Research Journal of Agricultural Science, 49 (3), 2017

IMPACT OF CLIMATE CHANGE ON WHEAT–PATHOGEN INTERACTIONS AND CONCERNING ABOUT FOOD SECURITY

Mirela PARASCHIVU[1,3], Otilia COTUNA[2], L.OLARU[1] , M. PARASCHIVU[1]

[1]University of Craiova, Agronomy Faculty, Craiova, Romania
[2]Banat`s University of Agricultural Sciences and Veterinary Medicine "King Michael I of Romania" Timisoara, Romania
[3]County Agriculture Consulting Office, Craiova, Dolj county, Romania

Corresponding author: paraschivumirela@yahoo.com; otiliacotuna@yahoo.com; paraschivum@yahoo.com

Abstract. *Agriculture is one of the most important sectors of many countries economy worldwide and it is highly dependent on the climate. Along with climate impact a range of regional and global political and economic factors intensify food insecurity and long term vulnerability in certain regions. Despite the findings suggesting that increases in carbon dioxide level (CO2) and temperatures can increase plant growth, the changes in global temperatures, frequency and intensity of droughts, extreme rain and snow falls, flooding and heat waves have already started to have significant impact on crop yields and concerning about future food security. The impact of climate change also need to be considered along with other factors that affect crop yields, such as specific biotic constrainers (pathogens) and its impact on the host-pathogen relationship. Moreover extreme temperatures and precipitation have been associated with changes in pathogens life cycles, increased incidence, pathogenicity, genetically recombination and aggressiveness traits, which involves the urge to rethink the integrated management strategies. Although, many previous studies have emphasized the sensitivity of plants to various biotic constrainers, the host-pathogen interactions are poorly understood in the context of climatic change. Therefore, it is a particular interest for those wheat pathogens that might affect yield dramatically with potentially serious implications for food security. The present review is focused on the impact of climate change on wheat diseases and host pathogen interactions taking into consideration case studies in order to understand better how the components of disease cycle are affected and to identify disease risk and prevent potential food security crisis. The response of pathosystems to climate change is of high interest currently in order to estimate disease risk on a large scale and to introduce new understandings in developing management strategies. However, further investigation need to be done in order to highlight how improving plant diseases management can enhance global food security in a changing climate.*

Key words: *climate change, extreme events, food security, host-pathogen interactions, plant disease, wheat*

INTRODUCTION

The global food supply has been facing increasing challenges during the first decades of the 21st century. In the last 20 years we have seen major changes to agricultural systems worldwide that have contributed to, and interacted with, new food systems. Scientists highlighted the transforming role of the interacting driving forces of population increase, income growth, urbanization, and globalization on food production, markets, and consumption.

The intensification of world agriculture has to happen in a time, when climate is becoming less predictable, fossil fuel dependency needs to be cut, and cropland and water resources are deteriorating (ALEXANDRATOS AND BRUINSMA, 2012; POPP ET AL., 2013).

Global climate change is caused by human activities, especially fossil fuel burning, large areas deforestation and changes into the land use. Since the last decade the atmospheric concentration of carbon dioxide (CO_2) has reached significantly higher levels that previous decades (SIEGENTHALER ET AL., 2005; CANADELL ET AL., 2007; SHAKUN ET AL., 2012) and increasing levels have been noticed for other greenhouse gases (SPAHNI ET AL., 2005, IPCC, 2013).

The planet's average surface temperature has risen about 2.0 degrees Fahrenheit (1.1. degrees Celsius) since the late 19th century due to human activities that causing significantly high levels of carbon dioxide (CO_2) in the atmosphere. According with the National Aeronautical and Space Administration (NASA) and the Oceanic and Atmospheric Administration (NOAA) data, globally-average temperatures in 2016 were 1.78 degrees Fahrenheit (0.99 degrees Celsius) warmer than the mid-20th century mean and the tendency on long-term seems to be clear. Also, phenomena such as El Niño causes corresponding variations in global wind and weather patterns, leading to short-term variations in global average temperature (NASA, NOAA report, Jan.2017).

Climate change is expected to have variable effects in different areas of the world impacting agriculture differently (ENGLER ET AL., 2011; HEYDER ET AL., 2011; TEIXEIRA ET AL., 2012).The current awareness of climate change in the agriculture land use (e.g. land sparing – save some natural ecosystems from conversion into cropland), crop production and future food security appears to be high, especially due to high uncertainties about future food production (DÖÖS AND SHAW, 1999) and estimations about population increase to 10 billion in 2050. However, changes in current framing systems need to be linked to the short-term adjustments and long term adaptations to the effects of climate change in agriculture, to the farm level decision makers, to policy decisions made at local, regional or large scales, to research sector and also with "unknown aspects", that to their complexity and long term observation have not yet been studies in detail (e.g. pests, diseases, changes in frequency of isolated and extreme weather events) (REILLY AND SCHIMMELPFENNING, 2000; SCHERM, 2004). The possible increases in extreme weather events might cause higher yield variability, lower harvestable yields, reductions/extensions in land use in some areas, introduction of new crop species, changes in soil organic matter levels, in nitrate leaching risk, in soil erosion and salinization, in new crop protection challenges (LEIRLÓS ET AL., 1999, REILLY, 1994, 1999; REILLY AND SCHIMMELPFENNING, 1999; YEO,1999; OLSEN AND BINDI, 2002; HEGERL ET AL. 2011;PERKINS ET AL., 2011; COTUNA ET AL., 2013a, b). The responses depend on the particularities of the agricultural systems and on the changes in the crop management. There are scenarios that climatic change will lead to a higher incidence of crop diseases (especially plant host and susceptibility, pathogen reproduction – shorter incubation - dispersal, survival and activity, host-pathogen relationship) and to a potentially larger use of pesticides (NEWTON ET AL., 2011; SUTHERST ET AL., 2011). The predicted impact of climate change on pathogens and host-pathogen relationship suggests that can be positive, negative or neutral depending on geographical and temporal distribution of inoculum amount and cultivars susceptibility (NEWTON ET AL., 2011; SUTHERST ET AL., 2011). Thus, new pathogens may occur in certain regions, while other pathogens may decreases to be economically important, following geographical distribution of the host and cropping technology (COAKLEY ET AL., 1999; GHINI ET AL., 2008; GHINI AND HAMADA, 2008;). General tendency is that pathogens are likely to remain limited to their host distribution and not become disconnected from them. There is serious concern that climate zones will move faster that it is possible for plant populations to track them, which is expected to determine disproportionate extinction of local endemic species (LOARIE ET AL., 2009). However, advanced knowledge about the impact of climate change on plant diseases is essential for adoption of integrated disease management measures, in order to avoid yield losses.

This review aims to discuss the impact of climate change on ones of the most important wheat pathogens (leaf rust – *Puccinia triticina*, stem rust – *P.graminis* f.sp. *graminis*, stripe rust – *P. striiformis* f.sp. *tritici*, Septoria tritici blotch (STB) - Zymoseptoria tritici and Fusarium Head Blight (FHB) - Fusarium graminearum) and host – pathogen relationship, especially temperatures and greenhouse gasses associated with.

CLIMATE CHANGE EFFECTS ON WHEAT-PATHOGEN RELATIONSHIP

Temperature

Higher temperatures are expected to occur in northern areas which will expand the cropping area for cereals by 2050; further more increased diseases severity and Area Under the Diseased Curve are expected too (GHINI ET AL., 2008).

HARVELL ET AL (2002) argue three hypotheses how pathogens will be influenced by climate change. He suggested that that rising temperatures will (i) increase pathogen development transmission, and generation number; (ii) increase overwinter survival and reduce growth restrictions during this period and (iii) alter host susceptibility.

Warmer climates are more favourable for virus-vectors proliferation, because they can complete a greater number of reproductive cycles and additional insect generations which suggests higher incidence of virus diseases in wheat (CAMMEL AND KNIGHT, 1992; NEILSON AND BOAG, 1996, HARRINGTON, 2002; NEWMAN, 2004; HARRINGTON ET AL., 2007; DOBSON, 2009). NEWMAN (2004) pointed out the simultaneous effect of higher temperatures and elevated CO_2 concentration lead to 10% earlier timing of cereal aphids peaks (as much as a month earlier) and to 10% increase in winged forms, which results in greater spread and incidence of Barley yellow dwarf virus for which the aphid is the vector.

Warmer winter temperatures may also allow wheat pathogens to overwinter in areas where they are limited now by cold, increasing the primary inoculum amount and causing greater and earlier infections during the following crop season. Also, warmer temperatures associated with cropping practices appear to have been associated with shifts in plant hosts for some pathogens, particularly when talking on long-term view (MADGWICK ET AL., 2011; WEST ET AL., 2012). Thus, Fusarium Head Blight (FHB) is expected to enhance higher levels of inoculum for subsequent wheat and barley crops in warmer northern latitudes due to introduction of forage maize in crop rotation (MAIORANO ET AL., 2008). For example, disease incidence of Fusarium head blight in the United Kingdom and Germany might increase middle of this century, whereas disease severity of Septoria tritici blotch might decrease in France end of this century (JUROSZEK.AND VON TIEDEMANN, 2013). Also, it is expected that wheat flowering will be around 2 weeks earlier by the 2050s (4 weeks earlier if we switch to using ‘Mediteranean-type’ cultivars) and harvest will be 3 weeks earlier (or 5 weeks). Consideration of these altered growth stages is important because without it we would conclude that the incidence of fusarium ear blight will reduce substantially due to a decrease in occurrence of suitable wet conditions for infection occurring in early flowering stage (date) (JUROSZEK. P., VON TIEDEMANN, A., 2013). In the case of F. graminearum, warmer spring weather will increase spore production and additional spore release from maize debris is likely to lead to an overall increase in fusarium ear blight on wheat. This is an example of an indirect effect of climate change on a crop disease.Climate change also has an impact on food safety, particularly on the incidence and prevalence of Mycotoxins. The main consequence of FHB is that trichothecene mycotoxins, such as deoxynivalenol (DON), accumulate in the grain, presenting a food safety risk and health hazard to humans and animals (GOSWAMI AND KISTLER, 2004).

Temperature can also affect disease resistance in plants, thus affecting the incidence and severity of the diseases. Ambient temperature perception in plants is well recognised and plants have been shown to be able to detect temperature changes as little as 1°C (ARGYRIS ET AL., 2005).

The efficacy of current resistance genes may be compromised under more extreme and variable climatic conditions. Thus, previous findings emphasized that under drought stress, resistance expression can be reduced or lost temporary, as well as reduced disease symptoms (BITA AND GERATS, 2013). Also, some organisms enhance their ability to generate variants as an adaptive response to climate change (because pathogens exert very intensive selection over few generations), changes which can later become fixed through conventional mutation and recombination (HOVMØLLER ET AL., 2016). For example, there is an increased range of stem rust a possible explanation is that enhanced levels of free radicals were found under drought-stressed conditions. The same breakdown problem occurred in response to cold stress, but not salt stress (STEWART, 2002).

Atmospheric carbon dioxide (CO_2) and other greenhouse gases

Also increases in CO_2 concentrations is expected to enhance crop yields and resource use efficiencies. (COAKLEY ET AL. 1999; PANGGA ET AL., 2013)

Changes in CO_2 concentration increase plant photosynthesis, transpiration rate per unit leaf area and resources use efficiency for water and nitrogen, enhancing wheat canopy, which impact both yield (increases in crop yield are 10-20% for C3 crops and 0-10% for C4 crops according with AINSWORTH AND LONG, 2005) and wheat-pathogen relationship (THOMSON ET AL.,1993; THOMPSON AND DRAKE, 1994; PRITCHARD ET AL., 1999; DOWNING ET AL., 2000, JONES AND CURTIS, 2000; LOLADZE, 2002; LI ET AL. 2003). Thus, some types of resistance can be more affected in some diseases in wheat (e.g. reduced expression of induced resistance (PLESSL ET AL., 2005), due to changes in host physiology and in pathogen cycles (e.g. higher spore production) leading to epidemics (CHAKRABORTY ET AL., 2003; GHINI ET AL., 2008). Analysing the effects of the increased CO_2 concentration on wheat pathogens, Manning and TIEDEMANN (1995) emphasised that wheat rusts and powdery mildew incidence increase due to the effect of carbohydrate contents which stimulates sugar-dependent pathogens.TIEDEMANN AND FIRSCHING (2000) analysed the combined effect of increased CO_2 and O_3 in wheat leaf rust (*Puccinia recondita* f.sp. *tritici*) and observed that wheat leaf rust was strongly inhibited by O_3, but unaffected by high CO_2 concentration. High level of SO_2 emissions seems to be correlated with incidence of *Phaeosphaeria nodorum* and *Mycosphaerella graminicola* in wheat (BEARCHELL ET AL., 2005; FITT ET AL., 2011). SHOW ET AL. (2008) reported that fluctuations in amounts of *P. nodorum* in grain were related to changes in spring rainfall, summer temperature and national SO_2 emission. Also, in leaves, annual variation in spring rainfall affected both pathogens similarly, but SO_2 had opposite effects.

Higher canopy growth will promote higher residue amount which favours necrotrophic pathogens development, while increased roots biomass will favour soil-born diseases occurrence. However, there is less knowledge about potential impact of climate change on soil-borne pathogens compared to foliar pathogens (EASTBURN ET AL., 2011).

Previous studies emphasized that the exposure to high CO_2 concentration affects the defensive response in plants against pathogens (BRAGA ET AL., 2006), altering cultivar resistance. Wheat pathogens and wheat-pathogen relationship are affected by CO_2 changes, which also interfere with uptake of systemic fungicides, with both positive and negative effects on efficacy (COAKLEY ET AL., 1999; GHINI ET AL., 2008).

Studying the impact of increased atmospheric CO_2 concentration plant viruses, MALMSTRÖM AND FIELD (1997) observed that CO_2 enrichment may increase the size of plants affected by barley yellow dwarf virus (BYDV) attenuating the dwarfing symptom due to the increase in root biomass and to the water-use efficiency by diseased plants, positively impacting the disease severity.

Also, changes in planth growth and physiology resulting from higher atmospheric CO_2 concentration associated with changes in temperatue and precipitation conditions, can affect the eficcacy of sistemic fungicides altering their penetration, translocation an mode of action into the plants. Changes in cultivars susceptibility can determine a new fungicide application calendar (CHAKRABORTY AND PANGGA, 2004; PRITCHARD AND AMTHOR, 2005).

MADGWICK ET AL. (2010) predicted that by the 2050s the risk of FHB epidemics and the number of crops where mycotoxin levels would exceed the limit set by the EU will increase across the whole of the UK.

Váry et al. 2015 investigated the effects of elevated CO2 on Septoria tritici blotch (STB), which infects leaves and Fusarium head blight (FHB), which infects flowers.The results showed that elevated CO2 increased the severity of both diseases and the acclimation of the pathogens and the plant worsened disease development. Thus, for FHB, the highest disease levels were found for plants that had been acclimated under elevated CO2 infected by pathogens that had also been acclimated at elevated levels affecting yield and reducing the number of grains by 76% and the weight of grain by 59%. In case of a resistant wheat variety it was observed that elevated CO2 lead to 27% lower number of grains produced was also and 20% lower weight of grain due to FHB. Also, increasing crop biomass by an average 17% by elevated CO2 (AINSWORTH AND LONG, 2005) will further increase the amount of pathogen inoculum in stubble and crop residues.

However, further new studies are needed to be done about the effect of CO_2 and other green gases concentrations on plant diseases in both controlled and field trials under cumulated action of other abiotic constrainers.

CONCLUSIONS

The results regarding the impact of climate change on wheat pathogens and host-pathogen relationship are very important demonstrating that wheat pathogens can adapt to new environment, despite the fact that currently we are not able to predict accurately the trajectory of each pathosystem under climate change.

Under climate change estimates of future crops response to different biotic and abiotic constrainers, food production and demand are associated with yield reduction and treaten to food security. Also, efficacy of pesticides under climate change can be altered by modifying fungicide residue dynamics in the foliage and the degradation of products. Wheat pathogens can be kept low by the adoption on larger scale of integrated pest management systems that will have to be adapted to this new reality. Including plant health considerations into agri-environment schemes is the key to future solution to respond to increased food demand in the context of climate change.

Also, new studies on the impact of climate changes on plants health, especially on key crops, are required to make good predictions in order to design solutions to new problems challenges or to old problems becoming more severe. Thus, improved models of plant diseases development under climate change are required for diversify adaptative management strategies, improving the sustainability and security of food production and to make biodiversity conservation more sustainable. A better understanding of the interractions among climatic factors, pathogens biology and spatial distribution of susceptible/resistant cultivars are keys to managing wheat diseases accross different geographical areas. Also, the adaptative management to climate challanges will be foscused on a mix of different approaches adapted to different situations (e.g. including genetic diversity patterns in models predicting climate change impact on plant health). On this terms it is necessary to recognize the importance of soil health, both in terms of its function as habitat for soil-borne plant pathogens and in relation of soil microbes in promoting plant health and sustainable productivity.

New models of crop and pest and pathogens interractions linked with more performant climate forcasting monitoring systems, breeding for durable resistance in wheat and improving modelling of the many interacting processes, would be an essential investment for future food security.

BIBLIOGRAPHY

AINSWORTH, E.A., LONG, S.P., 2005- What have we learned from 15 years of free-air CO_2 enrichment? A meta-analytic review of the responses of photosynthesis, canopy properties, canopy properties and plant production to rising CO_2. New Phytopathologist, 165:351-371.

ALEXANDRATOS, N., J. BRUINSMA. 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO.

ARGYRIS, J., TRUCO, M.J., OCHOA, O., KNAPP, S.J., STILL, D.W., LENSSEN, G.M., SCHUT, J.W., MICHELMORE, R.W., BRADFORD, K.J. -2005. Quantitative trait loci associated with seed and seedling traits in Lactuca. Theor Appl Genet 111:1365–1376

BEARCHELL. S.J., FRAAIJE, B.A., SHAW, M.W., FITT, B.D.L., 2005 – Wheat archive links long-term fungal pathogen population dynamics to air pollution. Proceedings of the National Academy of Sciences USA, 102:5438-5442.

BITA, C.E. AND GERATS, T. 2013 – Plant tolerance to high temperature in a changing environment: scientific fundamentals and production of heat stress-tolerant crops. Front Plant Science, 4:273.

BRAGA, M.R., AIDAR, M.P.M., MARABESI, M.A., GODAY, J.R.L., 2006 – Effects of elevated CO_2 on the phytoalexin production of two soybean cultivars differing in the resistance to stem canker disease. Environmental and Experimental Botany, 58:85-92.

CAMMEL, M.E., KNIGHT, J.D., 1992 – Effects of climatic changes on the population dynamics of crop pests. Adv. Ecol.Res. 22:117-162.

CANDELL, J.G., LE QUÉRÉ, C., RAUPACH, M.R., FIELD, C.B., BUITENHUIS, E.T., CIAIS, P., CONWAY, T.J., GILLETT, N.P., HOUGHTON, R.A., MARLAND, G., 2007 – Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity and efficacy of natural sinks. Proceedings of the National Academy of Science, v.104:1866-1887.

CHAKRABORTY, S., DATTA, S., 2003 – How will plant pathogens adapt to host plant resistance at elevated CO_2 under changing climate? New Pathologist, 159:733-742.

CHAKRABORTY, S., PANGGA, I.B., 2004 – Plant diseases and climate change. In: Gillians, M., Holmes, A (Ed.) Plant microbiology. London:BIOS Scientific, 163-180.

COAKLEY, S.M., SCHERM, H., CHAKRABORTY, S., 1999 – Climate change and plant diseases management. Ann.Rev. Phytopathology, 37:399-426.

COTUNA,OTILIA, SARATEANU, VERONICA, DURAU, CARMEN, PARASCHIVU, MIRELA, RUSALIN, GABRIELA, 2013a – Resistance reaction of some winter wheat genotypes to the attack of Fusarium graminearum L.Schw. in the climatic conditions of Banat plain. Research Journal of Agricultural Science, vol.45 (1):117-122.

COTUNA OTILIA, SARATEANU VERONICA, PARASCHIVU MIRELA, DURAU CARMEN, MICU LAVINIA – 2013b. Researches on the comportment of some foreign winter wheat to the attack of the pathogen Drechslera tritici repentis (Died.) Shoemaker. Research Journal of Agricultural Science, vol.45 (1) 2013: 123-128.

DOBSON, A. 2009 – Climate variability, global change, immunity and the dynamics of infectious diseases. Ecology, 90:920-927.

DÖÖS, B.R., SHAW, R. 1999 – Can we predict the future food production?A sensitive analysis. Global Environ. Change.9:261-283.

DOWNING, T.E., BARROW, E.M., BROOKS, R.J., BUTTERFIELD, R.E., CARTER, T.R., HULME, M., OLESEN, J.E.,PORTER, J.R., SCHELLBERG, J., SEMENOV, M.A., VINTHER, F.P., WHEELER, T.R., WOLF, J., 2000 – Quantification of uncertainty in climate change impact assessment. In: Dowing, T.E., Harrison, P.A., Butterfield, R.E., Lonsdale, K.G. (Eds.), Climate Change, Climatic Variability and Agriculture in Europe. Environmental Change Unit. University of Oxford, UK, 415-434.

EASTBURN, D.M., MCELRONE, A.J., BILGIN, D.D., 2011 – Influenceof atmospheric andclimatic change on plant pathogen interactions. Plant pathology, 60:54-69.

ENGLER, R., RANDIN, C.F., THUILLER, W., DULLINGER, S., ZIMMERMANN, N.E., ARAUJO, M.B., 2011 – 21st century climate change threatens mountain flora unequally across Europe. Global Change Biology, 17:2330-2341.

FITT, B.D.L., FRAAIJE, B.A., CHANDRAMOHAN, P., SHAW, M.W., 2011 – Impacts of changing air composition on severity of arable crop disease epidemics. Plant pathology, 60:44-53.

GHINI, R., HAMADA, E., 2008. Mudanças climaticas: impactos sobre doenças de plantas no Brasil. Brasilia: Embrapa/SCT, 331.

GHINI, R., HAMADA, E., BETTIOL, W., 2008 – Climate Change and Plant Diseases. Sci. Agric. 65, special issue, 98-107.

GOSWAMI, R.S. AND KISTLER, H.C., 2004- Heading for Disaster: Fusarium graminearum on Cereal Crops. Molecular Plant Pathology, 5:515-525.

HARRINGTON, R., 2002 – BYDV:the heat is on:barley yellow dwarf disease; recent advances and future strategies. In: Henry, M. Barley yellow dwarf diseases: recent advances and future strategies. Mexico, D.F.: CIMMYT, p.34-39.

HARRINGTON, R., CLARK, S.J., WELHAM, S.J., VERRIER, P.J., DENHOLM, C.H., HULLE, M., MAURICE, D., ROUNSEVELL, M.D., COCU, N., European Union Examine Consortium, 2007 – Environmental change and the phenology of European aphids. Global Change Biology, 13:1550-1564.

HARVELL, C. D., MITCHELL, C. E., WARD, J. R., ALTIZER, S., DOBSON, A. P., OSTFELD, R. S., & SAMUEL, M. D., 2002 - Climate warming and disease risks for terrestrial and marine biota. Science, 296(5576), 2158-2162. DOI: 10.1126/science.1063699

HEGERL, G.C., HANLON, H., BEIERKUHNLEIN, C. 2011 – Climate science: lusive extremes. Nature Geoscience, 4:142-143.

HEYDER, U., SCHAPHOFF, S., GERTEN, D., LUCHT, W., 2011 – Risk of severe climate change impact on the terrestrial biosphere. Environmental Research Letters, 6.

HOVMØLLER, M.S., WALTER, S., BAYLES, R., HUBBARD, A., FLATH, K., SOMMERFELDT, N., LECONTE, M., RODRIGUEZ-ALGABA, J., HANSEN, J.G., LASSEN, P., JUSTESEN, A.F., ALI, S., DE VALLAVIEILLE-POPE, C., 2016 - Replacement of the european wheat yellow rust population by new races from the centre of diversity in the near-himalayan region. Plant Pathology 65: 402-411.

IPCC. Climate change 2013: the physical science basis. Stockholm, Sweden: IPCC Assessment Report, 5:1535.

JONES, M.H., CURTIS, P.S., 2000 – Bibliography on CO_2 effects on vegetation and ecosystems: 1990-1999 literature. http://cdiac.esd.ornl.gov/epubs/cdiac/cdiac129/cdiac129.html. Accesed 10.04.2017.

JUROSZEK, P., VON TIEDEMANN, A., 2013. Climate change and potential future risks through wheat diseases: a review. European Journal of Plant Pathology, 136:21-33.

LEIRLÓS, M.C., TRASAR-CEPEDA, C., SEOANE, S., GIL-SOTRES, F., 1999 – Dependence of mineralization of soil organic matter on temperature and moisture. Soil Biol. Biochemistry, 31:327-335.

LI, F., KANG, S., ZHANG, J., COHEN, S., 2003 – Effects of atmospheric CO_2 enrichment, water status and applied nitrogen on water and nitrogen-use efficiencies of wheat. Plant and Soil, 254:279-289.

LOARIE, S.R., DUFFY, P.B., HAMILTON, H., ASNER, G.P., FIELD G.B., ACKERLY, D.D., 2009 - The velocity of climate change. Nature 462:1052-1055.

LOLADZE, L.R., 2002 – Risisng atmospheric CO_2 and human nutrition: toward globally imbalanced plant stoichiometry? Trends in Ecology and Evolution, 17:457-461.

MADGWICK, J.W.,WEST, J.S., WHITE, R.P. ET AL., 2010 - Impacts of climate change on wheat anthesis and fusarium ear blight in the UK. European Journal of Plant Pathology 129, (in press).

MADGWICK, J.W., WEST, J.S., WHITE, R.P., SEMENOV, M.A., TOWNSEND J.A., TURNER, J.A., 2011 – Impacts of climate change on wheat anthesis and Fusarium ear blight in the UK. European Journalof Plant Pathology, 130: 117-131.

MAIORANO, A., BLANDINO, M., REYNERI, A., VANARA, F., 2008 – Effects of maize residues on the Fusarium spp. infection and deoxynivalenol (DON) contamination of wheat grain. Crop Protection, 27:182-188.

MALMSTRÖM, C.M., FIELD, C.B., 1997 – Virus-induced differences in the response of oat plants to elevated carbon dioxide. Plant, cell and Environment, 20:178-188.

NEILSON, R., BOAG, B., 1996 – The predicted impact of possible climatic change on virus-vector nematodes in Great Britain. Eur.J.Plant Pathol. 102: 193-199.

NEWMAN, J.A., 2004 – Climate change and cereal aphids: the relative effects of increasing CO_2 and temperature onaphid population dynamics. Global Change Biology, 10:5-15.

NEWTON, A.C., JOHNSON, S.N., GREGORY, P.J. 2011 – Implications of climate change for diseases, crop yields and food security. Euphytica, 179:3-18. NOAA report, Jan. 2017.

OLSEN, JØRGEN E., BINDI, M., 2002 – Consequences of climate change for European agricultural Productivity and use and policy. European Journal of Agronomy, 16: 239-262.

PANGGA, I.B., HANAN, J., CHAKRABORTY, S. 2013 - Climate change impacts on plant canopy architecture: implications for pest and pathogen management. Eur J Plant Pathol 135:595–610

PERKINS, L.B., LEGER, E.A., NOWAK, R.S., 2011 – Invasion triangle: an organizational framework for species invasion. Ecology and Evolution, 1:610-625.

PLESSL, M., HELLER, W., PAYER, H.D., ELSTNER, E.F., HABERMEYER, J., HEISER, I., 2005 – Growth parameters and resistance against Drechslera teres of spring barley grown at elevated ozone and carbon dioxide concentrations. Plant Biology, 7:694-705.

POPP, J., PETÖ, K., NAGY, J., 2013 – Pesticide productivity and food security. A review. Agronomy for Sustainable Development, vol. 33 (1): 243-255.

PRITCHARD, S.C., ROGERS, H.H., PRIOR, S.A., PETERSON, C.M., 1999 – Elevated CO_2 and plant structure: a review. Global Change Biology, 5: 807-837.

PRITCHARD, S.C., AMTHOR, J.S., 2005 – Crops and environmental change. Brighamton: Food Products Press, 421.

REILLY, J., 1994 – Crops and climate change. Nature, 367:118-119.

REILLY, J., 1999 – What does climate change mean for agriculture in developing countries? A comment on Mandelsohn and Dinar. World Bank Obs. 14: 295-305.

REILLY, J., SCHIMMELPFENNING, D., 1999 – Agricultural impact assessment, vulnerability and the scope for adaptation. Climate Change 43:745-788.

REILLY, J., SCHIMMELPFENNING, D., 2000 – Irreversibility, uncertainty and learning: portraits of adaptation to long-term climate change. Climate Change 45:253-278.

SCHERM, H., 2004 – Climate change: can we predict the impacts on plant pathology and pest management? Canadian Journal of Plant pathology, 26:267-273.

SHAKUN,J.D, CLARK P.U., HE, F., MARCOTT, S.A., MIX, A.C., LIU, Z., OTTO-BLIESNER, BETTE, SCHMITTNER, A., BARD, E., 2012 - Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. Nature, 484: 49-54.

SHAW, M.W., BEARCHELL, S.J., FITT, B.D., FRAAIJE, B.A., 2008 - Long-term relationships between environment and abundance in wheat of Phaeosphaeria nodorum and Mycosphaerella graminicola. New Phytol, 177 (1):229-238.

SIEGENTHALER, U., STOCKER, T.F., MONNIN, E., LUTHI, D., SCHWANDER, J., STAUFFER, B., RAYNAUD, D., BARNOLA, J.M., FISCHER, H., MASSON-DELMOTTE, V., JOUZEL, J., 2005 – Stable carbon cycle-climate relationship during the late pleistocene. Science, 301:1313-1317.

SPAHNI, R., CHAPPELLAZ, J., STOCJER, T.J., LOULERGUE, L., HAUSMMANN, G., KAWAMURA, K., FLUCKIGER, J., SCHWANDER, J., RAYNAUD, D., MASSON-DELMOTTE, V., JOUZEL., J., 2005 – Atmospheric methane and nitrous oxide of the late pleistocene from Antarctic ice cores. Science, 310:1317-1321.

SUTHERST, R.W., CONSTABLE, F., FINLAY, K. J., HARRINGTON, R., LUCK, J., ZALUCKI, M.P., 2011 – Adapting to crop pest and pathogen risks under a changing climate. Wiley Interdisciplinary Reviews – Climate Change, 2:220-237.

STEWART, K.J., 2002 – Abiotic stress and mlo-resistance breakdown to barley powdery mildew. Dphil Thesis, University of Oxford.

TEIXEIRA, E.I., FISCHER, G VAN VELTHUIZEN, H., WALTER, C., EWERT, F. 2012 – Global hot-spots of heat stress on agricultural crops due to climate change. Agricultural and Forest meteorology, in press doi:10.1016/j.agrformet.2011.09.002

THOMSON, G.B., BROWN, J.K.M., WOODWARD, F.I., 1993 – The effects of host carbon dioxide, nitrogen and water supply on the infection of wheat by powdery mildew and aphids. Plant, Cell and Environment, 16:687-694.

THOMSON, G.B., DRAKE, B.G., 1994 – Insects and fungi on a C3 sedge and a C4 grass exposed to elevated atmospheric CO2 concentrations in open-top chambers in the field. Plant, Cell and Environment, 17:1161-1167.

TIEDEMANN, A.V., FIRSCHING, K.H., 2000 – interactive effects of elevated ozone and carbone dioxide on growth and yield of leaf rust-infected versus non-infected wheat. Environmental Pollution, 108:357-363.

VÁRY, Z., MULLINS, E., MCELWAIN, J. C. AND DOOHAN, F. M., 2015 - The severity of wheat diseases increases when plants and pathogens are acclimatized to elevated carbon dioxide. Global Change Biology, 21: 2661–2669.

WEST, J.S., HOLDGATE, S., TOWNSEND, J.A., EDWARDS, S.G., JENNINGS, P., FITT, B.D.L., 2012- Impacts of changing climate and agronomic factors on fusarium ear blight of wheat in UK. Fungal Ecology, 5:53-61.

YEO, A., 1999 – Predicting the interaction between the effects of salinity and climate change on crops plants. Sci. Hort. 78:159-174.