Chapter 17

The Impact of Climate and Global Change on Crop Production

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1. INTRODUCTION

Changing climate adds a very significant dimension to the complex problem of ensuring that agriculture worldwide can feed the burgeoning human population. Ensuring food security must reduce environmental damage, not add to it. Population growth, the loss of fertile land through degradation and its use for housing and industry, reduced water supplies and aspirations for an increasingly protein-based diet are integral parts of this problem. Supplying adequate and appropriate food against a background of changing climate is the paramount problem that scientists of all disciplines and politicians must solve collectively. Without a solution that is equitable to the environment and mankind, the spectres of famine and war stalk our Planet.

Historical analyses such as that of Therrell et al. [1] for maize yield over the period 1474–2001 demonstrate the close link between food supply and climatic change. The implications of changing climate have been recognised scientifically for well over a century [2–5]. Change may be beneficial, at least in the short term, as demonstrated by Magrin et al. [6] who showed that recently Argentinian yields of wheat, maize, sunflower and soybean have benefited from increased precipitation, decreased maximum and increased minimum temperatures.

Climate Change: Observed Impacts on Planet Earth

The first formal scientifically validated link between observed global changes in physical and biological systems and human-induced climate change predominantly from increasing concentrations of greenhouse gases was demonstrated by Rosenzweig et al. [7]. They surveyed 29 500 data series of which 90% ($P \ll 0.001$) demonstrated that changes at the global scale are in the direction that would be expected as responses to global warming. In biological systems, 90% of the data sets showed that plants and animals are responding consistently to temperature change. This is mostly illustrated by phenological change with earlier blooming, leaf unfolding and spring arrivals. Events on the current scale have not visited the Earth in the past three quarters of a million years [8]. Previously, however, no one single species (man) has gained full control of the Planet's entire resources and reproduced itself in unprecedented numbers at a rapid rate. The Earth's resources are in imminent danger of exhaustion and its environment is changing in a manner that enhances the process.

Stern [9] identified that 'if no action is taken to reduce emissions, the concentration of greenhouse gases in the atmosphere could reach double its pre-industrial levels as early as 2035, virtually committing us to a global average temperature rise of over 2 °C. In the longer term there would be more than a 50% chance that temperature rise would exceed 5 °C'.

2. IMPACT ON PLANT GROWTH AND REPRODUCTION

Blackman's Principle of Limiting Factors [10] – 'when a process is conditioned as to its rapidity by a number of separate factors, the rate of the process is limited by the pace of the "slowest" factor' – applies equally now as it did a century ago. The basic principles of plant physiology likely to govern responses to climate change are broadly understood [11,12]. While some elements in the changing environment may promote plant growth and reproduction, others will be in short supply and cause physiological stresses. What differs now is that the magnitude of stress is more substantial. Growth of C_3 plants[1] (temporal and boreal) increases with rising carbon dioxide levels more than with C_4 plants[2] (warm tropical). The relatively small group of plants using the Crassulacean acid metabolisms (CAM) pathway (such as members of the Cactaceae) may be favoured by increased carbon dioxide concentrations and temperatures [13]. Where the C_3 plants are in association with benign nitrogen fixing microbes (e.g., legumes) there appears to be added benefit. Benefits of additional carbon dioxide concentration are greater for annuals as compared with perennial plants. Leaf area increases as a result of raised photosynthesis with earlier and more complete light interception and

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[1] C_3 plants form the three carbon compound 3-phosphoglyceric acid as a first stage in photosynthesis.

[2] C_4 plants form the compound 4-carbon oxaloacetate as a first stage in photosynthesis.

resultant greater biomass production. But maintenance costs increase with higher demands for energy and rising respiration. Leaf turnover rises partly due to shading effects consequently photosynthesis per leaf falls. Stomatal opening is reduced with increased carbon dioxide. This is beneficial in limiting the impact of aerial pollutants like nitrogen oxides (NO_X), sulphur dioxide (SO_2) and ozone (O_3) but does inhibit water uptake. Stomatal conductance and transpiration rates drop as carbon dioxide concentrations rise. This effect is less marked when measured on a ground area (canopy evapotranspiration) basis versus consumption measured against leaf-area. There is an increase in water use-efficiency in terms of dry matter formed relative to unit of water transpired. Consequently, leaf temperature increases raising the rate of plant development especially in early growth stages.

Ultimately, however, reduced transpiration and resultant higher temperatures in the leaves leads to accelerated tissue senescence. Whether effects are beneficial or not depends on the extent to which temperatures rise and exceed the optimum for efficient photosynthesis. Overall, the data suggest that elevated carbon dioxide may have positive benefits for C_3 plants including yield stimulation, improved resource-use efficiency, more successful competition with C_4 weeds, less damage from ozone toxicity and in some cases better pest and pathogen resistance [14].

Benefits from increased atmospheric carbon dioxide may be counterbalanced by adverse effects of rising temperatures. Although warming accelerates plant development it reduces grain filling, limits nutrient-use efficiency, increases water consumption and favours C_4 weeds over C_3 crops plants. Changes in the water balance and amount of water available in the soil are crucial for crop growth. In grasslands, 90% of the variance in primary production can be accounted for by annual precipitation [15]. Calculations using the Penman–Monteith equation predict that potential evaporation increases by about 2–3% for each 1 °C rise in temperature [16]. While biomass and yield increase with rising carbon dioxide concentrations dry matter allocation patterns to roots, shoots and leaves also change. Root to shoot ratios increase with elevated carbon dioxide favouring root and tuber crops. Conversely, rising temperature and reduced transpiration limit biomass and seed production drops. Non-structural carbohydrate levels increase but protein and mineral nutrient content fall hence food quality declines both for herbivores and for humans [17].

Currently, ~25% of crop production is lost to the ravages of pests and pathogens between the field and consumer's plate. Climate change will alter phasing of life cycle stages and their rates of development for pests and pathogens and associated antagonistic organisms. It may modify mechanisms of host resistance and host–pathogen relationships. The geographical distribution of hosts and pathogens will alter. The level of crop losses will increase while the efficacy of control measures [18] could fall when faced with greater populations of pests and pathogens. Increased fecundity of fungi results from elevated carbon dioxide. The rate of insect development accelerates as temperatures rise. In warmer conditions they grow and reproduce more quickly and there are more generations per season. For example, the common house fly (*Musca domestica*), although not a direct crop pest is a disease vector and nuisance, populations are predicted to rise by 244% by 2080 [19] as a result of rising temperatures. More aggressive pest and pathogen strains are postulated to develop under elevated carbon dioxide. Increased rainfall events would reduce weather-windows for spray application and allow greater likelihood of contact sprays being washed off. Raised carbon dioxide could increase the thickness of epicuticular waxes resulting in slower penetration of pesticides. Raised aerial carbon dioxide concentrations are unlikely to have much impact within the soil since they are already 10–15 times higher than in air. Rising temperatures could increase the range of pathogens as suggested for *Phytophthora cinnamomi* by Brasier [20]. Similarly, increased spread is likely for rice blast (*Magnaporthe grisea*), wheat scab (*Fusarium* spp.), stripe rust (*Puccinia striiformis*) and powdery mildew (*Blumeria graminis*). Boag et al. [21] estimated that each 1 °C rise in temperature would allow soil-borne nematodes to migrate northwards by 160–200 km. A similar rise would allow leaf rusts of wheat and barley and powdery mildew infection to rise by 2–5-fold [22]. The effects of climate change on pest and pathogen outbreaks are already being seen in the United Kingdom and Western Europe for example, insect pests such as Diamondback moth (*Plutella xylostella*), pathogens like bacterial black rot (*Xanthomonas campestris* pv. *campestris*) and various *Phytophthora* spp. have become well established causing damage respectively, to field brassicas and a wide range ornamentals.

One of the most dramatic examples of the interaction between climate change and husbandry change that exacerbates disease problems is that of the soil-borne microbe *Plasmodiophora brassicae* which causes clubroot disease of brassicas. Previously, this pathogen was held in check in the British winter oil seed rape (*B. napus*) plants because it was a predominantly winter crop. This meant that it was drilled in late August to early September into cooling soil. The seed germinated and produced rosette plants by November which formed the components of yield before growth recommenced in mid to late February. The pathogen was inactive in the cold winter soils. Consequently, the crop could grow and yield in summer with little damage from *P. brassicae* in contradistinction to the spring drilled crops of Continental Europe which succumbed to clubroot as both developed as the soils were warming. Now the British crop is being sown in late July to early August and the soils retain heat through the winter as a consequence *P. brassicae* remains actively causing damage throughout the year. Greater soil moisture content in the autumn and winter because of increased rainfall has only served to offer the pathogen improved opportunities for spread and multiplication [23].

Significant increases in mammalian vermin such as rats (*Rattus* spp.) are noted. Warmer conditions for extended periods enable them to retain activity without any forms of hibernation and in consequence more litters are produced. These are becoming major problems for field vegetables especially in late autumn. Means of control are limited especially in crowded sub-urban areas which exacerbates the problem. Similarly, avian vermin like wood pigeons (*Columba* spp.) are increasingly despoiling food crops. Both these animals contaminate produce with urine and excrement that frequently is infected with bacterial pathogens capable of causing human diseases. Overall, while temperature increases would have significantly increase the severity and spread of plant diseases, precipitation will act as a regulator [24]. Climate change models are not yet sufficiently sensitive or detailed to incorporate estimations of the impact of change on microbial activity. Extreme weather events such as excessive rainfall and consequent flooding are most likely to worsen the incidence of crop pathogens. A major effect of climate warming in temperate zones could be increased winter survival of pests and pathogens.

In more northerly latitudes there will be shifts in patterns for growth and reproduction especially woody perennial plants. There is a substantial body of information dating back to the early 1700s in Great Britain on which predictions of the effects of climate change may be based [25]. Climate change disturbs the synchrony between temperature and photoperiod and because insects and pathogens show individual patterns of response to temperature, carbon dioxide and photoperiod there will be a loss of evolved phasing which damages the relationships between plants and the environment. This adversely affects the temporal and spatial associations between species interacting within specific ecosystems and at different trophic levels. Rosenzweig et al. [7] identify shifts in blossoming, leaf unfolding, migrations and time of reproduction, species distributions and community structure. Both in nature and in crop production there will be a shortage of ‘chilling events’ in the autumn which encourage perennial plants to acclimate and ultimately enter a dormant state. Dormancy is likely to be much less profound and more easily broken [26].

Phenology studies (the study of times of recurring natural phenomena especially in relation to climatic conditions) already show clearly that flowering times of bulbous and deciduous woody species have advanced by anything up to 1 month in the last 30 years. Freezing events will become sporadic, unpredictable and frequently severe. The result for woody plants that have developed early, season growth will be the loss of flowering and fruiting tissue. Most of these plants are incapable of replacing these organs until the following year. As a consequence an entire season’s growth and reproduction fails. Fruit and seed production is lost. If this happens over successive seasons then ultimately the plants will die. This will be a substantial problem for commercial fruit crops and for amenity and natural plantings. The likelihood is that the ‘forest giant’ trees (oak, *Quercus* spp., beech, *Fagus* spp., elm, *Ulmus* spp.) will suffer most. It also means that top fruit such as apples (*Malus sylestris*) and pears (*Pyrus communis*) and stone fruit such as apricot (*P. armeniaca*), cherry (*P. avium*) and plum (*P. domestica*) will be forced into earlier-flowering and will have entire crops destroyed.

Nutrient acquisition is closely associated with overall plant biomass and is strongly influenced by the available root surface area. When climate change alters root exploration in the soil a restriction of nutrient acquisition follows leading to stress and reduced growth. Nutrient replacement management will be required where crop spectra change following the effects of temperature and carbon dioxide availability [27].

Climate change has both direct and indirect effects on soil erosion. Devastating soil erosion results from even modest rainfall falling onto bare soil. Increased soil erosion accelerates the loss of crop productive land. An avoidance of erosion prone crops, that is, those which are either slow or fail completely to provide full canopy closure is one strategy. An increase from 24% to 46% of the total land area of England and Wales which has a moderate to high risk of erosion is predicted as a result of climate change [28]. Heavy rainfall events in the Great Brittain such as the extensive flooding in 2007 wiped out crops and opportunities for autumn planting because of soil degradation at a direct cost of £3 × 10^9 [29].

Increasingly, severe wind events are thought likely [30]. Because of the technical complexity of analysing wind effects there is little data that identifies the consequences of this prediction. In northern Europe, winter and early spring winds are frequently associated with periods of intense cold. These are disastrous events for all types of plant but especially young emerging seedlings. Wind damage to young seedlings is underestimated in its impact on yield and quality. Even relatively low speed winds pick up soil particles that then abrade the leaves and stem tissues of emerging seedlings. Abrasion of this type causes cryptic stress in crops which is manifested later at harvest. Winds of greater intensity rock and twist seedlings leading in severe cases to breakage of the stems at ground level. Seedlings that remain in the soil are frequently badly damaged and the disrupted stem tissue permits invasion by collar rotting pathogens.

The odours emitted by damaged tissue are powerful attractants for pests such as root flies (e.g., *Delia* spp.). Physiological disorders that may become manifested later in the plant's life can be initiated by stress in the seedling stage. Where wind gusts are very powerful then both soil and seedlings are collected and transported many hundreds of metres or even further. Spring winds do substantial damage to woody perennials especially fruit trees. The damage may not be apparent in the year of the event. With large trees root damage may take a least one season to cause an effect and then lead to foliar chlorosis and die back. This is frequently followed by pest and pathogen invasion which compounds the damage. Wind in summer is damaging because trees are in full foliage. This makes the aerial parts much heavier and limbs are more easily removed. Wind will also cause significant damage to horticultural structures. Glasshouses, polyethylene tunnels and low level field covers are susceptible to wind damage. Swedish research indicates that climate change will increase the damage to forest trees [31]. Increased intensity of wind, changed direction and frequency of wind events each contributes to these effects.

3. SCALE OF THE PROBLEMS

Some 1.5×10^9 ha of land is used worldwide for crop production and of this 960×10^6 are in developing countries [32]. In the last 30 years, the world's cropped area has expanded by $\sim 5 \times 10^6$ ha annually with Latin American countries accounting for 35% of this increase by deforestation. Land is the basic resource that cannot be created. There is, therefore, a finite point beyond which the cropped area cannot rise. About 40% of the world's arable land is now degraded to some degree, most of this land is in the poorer nations in densely populated, rain-fed farming areas where overgrazing, deforestation and inappropriate land-use compound other problems. About 3×10^9 ha (one fifth of the world's land surface) is under forest ecosystems. Russia, Brazil, Canada, USA, China, Australia, Congo and Indonesia account for 60% of the world's forest land. In the decade of 1990s, 127×10^6 ha of forests were cleared and 36×10^6 ha replanted. Africa lost 53×10^6 ha of forest mainly converted into cropped land. Two-thirds of the world population live in areas receiving 25% of the annual rainfall. About 70% of the world's fresh water goes to agriculture and that figure rises to 90% in nations relying on extensive irrigation. Currently, 30 developing nations face water shortages and by 2050 this will reach 50 nations mostly in the 'developing country' grade. Water scarcity and the degradation of arable crop land are the most serious obstacles that inhibit increases in food production.

Against this background, Smith and Almarez [33] have summarised the dangers of climate change to crop production. Extremes in temperature are dangerous to crop production especially where growth has accelerated due to added carbon dioxide. More northerly zones become wetter and warmer which could benefit crop production in the short term but the tropics and subtropics become hotter and drier. Calculations based on three out of four Climate Change Models show consistent increases in areas of arid land in developing countries. Africa is thought to be the region most vulnerable to negative impacts of climate change on crop production [34].

Currently, 1.080×10^9 ha of land in Africa has a growing period of less than 120 days. With climate change by 2080s this expands by 5–8% (equal to $58–92 \times 10^6$ ha). This change is accompanied by a loss of $31–51 \times 10^6$ ha of land in favourable growing zones with growing period lengths of 120–270 days per year. About 1×10^9 people worldwide and of that 180×10^6 in Africa live in vulnerable zones currently relying on agriculture for their living. By 2080s land areas with increasingly severe constraints for crop production in the world zones amounts to: Central America and Caribbean (1.2–2.9% of 271×10^6 ha); Oceania and Polynesia (0.3–4.3% of 848×10^6 ha); Northern Africa (1.9–3.4% of

547×10^6 ha) and West Asia (0.1–1.0% of 433×10^6 ha). In Southern Africa, an extra 11% (of 266×10^6 ha) could suffer severe constraints to cropping. By 2080s decreases in potentially good agricultural land are: Northern Europe 1.5–1.9% (with Great Britain and Ireland particularly affected); Southern Europe 0.2–5.9% (especially Spain); Northern Africa 0.5–1.3% (especially Algeria, Morocco and Tunisia); Southern Africa 0.1–1.5% (especially South Africa) and in East Asia and Japan 0.9–2.5% (especially China and Japan).

Venezuela, New Zealand, Mozambique, Sudan and Uganda are individually nations with good agricultural land that is especially vulnerable. Some economists make the assumption that by 2080 consumers will be much richer than today and separated even more from agricultural production processes earning their income in non-agricultural industries. Hence, they postulate, that changes in consumption will depend more on food prices and on income differences than on local agricultural production. They suggest further that the share of undernourished in the world total population falls below 20% when an arbitrary index of 130 is reached whereby aggregate food supply exceeds aggregate food requirements by 30%. Hunger is completely eliminated where this index reaches 170. Fischer et al. [32] postulate that 'the trade system will (*only*) mitigate local climate-change impacts when consumers can afford to buy food on the international market... (*but*) food prices rising due to climate change may put an extra burden on those consumers who depend on imports, even without a region experiencing direct local climate-change impacts on production conditions' (*my parenthesis*). The economic and climate change models give starkly different prospective outcomes for 2080. Either 'climate change impacts on agriculture will increase the number of people at risk of hunger' or 'with rapid economic growth *and a transition to stable population levels*, poverty, and with it hunger – though negatively affected by climate change – would become a much less prevalent phenomenon than it is today' (*my italics*).

4. CLIMATE CHANGE MODELS

Estimating the effects of climate change depends on the climate change model used and postulates applied for the response or adaptation of the farming community and the new husbandry practices developed from scientific and technological advances. Evidence suggests, as might be expected, that higher resolution land surveying models provide more realistic postulated responses in terms of the effects of climatic change and crop response compared with coarser scale models.

This is especially the case for regions with complex geomorphology such as areas with high relief, the mountainous areas, complex coastlines or complex patterns of land use [35]. Currently much prediction is 'clairvoyance'. Considerable changes to agricultural practice will be needed not least in the characteristics of cultivars bred to withstand the impact of climate change

[36]. Where refinement was increased and the scale of study decreased from hundreds of kilometres to more regional levels then it became apparent that for a wide range of crops in the USA (corn, *Zea mays*, cotton, *Gossypium* spp., soybean, *Glycine max.*, hard red spring wheat, hard red winter wheat, soft white wheat, durum wheat (*Triticum* spp and sorghum, *Sorghum vulgare*) climate change correlated with increasing yield reduction. This proved correct for regions such as the Lakes States, Corn Belt, Northern Plains, Delta States and Southern Plains. Considering this aspect for soybean and sorghum crops in detail [37], fine scale (50 km Regional Climate Model, RCM) compared with coarse definition (300 km Commonwealth Scientific and Industrial Research Organisation, CSIRO Model) considerably raised the level of yield loss irrespective of adaptive husbandry effects for these two crops. With other crops such as cotton the use of irrigation could mitigate the effects of climate change [38]. But this does not allow for decreased availability of water which may accompany climate change compounded by other factors such as population growth and migration. Determinants of variability differ across crops such that for winter wheat the key effect comes from temperature applied during the vernalisation growth stage while for corn (maize) it is the availability of water during grain filling [39]. Recognition of such environmental effects at specific stages in the growth and reproduction of crops has been achieved by agronomists and plant breeders long before climate change emerged as an issue.

5. WINNERS AND LOSERS

While climate change is a global problem, at least initially the biggest losers are likely to be in under developed and developing regions, particularly Africa. Although African farmers are already adapted to local conditions, net revenues would fall with more warming or drying [40]. Dryland crop and livestock farmers are especially vulnerable, with temperature elasticities of –1.9 and –5.4, respectively. Irrigated cropland tends to benefit from marginal warming because irrigation mutes climatic impacts. But these farms are currently located in relatively cool regions of Africa. With precipitation elasticities of 0.4 for dryland crops and 0.8 for livestock across Africa, net revenues for dryland crops and livestock will increase if precipitation increases with climatic change and fall where precipitation decreases. Net revenues for irrigated land follow in the same direction but to a lesser extent (elasticity of 0.1). Increases in precipitation have unambiguously beneficial effects on African farms. As temperatures warm the effects on African farms becomes steadily more harmful. Farms located in currently hotter and drier areas are at greater risk because they are already in a precarious state for agriculture. Dryland farming throughout Sub-Saharan Africa is vulnerable to warming. In the East, West and Sahel regions dryland farming is especially risky.

By contrast irrigated crops in parts that are relatively cool now such as the Nile Delta and the Highlands of Kenya enjoy marginal gains from warming. Because Sub-Saharan African economies depend more heavily on agriculture, total gross domestic product (GDP) and *per capita* income are also vulnerable. By contrast, non-agricultural GDP in Northern Africa is more diversified and so the economies of these countries are less vulnerable to climate change. Adaptation through scientific and technological advance has moved too slowly in Africa compared with the rest of the World. As a consequence the risks from climate change are far greater there than elsewhere.

Specific crop studies of maize and sorghum production in Botswana by Chipanshi et al. [41] using the African core climate change scenario showed that simulated yields declined by 363% for maize and 31% for sorghum in the sand veldt region. Yield reductions in the hard veldt were 10% for maize and sorghum. Growing season became shorter, reduction in the sand veldt being 5 and 8 days for maize and sorghum, respectively, and correspondingly 3 and 4 days in the hard veldt region. Currently, lack of water is the main crop yield constraint. Both maize and sorghum are C_4 with optimal photosynthesis at higher temperatures (30–35 °C) and insolation than C_3 plants. But elevated carbon dioxide concentrations may well negate these benefits. Instead C_3 plants outperform C_4 plants with elevated carbon dioxide [42] and most weeds of maize and sorghum are C_3 types.

Weed competition will, therefore increase. Also the problems of the sandy environment such as degraded fertility and erosion will increase. Arenosol soils that cover more than half of Botswana are most liable to wind erosion and a drier warmer climate can only exacerbate erosion and nutrient loss. Since 1990 satellite evidence shows that soil exposure around settlements and boreholes and the encroachment of woody weeds on bare soil areas have been taking place [43] and are likely to result from a combination of climate warming and over grazing. Similar conclusions come from a study of Kenyan agriculture by Kabubo-Mariara and Karanja [44], showing that climate change produced adverse effects with substantial negative impact on net crop revenue. Temperature rises were more important than changes to precipitation there is a nonlinear relationship between temperature and revenue on the one hand and precipitation and revenue on the other.

The key food crop for at least half of the world's population is rice (*Oryza sativa*). Reliance is greatest in under developed and developing nations. Studies of the rice cultivar IR36 simulating yield changes with increasing carbon dioxide levels and temperature have been made using the INFOCROP model for the Tamil Nadu region of India. Crop duration, days to anthesis, leaf area index and dry matter percentage (DMP) all fell resulting in with lower grain yield per square metre. The authors conclude that crop husbandry will need to improve substantially [45] in order to offer any chance of sustaining the food supply. Bangladesh is also a region highly vulnerable to the impact of climate change and requires adaptation strategies to reduce this risk. Here suggestions are made that greater use could be made of locally adapted plants such as *Jatropa curca* and *Simmondsia chinensis* as supplies of biofuel extracted these oilseeds [46].

Broad level analyses of Chinese agriculture [47] used country – level cross sectional data on agricultural net revenue, climate and other economic and geographical data for 1275 agriculturally dominated counties. Under most climate change models higher temperature and more precipitation would have an overall positive impact on China's agricultural output. But impacts vary seasonally and regionally. The autumnal effects are most significant and the spring time ones most negative. Applying the model to five climatic scenarios in the year 2050 shows that the East, the Central part, the South, the northwest part of North East and the Plateau would benefit from climate change. The South West, North West and southern part of the North East may be negatively affected. The authors reach the general conclusion that overall China benefits from climate change. But this neglects the impact on many millions of people living in those parts where the effects are deleterious.

A realistic study comes from Russia where it is suggested that the shortage of water for irrigation may override any advantages accrued from temperature increases and the availability of high grade soils for grain and other crop production. As a consequence Dronin and Kirilenko [48] analysed strategies for food security based on previous systems in Russian agricultural history, viz Free Market, Big Commune/War Communism, Developed Socialism and Fortress Market employed to provide interregional food exchange. They deliberately omitted the strategy of compensating for short falls in food by substituting imports. The Free market model outperformed the others but the Fortress Market also succeeded as no regions were threatened by grain shortage. Several adaptation measures are identified such as moving meat production northwards and the exploitation of genetically modified cultivars. The authors note that increased irrigation could mitigate some effects of climate change especially in Southern Russia. But they admit that water supply will come under severe restrictions and hence this should not be seen as a route for adaptation.

One of the prime sources of food exports is the USA. Hence studies of the impact of climate change there have ramifications for the world's population collectively. A broad scale review of major crops effects by Chen et al. [49] identified as might be expected that climate change effects varied for different crops. For corn (maize) precipitation and temperature have opposing effects on yield levels and variability, increased rainfall raises yield and decreases variance. Temperature has the reverse effect. For sorghum higher temperatures reduced yields and yield variability. Increased rainfall raised sorghum yields and its variability. The authors used the Hadley and Canadian climate change models, and these indicated that future variability decreased for corn and cotton but increased for soybeans while effects for wheat and sorghum were mixed. Increased variability equates with unreliability in harvest volume which is an unwelcome outcome for all sections of the food chain from field to plate.

Reviewing climate change effects in more detail Changnon and Hollinger [50] studied the production of corn (maize) in the Mid-Western USA. There appears to be a potential for up to 40% increases in rainfall since there has been steadily increasing rainfall over past 50 years in the Midwest. But this translated into little effect on yield unless the rainfall coincided with the drought stressed summer period. The impact of increased soil moisture depends on timing and season. Using two climate change models, the United Kingdom Hadley Centre for Climate Prediction and Research model and the Canadian Centre for Climate Modelling and Analysis model for studies of wheat production in the Great Plains region of the USA, Weiss et al. [51] concluded that yield and percent kernel nitrogen could not be sustained at current levels especially in the arid part of Nebraska. This translates into a loss of quality in the flour required for bread making [52]. The authors identify needs for new cultivars to increase nitrogen uptake and translocation, simply adding extra quantities of nitrogen fertiliser is not the agronomic, economic or environmental answer.

Perennial crops are affected by climate change, not only during the growing season but also while they are dormant. Winter chill hours and chill degree hours are diminishing across the fruit and nut producing regions of California, losses range from 50 to 260 h per decade [53]. By the end of the twenty-first century, Californian orchards are expected to receive less than 500 chill hours per winter which will have a significant deleterious effect on the fruit and nut industries of that State.

Further north there are evaluations of spring wheat, maize, soybean and potato crops in seven agricultural regions of Southern Quebec. These were made in relation to increased carbon dioxide and temperature with resultant acceleration in crop maturation caused by reduced soil moisture availability. Adaptive moves would be needed to cancel out negative effects caused by climate change [54]. A similar conclusion comes from studies of wheat production in parts of South Australia which will cease to be economically viable [55] based on critical yield thresholds. Farmers' adaptation options and adaptive capacity, market fluctuations and agricultural technology levels including genetic alteration and the products of plant breeding will affect future levels of critical yield threshold.

The impact of climate change on European agriculture has received considerable attention. As in the wider world there are some initial beneficiaries particularly in more northerly areas. In northern Europe yields increase as new crops and cultivars emerge. For example, analyses indicate that in the short term German farmers may benefit from climate change, with maximum gains where the temperature increase is +0.6 °C. In the longer term there may be losses [56]. This work is based on theoretical modelling which is unable to take all effects into account. Similarly, in North Eastern Austria studies using the Global Circulation Model (GCM) predict a rise in temperature of between 0.9 and 4.8 °C between 2020s and 2080s. Warming decreases crop growing period which reduces yields, but increased precipitation linked to higher temperatures and carbon dioxide raises yield for crops such as winter wheat and soybean [57]. Spring barley (*Hordeum vulgare*) is the most important cereal crop in Central and Western Europe [58] because of its use for animal feed. In the Czech Republic soil water content increases. This is a key factor in determining yield. Yields increase by 54–101 $kg{\cdot}ha^{-1}$ per 1% increase in available soil water content on sowing day. Doubling carbon dioxide increased yield by 13–52% and opportunities for earlier sowing further enhances yield. Adverse effects can be expected in southern Europe, water shortages reduce yield but farmers could adapt their husbandry to prevailing conditions aided by technological progress. Adaptation needs to be quantified and built into simulation models determining the impact of climate change [59]. The variability of sugar beet (*Beta vulgaris*) yield (measured as coefficient of variation) [60] will increase by half from 10% to 15% compared with 1961–1990 with serious implications for commercial planning in the sugar industry. Climate change is expected to bring yield increases of around 1 $t{\cdot}ha^{-1}$ of sugar in northern Europe and comparable losses in yield in France, Belgium and west/central Poland over 2021–2050. The figures mask significant increases in yield potential due to earlier springs and accelerated growth offset by losses due to drought stress. The effects of carbon dioxide concentration on biomass production are approximately linear from 360 to 700 ppm CO_2 [61]. Areas with existing drought problems will suffer from a doubling of losses and they will become a serious new problem in North Eastern France and Belgium. Overall west and central Europe will potentially see losses from drought rise from 7% (1961–1990) to 18% (2021–2050).

In Spain High Resolution Climate Models (HRCMs) were used to study potential yields and showed crop failures of winter wheat in the south but yield increases for spring wheat in northern and high altitude areas [62]. While in Turkey a study by Umetsu et al. [63] considered the Lower Seyhan Irrigation Project in Turkey using an expected value–variance (E–V) model. Under water constraints farmers chose to grow high value added crops such as watermelon (*Citrullus vulgaris*), citrus (*Citrus* spp.), cotton, fruits and vegetables. But because of rising cost of water gross revenue fell even with this business model. Adaptation by increasing irrigation and nitrogen use are advocated by Haim et al. [64] as means of mitigating the adverse implications of climate change by 2070–2100 for Israeli wheat and cotton production. Since water supply for this entire region will be at a premium by then such strategies for adaptation may not be feasible.

Wine production is a good example of a worldwide product where clear differences in advantage or disadvantage emerge from climate modelling. Changes in cool climate areas such as the Mosel Valley, Alsace, Champagne and the Rhine Valley could lead to more consistent vintage quality and potentially the ripening of warmer climate cultivars [65]. But those regions currently growing close to the climatic optimum for grape (*Vitis vinifera*) cultivars, for example, Southern California, southern Portugal, the Barossa Valley and the Hunter Valley may become too hot for quality wine production. Winter temperature changes would also affect viticulture by making regions that experience hard winter freezes (e.g., Mosel Valley, Alsace and Washington) less prone to vine damage, while other regions (e.g., California and Australia) would have such mild winters that latent bud hardening may not be achieved and cold-limited pests and pathogens may increase in both number and severity.

As a general conclusion, climate gets warmer and where temperature rise is extreme then this is dangerous both directly to humans and indirectly through the effects on food supply. The spring, summer and autumn seasons get longer and this effect becomes more dramatic in higher latitudes. In these areas the climate becomes drier, for example, in parts of Canada this reduces the area available to produce hard red spring wheat, in Quebec fruit trees are moved northwards and reduced snow cover makes it difficult for forage legumes to survive in winter. Glaciers have retreated round the world by up to 30% in the twentieth century. The result is less water flowing through the rivers hence reduced amounts available for irrigation. Extreme weather events become more common, increasing droughts and tropical storms make crop production more difficult. Potentially there are changes to soil organic matter. Higher temperatures accelerate the breakdown of soil organic matter. Less organic matter means lower yields because of a lack of nutrients and water. As a counterweight increased carbon dioxide concentration raises soil organic matter content resulting in greater microbial activity. Increased carbon dioxide means more photosynthate for nitrogen fixation encouraging the growth of C_3 plants. Soil erosion increases as a result of more severe wind events. Rising sea levels also mean that adjacent land becomes more saline. Pests and pathogens move and propagate more quickly resulting in greater losses to crops.

6. ADAPTATION

The assessment of winners and losers is solely a snap shot of potential effects and implications. It becomes abundantly evident that as the twenty-first century progresses food production worldwide is threatened. But adaptation and consequent mitigation can be achieved through science and technology. As in the 1960s their capacities to provide means by which agriculture can adapt to its changing environment are crucial for the security of the food chain [66]. In general intensive systems such as horticulture have greater potential to adapt, or be adapted, to changing climates than extensive and low-input systems. As an example, the assessment by Weatherhead et al.

[67], showed that in East Anglia, Great Britain's area of intensive field crop agriculture, water availability for crops will decrease by the 2020s, but farmers could still produce high value irrigated crops such as fresh vegetables and potatoes by reducing irrigation to other crops, installing more reservoirs to hold water from expectedly increased winter rainfall, using winter abstraction into the reservoirs and using more efficient irrigation systems such as low level drip fertigation[3]. But farming will be more financially vulnerable because of reduced net margins. The availability of water and nutrient resources and ability of plants to make efficient and effective use of them become crucial factors. This contention is supported by Hopkins et al. [68], who identify the agricultural responses needed for adaptation to climate change as: new crops, increased irrigation and changes in land use patterns for crops and livestock.

The biodiversity changes that will affect the availability of benign organisms that aid crop growth will be affected by: the timing of seasonal events and hence loss of synchrony between species and the food and other resources that they require; changes in species abundance and range, habitat alterations in chemical, physical and biological terms; altered water regimes and increased decomposition. Farming can respond to climate change with modifications to current husbandry systems. This only allows compensation for the immediate short term effects of climate change over the next decade or so. More radical change demands substantial programmes of research and development on a co-ordinated worldwide basis. Only genotype change can provide the level of mitigation needed, without this as illustrated by Challinor et al. [34], with studies of ground nut (*Arachnis hypogaea*) yields can drop by 70% as a result of increased temperatures as the century progresses. The importance of genetics and breeding linked with environmental and husbandry measures cannot be over emphasised [69]. Fortunately, science through current studies of the molecular processes of inheritance has considerable knowledge in store. Deploying this basic knowledge into applied science and technology demands united political decisions at intergovernmental level. As part of such decisions there must be recognition that coherent provision for knowledge transfer from the scientists' laboratories in to farming practice is a paramount necessity [70]. For the past generation at least governments worldwide have expected that free market forces would facilitate knowledge transfer. This has not happened as the free market system is not capable of providing knowledge transfer to individual farming enterprises in an effective manner. Providing adequate numbers of properly educated and experienced crop specialists capable of translating science and technology into farming practice is an essential component of coping with climate change and feeding mankind.

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[3] Fertigation = combined irrigation and liquid nutrient supply.

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