568-2.htm

[5]   Nielson H (2007): Action Plans for Pesticide Use Reduction in Denmark. In Pesticide Use Reduction Strategies in Europe. Six case studies. Pesticide Action Network Europe (PAN Europe) (ed.) London.

The correlation coefficient (r) was calculated with Excel and in addition in a self pro-grammed database solution, this database also created the linear regression figures.

Pesticide Action Network Asia and the Pacific (PAN AP) is one of the five regional centres of PAN, a global network working to eliminate the human and environmental harm caused by pesticides, and to promote biodiversity-based ecological agriculture.   PAN AP while linked to the international network, has evolved with a strong Asian perspective, linked with the movements of peasants, agricultural workers and rural women and guided by the strong leadership of grassroots and advocacy groups. Our vision is a society that is truly democratic, equal, just, culturally diverse, and based on food sovereignty, gender justice and environmental sustainability.

 PAN AP's work areas are focused on advancing and asserting food sovereignty and biodiversity based ecological agriculture; strengthening rural women's empowerment and protecting people's health and the environment from highly hazardous pesticides and campaigns on protecting the rice heritage of Asia as well as genetic engineering in food and agriculture.