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Climate Change and Virtual Water Implications for UK Food Security

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Implications for UK Food Security

David Oscar Yawson

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Climate Change and Virtual Water:
Implications for UK Food Security

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LIST OF ABBREVIATIONS AND ACRONYMS

ABA	Abscisic acid
AWC	Available Water Capacity
BAU	Business As Usual
BWR	Blue Water Requirement
CGMS	Crop Growth Monitoring System
CLD	Causal Loop Diagram
CWR	Crop Water Requirement
CYFS	Crop Yield Forecasting System
DAS	Days After Sowing
DECC	Department of Energy and Climate Change
EE	East of England
EEA	European Environment Agency
EM	East Midlands
ET	Evapotranspiration
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FBEM	Feed Barley Equivalent Meat
FBS	Food Balance Sheet
FC	Field Capacity
GCMs	Global Climate Models
GHG	Greenhouse gas
HES	High Emission Scenario
HGCA	Home Grown Cereals Authority
HI	Harvest Index
IPCC	Intergovernmental Panel on Climate Change
LES	Low Emission Scenario
MARS	Monitoring Agriculture with Remote Sensing
MENA	Middle East and North Africa
MES	Medium Emission Scenario
NEE	North East England
NES	North East Scotland
NI	Northern Ireland
NVWF	Net Virtual Water Flows
NWE	North West England
NWS	North West Scotland
OECD	Organization for Economic Co-operation and Development
PET	Potential Evapotranspiration
PWP	Permanent Wilting Point
RCMs	Regional Climate Models
RMSE	Root Mean Square Error
ROS	Reactive Oxygen Species
SEE	South East England
SES	South East Scotland
SINFO	Soil Information System
SMU	Soil Mapping Unit
SRES	Special Report on Emission Scenarios

STU	Soil Typological Unit
SWB	Soil Water Balance
SWC	Soil Water Content
SWD	Specific Water Demand
SWE	South West England
SWS	South West Scotland
TBWR	Total Blue Water Requirement
TVW	Total Virtual Water
UAA	Utilized Agricultural Area
UK	United Kingdom
UKCP	UK Climate Projections
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USDA	United States Department of Agriculture
VWC	Virtual Water Content
VWF	Virtual Water Flows
WA	Wales
WM	West Midlands
WFD	Water Framework Directive
WG	Weather Generator
WP	Water Productivity
WUE	Water Use Efficiency
YH	Yorkshire and Humber

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DEDICATION

To my daughter, Nana Dekyi Nhyira Yawson, who is full of life, joy and laughter.

Your birth renewed my resilience to adversity and hope for better things to come.

DECLARATION

I, **David Oscar Yawson**, declare that I am the author of this thesis; that, unless otherwise stated, all references cited have been consulted by me; that the work of which the thesis is a record has been done by me and that it has not been previously accepted for a higher degree.

Signature.....

Date:

ABSTRACT

Demand for both food and water are projected to increase substantially in the next four decades. Water scarcity is also projected to increase in scale and complexity. Climate change is projected to increase temperatures, spatio-temporal variability in rainfall, frequency and severity of droughts and soil water stresses to crops. Due to the crucial role of water in crop growth and yield formation, prolonged or severe soil water deficits in crop producing areas can result in substantial yield penalties. The potential of food trade to help address food insecurity as a result of insufficient water availability for crop production has been rationalized in the virtual water concept. The aim of this thesis was to improve the evidence base for understanding and evaluating the relationships between future water availability for crop production and food trade (or virtual water flows), and the utility of the virtual water concept to inform policy and management decisions on water-food security.

The UK and barley were used as a model country and crop, respectively. Three crop growth simulation models (AquaCrop, CropWat and WaSim) were evaluated for their abilities to estimate the water use of 10 barley genotypes. Subsequently, the effect of projected climate change on UK barley yields in the 2030s, 2040s and 2050s was simulated using the high, medium and low emission scenarios data from the UK Climate Projections 2009 (UKCP09). Projections of total UK feed barley supply and demand were performed to quantify potential virtual water flows and to analyze the implications for food security and policy.

The results show that the predicted water use of barley differed between the models but not among the genotypes. Predicted seasonal water use of the barley genotypes ranged from 241.4 to 319.2 mm. Based on the root mean square error (RMSE) and the index of agreement (D-Stat) values, CropWat performed poorly while AquaCrop and WaSim performed excellently. Barley yields under projected climate change increased substantially over baseline yields in all UK regions. Projected mean barley yields for the UK ranged from 6.04 tons ha⁻¹ (2030s) to 7.77 tons ha⁻¹ (2050s). In spite of the projected increase in yields, the UK faces the risk of large deficits in feed barley and meat supply from the 2030s to the 2050s due to a combination of population growth, increased per capita meat demand and reductions in land area allocated to barley production. Finally, current water scarcity concepts were found to be incompatible with water availability and consumption in crop producing areas, a situation that diminishes the usefulness of the virtual water concept for policy. To address this deficiency, a framework for making water scarcity compatible with crop production was proposed.

In conclusion, the poor performance of CropWat has implications for its wider use in quantifying global virtual water flows associated with crop trade. Eventhough UK barley yields are projected to increase under projected climate change, the projected deficits in feed barley and meat supply threatens to destabilize future UK food security. The UK can rely on import to offset the large deficits in feed barley and meat supply but can use the proposed framework to reduce the effect of its imports on water scarcity in the exporting countries. The proposed framework improves understanding and evaluation of the role and usefulness of the virtual water concept in water-food security policy and management decisions.

CHAPTER 1

INTRODUCTION

Water is an essential resource for crop production, ecosystem services and socio-economic development. Apart from its direct consumption for domestic and health purposes, water is crucial to the systems that drive life and economy such as industrial production, energy production, transportation, food production, environmental control, and sustenance of ecosystem services and values. While access to both water and food is a fundamental human right (Dubreuil, 2006; UN, 1948), the production of food is directly and intricately locked up with sufficient water availability. This thesis explores the relationships between future water availability for crop production and the role of food trade in ensuring food security in a changing climate. This Chapter introduces the general background and context, the aims and objectives, and the structure of the thesis.

1.1 Background and Context

1.1.1 Critical Role of Water in Food Production

For crops, water plays a crucial role in photosynthesis, translocation of assimilates, acquisition and utilization of mineral nutrients, hydration and turgidity of cells (Pinheiro & Chaves, 2011; Barnabà *et al.*, 2008; Passioura, 2006; 2002; Gardner & Gardner, 1983; Boyer, 1982). Water and carbon dioxide (CO₂) are the two main raw materials used in

photosynthesis, the key process by which biomass is produced by crops. For photosynthesis to occur, stomata must open to conduct CO₂ from the atmosphere to the chloroplasts while water is transpired along the same route both to deliver solutes to the shoot and to cool the leaves. Transpiration accounts for 99% of water abstracted from soil by crop roots while the remaining 1% is used in metabolic activities (Hess, 2010; Shahin, 2003). The formation and realization of yield potential in crops are regulated by the interaction of light, nutrient and water availabilities (Rajala *et al.*, 2011). In cereals, for example, water is often the primary regulator of yield formation (Rajala *et al.*, 2011; Barnabàs *et al.*, 2008; Araus *et al.*, 2002). The availability of sufficient water in the root zone is therefore crucially important to drive photosynthesis, biomass production and yield formation (Rajala *et al.*, 2011; Barnabàs *et al.*, 2008; Boyer & Westgate, 2004; Rockström, 2003; Araus *et al.*, 2002).

Globally, agriculture has the largest share of land use (Foley *et al.*, 2011), with rain-fed agriculture covering about 80% of cultivated land and contributing about 60% of yield (Foley *et al.*, 2011; De Fraiture & Wichelns, 2010; Thenkabail *et al.*, 2010; Rockström, 2003). Seasonal or intra-seasonal water stress is the most frequent abiotic stress that limits crop yields in most rain-fed agro-ecosystems (Rajala *et al.*, 2011; Barnabàs *et al.*, 2008; Boyer & Westgate, 2004; Araus *et al.*, 2002; Boyer, 1982). The duration and timing of water stress, especially at critical growth stages, such as anthesis and grain-filling in cereals, can have a profound effect on yield. Prolonged periods of soil water deficit can lead to premature senescence of crops and substantial yield penalties (Anjum *et al.*, 2011a; Rajala *et al.*, 2011; Barnabàs *et al.*, 2008). This suggests that the production of food depends on the timely availability of water in sufficient quantities.

1.1.2 Water Is Becoming Scarce

It is now widely acknowledged that water is becoming scarce due to overexploitation, pollution, inefficient management and increasing demand and competition among water use sectors (Vörösmarty *et al.*, 2010; Chapagain & Orr, 2009; Rijsberman, 2006). Water scarcity will remain a major challenge to human security and development in general through the 21st century (WRI, 2003). Available evidence suggests that water scarcity is expanding geographically and is very likely to increase in severity and complexity in the future if current abstraction and management practices continue (De Fraiture & Wichelns, 2010; Kummu *et al.*, 2010; Vörösmarty *et al.*, 2010; Falkenmark *et al.*, 2009; Falkenmark & Molden, 2008; Molden, 2007; Yang & Zehnder, 2007; Islam *et al.*, 2006; Arnell, 2004; Falkenmark, 1997). In Europe, approximately 113 million people live in water-stressed areas and water scarcity is increasing steadily, especially in the southern, Mediterranean region (EEA, 2010). It has been projected that, by 2050, a third of the global population will live in water-scarce countries (Falkenmark *et al.*, 2009; Yang & Zehnder, 2007).

Projections indicate that climate change, population growth, urbanization, economic development and certain legislative instruments (e.g. EU Water Framework Directive, WFD 2000) will interact in complex ways and across multiple scales to complicate or exacerbate future water scarcity (Foresight, 2011; Hanjra & Qureshi, 2010; Hughes *et al.*, 2010; Strzepek & Boehlert, 2010; Bates *et al.*, 2008; Marcotullio *et al.*, 2008; IPCC, 2007). In particular, climate change will increase temperature and variability in precipitation, with adverse implications for water availability and requirement for crop production (IPCC, 2007). Irrigation is the main response to crop-water deficit. If irrigation

is properly applied, yields of irrigated crops can far exceed those of rain-fed production (Hanjra & Qureshi, 2010; Ali & Talukder, 2008). Irrigation already accounts for 70% of global water withdrawal (or over 80% in semi-arid and arid agro-ecosystems), making crop production the most water intensive human activity (De Fraiture & Wichelns, 2010; Faramarzi *et al.*, 2010a; Liu *et al.*, 2009; Molden, 2007; Rockström, 2003). Irrigation, however, can put agriculture and crop production in direct competition with other water-use sectors, particularly when water is in short supply. The complexity and spatio-temporal dynamics of water scarcity suggest a need for studies on the risk and extent of water stresses in predominantly rain-fed crop producing areas under future climates.

1.1.3 Water Scarcity Undermines Food Security

Food security can be defined from several perspectives depending on the purpose, context or scale of application (Gorton *et al.*, 2009; Pinstруп-Andersen, 2009; Rocha, 2007). The most widely used definition of food security is: “*food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*” (FAO, 2006a). The dimensions of food security are availability, access, utilization and stability of the first three dimensions (FAO, 2006a). In this thesis, food security is defined as the “*the risk of adequate food not being available*” (Chakraborty & Newton, 2011; Newton *et al.*, 2011).

The inexorable dependence of food production on water availability implies that water scarcity constitutes a direct threat to food security. The global population is

projected to increase from 7.2 billion at the end of 2013 to 9.2 billion in 2050 and increase by a further 0.2 billion between 2050 and 2100 (UNDP, 2006). Thus, demand for food and water will increase sharply up to 2050 (Spring, 2009). Projections suggest that global food production needs to increase by 50-70% over 2005/07 levels to meet the projected demand in 2050, with cereal and meat production needing to increase by nearly 1 billion and 200 million tons respectively (Alexandratos & Bruinsma, 2012; Spring, 2009; FAO, 2009). The implications of these projections are that agricultural water demand will increase substantially. Water stress in rain-fed agro-ecosystems is projected to become widespread, more frequent, and increase in severity due to climate change (Dai, 2011). However, as water scarcity increases, it is likely that water will be treated as a commodity and the principle of efficient allocation of resources will likely shift water away from primary sectors (such as agriculture) that have low return on investment to more economically productive sectors such as industry (Dinar & Moigne, 1997). Given this context, the hard question remains how to ensure food production in sufficient quantities in a manner that is ecologically and economically efficient, sustainable, and does not disturb supplies to other water-use sectors. There is, therefore, a need to assess the viability of current rain-fed crop production systems under future climatic conditions.

1.2 The Role of Virtual Water in Ensuring Water-Food Security

There is an urgent need to find options for maintaining both water and food security simultaneously under possible future water-scarce conditions. Two key qualifications of such options should be the ability to illuminate understanding of the

inevitable tradeoffs required in the nexus of water and food security, and the ability to effectively link the agro-ecological and socio-economic conditions that underpin the food system to policy and management decisions. Virtual water is one of such options. Virtual water refers to the volume of water used in producing a unit food commodity that is traded (Allan, 2003; 2001; 1999; 1997). The strength of virtual water as a potential policy tool derives from the proposition that water-scarce regions can maintain food security by importing water-intensive food commodities from water-abundant regions and thereby save water that can be allocated to alternative uses (Allan, 2003; 2001). In contrast to engineered solutions that only move water to people, the virtual water proposition is an agro-economic solution that highlights the potential of food trade to move food and ‘hidden water’ to people at the same time (Allan, 2003; 1997). In this connection, virtual water also highlights the neglected fact that the entire food system is a ‘business’ that subsists on economic rationality and, therefore, food trade should be seen as part of the solution.

The virtual water proposition is a useful adaptive option because water scarcity is a localized phenomenon due to differences in the spatio-temporal distribution of precipitation and management of local interventions in the hydrological cycle (Yang *et al.*, 2006; Allan, 2003; Yang & Zehnder, 2002). The impacts of climate change on water availability and crop production will also be spatially and temporally uneven (Bates *et al.*, 2008; IPCC, 2007). Thus, disregarding the uncertainties in projections of future precipitation patterns (IPCC, 2007), there are, and there will be, regions of relative water abundance (such as temperate Europe) or relative water scarcity (such as Middle East and North Africa or Mediterranean Europe). All things being equal, the interlocked

relationship between water availability and food production implies that water-scarce regions are most vulnerable to food insecurity, which has potentially far-reaching consequences for socio-political stability and security across multiple scales. It has been shown that effective use of virtual water can augment food security significantly and result in water savings in water-scarce regions (Chapagain & Orr 2009; El-Sadek, 2009; Chapagain *et al.*, 2006; Allan, 2001; 1997).

Food trade has played a key role in the circulation of food across the globe and the development of other key resources, such as land and water, and contributed substantially to socio-economic development and political stability (Defra, 2008; de Fraiture *et al.*, 2007). In monetary terms, global food exports have increased from US\$ 224,000 million to US\$ 913,000 million between 1980 and 2007 (WTO, 2009). Projections of future food demand and supply show that food trade will increase substantially and play an increasing role in food security in the next few decades, but competition for food on the global market is also likely to intensify (Aldaya *et al.*, 2010a; Parry, 2007; Parry *et al.*, 2004). For example, Hongyun & Liange (2007) estimated that a 3% increase in China's food imports will correspond with a 10% reduction in food availability on the global market.

Virtual water offers an opportunity for national and global analysis of food security situations in the context of climate change and water scarcity to inform adaptive food production and trade decisions and policies. As observed by Brichieri-Colombi (2004), "*water resources planning and management should have as its primary object the maximization of some human welfare function in the face of constraints related to resource scarcity and a commitment to minimizing negative social, ecological and economic impacts*". Thus, in the context of potential future water scarcity and the need to

increase food production substantially to satisfy demand, food trade or virtual water flows should be integral to the suite of options for addressing future water and food security issues across varying spatio-temporal scales (Brown *et al.*, 2009; Dabrowski *et al.*, 2009a; Roth & Warner, 2007). There is therefore a need to understand the future drivers and directions of virtual water flows for specific crops and countries. There is also the need for more studies to improve understanding of the advantages and disadvantages of integrating virtual water in water-food security policy and how this can be achieved in different contexts of ecological, political, socio-economic and water availability that underpin food production, trade and consumption (Wichelns, 2010a; 2010b; Neubert & Horlemann, 2008; Brown *et al.*, 2009; Allan, 2003). Specifically, there is the need for empirical studies to improve the evidence base of quantifying virtual water flows and demonstrating the utility of virtual water for policy.

1.3 Rationale, Scope, Aims and Objectives

1.3.1 Rationale and Scope

Climate change projections raise the need for countries to assess their future food production and trade situations. According to Huang *et al.* (2011), the effects of climate change on agricultural production and trade patterns remains unclear. However, the projected increase in variability in precipitation resulting from climate change is likely to cause spatio-temporal shifts in water availability and, consequently, crop production and yields (IPCC, 2007) particularly of cereals, which are the dominant staple food crops, largely grown in rain-fed agricultural systems, and are sensitive to water stresses at critical

growth stages (Anjum *et al.*, 2011a; De Fraiture & Wichelns, 2010). These changes are likely to affect the direction and volumes of trade flows of particularly grains and livestock products (Huang *et al.*, 2010; 2011). In the UK, apart from the significant longitudinal and latitudinal variability in rainfall, climate change is projected to cause drier summers and wetter winters (Jenkins *et al.*, 2009; Murphy *et al.*, 2009), with adverse implications for both winter- and spring-grown crops and challenging water management especially in England and Wales where water scarcity issues are prominent (Charlton & Arnell, 2011). Policies addressing climate change mitigation and adaptation, energy, land use and agricultural water use will also affect future cost of production and trade flows of food commodities. Market forces and economic incentives will also influence farmers' decisions on what crops to produce, technologies to adopt, the quantity of production and, ultimately, food security (Huang *et al.*, 2011).

Cereals (mainly wheat and barley) account for 50% of UK land use for arable crop production (Defra, 2011). In terms of area and quantity harvested, barley is the most important arable crop in Scotland and second only to wheat in the UK (Defra, 2011). Barley plays significant socio-economic roles in the malting industry and animal feed production (Defra, 2011). It is therefore important in UK's food security. There is little information on the effect of climate change on the future production of barley, the associated virtual water flows and the consequences for food security. Currently, the UK is self-sufficient and a net exporter of barley grains (Defra, 2011; FAOSTAT, 2009). Given the importance of barley to the UK, it is important to assess how climate change will affect future UK barley production, self-sufficiency, trade flows and consequences for the production of animal food products. This thesis focuses on the effect of climate change

on the viability of barley as a rain-fed crop across the UK, from the 2030s to 2050s, as a basis for exploring the role of virtual water in water-food security and policy. This thesis is, therefore, different from previous studies of virtual water flows or the water footprint of the UK (e.g. Feng *et al.*, 2010; Yu *et al.*, 2010; Chapagain & Orr, 2008).

In the context of virtual water, the focus on UK is appropriate as it has characteristics amenable to exploring different aspects of the virtual water concept. The UK is a relatively wet country with a high agricultural capability (Knox *et al.*, 2010; Weatherhead, 2008; 2006). Its cereal production is entirely rain-fed (Knox *et al.*, 2010; Weatherhead, 2008; 2006). In addition, the UK is a strong trading nation which has relied extensively on food import to satisfy its food needs since its industrial revolution (Defra, 2008). Even though exigencies after the two world wars boosted domestic production to increase self-sufficiency, the restoration of global peace and stability, coupled with economic motivations, gradually shifted the UK towards increasing food imports (Defra, 2008). Currently, two-thirds of the UK water footprint is external (Chapagain & Orr, 2008) and imported food could constitute over 50% of its total food supply by 2030 (Foresight, 2011). Even during the food crisis of 2008 (due to low global grain supply and high prices), the values of UK's food import and export were US\$ 54 billion and US\$23 billion respectively (WTO, 2009). This made the UK the world's 5th largest food trading country by monetary value, with a large import to export ratio. Moreover, the UK has expressed security concerns over both domestic and international water scarcity. In 2006, British Defence Secretary, John Reid, indicated that British armed forces should be combat-ready for anticipated water wars in the coming years (The Independent, 2006). In business circles, both PepsiCo and Unilever recognized the adverse implications of

growing water scarcity for business in their 2010 reports and committed themselves to reducing the impact of applied water of their farmers operating in water-stressed areas (PepsiCo, 2010; BBC News, 2010). The Water Act (2003) also aims to increase water allocation to domestic use, and reduce agricultural water abstraction. These characteristics make the UK a suitable model country for exploring the relevance of the virtual water concept for water-food security under future conditions.

By focusing on a single crop and a single country, this thesis seeks to contribute to the development of the evidence base for quantifying and evaluating virtual water for water-food security. The conflation of several crops and countries in a single study, which has been the convention in most virtual water studies, masks important inter-crop, international and intra-national differences regarding water use, food use and the role of virtual water in food security. To understand the role of virtual water in a country's water-food security better, a detailed study based on a single (or few) important crops to that country from production to distribution to end uses, vis-à-vis relevant sectoral policies and structural issues, is necessary. It is by this approach that the link between domestic production and international trade, as well as the factors that underpin this link, can be understood.

In order to ease tracking or quantification of different stocks and flows, the main sources of water used in crop production has been classified into green and blue (Hoff *et al.*, 2010; Chapagain & Orr, 2009; Rockström, 2003; 2001). Green water refers to the fraction of precipitation that is stored in the unsaturated zone of soil and is used by crops in evapotranspiration, while blue water refers to surface and groundwater that is available to crops only through irrigation (Hoff *et al.*, 2010; Chapagain and Orr, 2009). Green water

constitutes 80% of water use in global crop production and virtual water flows and it is expected to play a major role in future food production, virtual water flows and water-food security (Chapagain & Hoekstra, 2011; Hoff *et al.*, 2010; Rockström *et al.*, 2009; Chapagain *et al.*, 2006; Rockström, 2003; 2001). Yet, water use of rain-fed crops, and green water consumption in general, is rarely measured (Hess, 2010) as it is considered economically unimportant due to its low opportunity cost (Yang *et al.* 2006). This thesis focuses on future availability of green water for barley production in the UK. Because barley is currently a rain-fed crop in the UK, this thesis does not consider irrigation. The focus on green water also enables analysis of the limitations of current water scarcity concepts for crop production.

Finally, the thesis contributes to addressing the deficiencies of virtual water for policy use that arise from certain conceptual and analytical weaknesses (Wichelns 2010a; 2010b). A substantial part of the virtual water literature has been devoted to coarse quantifications of virtual water flows and water savings based on several crops and countries at the same time (e.g. El-Sadek, 2011; Zeitoun *et al.*, 2010; Dabrowski *et al.*, 2009b; Yang & Zehnder, 2007; Chapagain *et al.*, 2006; Yang *et al.*, 2006; Hoekstra & Hung, 2002). Progress in the virtual water and water footprint literature can be summarized as (a) efforts to improve estimates of virtual water flows and savings by employing sophisticated methods and increasing the number of crops and or countries, (b) methodological expansion to quantify the scale of water pollution in exporting countries, and (c) raising awareness about the hidden effects and dependence of consumers in importing countries on the resources in exporting countries (Wichelns, 2010a). Similarly, the key debate on the relevance of virtual water for policy has revolved and stagnated

around answering the question whether relative water endowments dictate the structure and pattern of food trade, and whether estimated water savings are accurate and useful (Wichelns, 2010a; 2010b; Neubert & Horlemann, 2008). Consequently, trade theories or economic principles have been applied or promoted as a means to explain the structure and direction of virtual water flows (Wichelns, 2010a; 2010b; Novo *et al.*, 2009 Neubert & Horlemann, 2008; Roth & Warner, 2007; Ramirez-Vallejo & Rogers, 2004; Wichelns, 2004; 2001; Allan, 2003; Lant, 2003; Earle, 2001). Such efforts have yielded mostly unsatisfactory results, making some authors suggest that the virtual water concept is inaccurate and irrelevant for policy use (e.g. Ansink, 2010; Ramirez-vallejo & Rogers, 2010). Conceptual and policy issues regarding accuracy and usefulness of estimated water savings have been discussed by Wichelns (2010a; 2010b). The application of trade theories is beyond the scope of this thesis. However, this thesis aims to advance the debate and improve understanding and evaluation of the role of virtual water in water-food security and policy by clarifying the conceptual relationships among the basic components (water scarcity, food trade and food security) of the virtual water proposition. This thesis therefore seeks to strengthen the conceptual linkages amongst the components of virtual water as a basis for understanding and evaluating the relevance of virtual water flows for water-food security and policy.

1.3.2 Aims and Objectives

The overall purpose of this thesis is to improve the evidence base for understanding and evaluating the relationships in the continuum of future crop-water

availability, crop production and crop commodity trade (virtual water), and evaluating the utility of virtual water for water-food security and policy. Specifically, the thesis aims to use the UK as a model country and barley as a model crop to improve understanding of the role of green water availability and the feedback relationships among water scarcity, virtual water and food security in the context of projected changes in climate, land use and population. The information from this research will contribute to scientific opinion that will feed into UK's food security policy and resilience to climate change. Even though the UK and barley are used as a model country and crop respectively, the findings and issues identified will have much wider applications. The specific objectives of the thesis are:

- To evaluate and select appropriate water-driven crop-growth simulation model for estimating the water use and effect of water stresses on barley yield in a northern temperate environment.
- To assess the effect of temporal availability of green water under projected climate change on UK regional barley yields in the 2030s, 2040s and 2050s.
- To quantify future UK national barley demand and supply balances, trade position and potential virtual water flows associated with barley trade.
- To use the findings as a basis to explore and evaluate the utility of virtual water for water-food security and policy.

1.4 Thesis Structure

The current Chapter has presented the context, rationale, aims and objectives of the thesis. Chapter 2 is a literature review on the relevant themes of this thesis: water scarcity and food security relationships, climate change, and options for ensuring food security under water scarce conditions. The methods and results of the thesis are presented in Chapters 3 to 6, each focusing respectively on evaluation of crop-growth simulation models, climate change effects on barley yields, future barley demand and supply balances, and evaluating the utility of virtual water in water-food security and policy. Chapter 7 presents a synthesis of the results and conclusions of the thesis.

CHAPTER 2

LITERATURE REVIEW

This Chapter is organized around the three main themes relevant to the thesis. The first theme presents the interlocked relationship between water and food production, the scale of water requirement for future food production, and the risk of global water scarcity. The limitations of current water scarcity concepts for crop production and the complications of climate change on water availability for food security (as defined in Section 1.1.3) are also presented. The second theme explores the opportunities and challenges of key options for adapting food security to water scarcity. The third theme presents virtual water as a potential complementary tool for ensuring food security under water-scarce conditions, reviews work on virtual water, and explores the issues that potentially need to be addressed to make virtual water an acceptable policy tool.

2.1 Crop Production Depends on Water Availability

Water is crucial for photosynthesis and nutrient uptake by crops. Crops invest about 99% of water they take up into satisfying evapotranspiration (ET) requirements and the remaining 1% into metabolic activities (Hess, 2010; Shahin, 2003). Water constitutes about 70-90% of the fresh weight of actively growing plants (Gardner & Gardner, 1983). The formation and realization of yield potential in crops are regulated by the interaction of light, nutrient and water availability (Rajala *et al.*, 2011). In cereals, for example, water is the primary regulator of yield formation (Rajala *et al.*, 2011; Barnabàs *et al.*, 2008; Araus *et al.*, 2002). Hence, achieving yield potential depends on the availability of water in the

root zone. Water-deficit stress occurs in all agro-ecosystems and is the key limiting factor for crop productivity in most agro-ecosystems, (Barnabàs *et al.*, 2008; Araus *et al.*, 2002; Gardner & Gardner, 1983; Boyer, 1982), especially in semi-arid and arid environments where the evaporative demand of the atmosphere exceeds the water available for crop evapotranspiration (Hoff *et al.*, 2010; Faramarzi *et al.*, 2010a; Rockström *et al.*, 2010; Allen *et al.*, 2006). Water stress in crops refers to a condition in which the water potential and turgor are decreased sufficiently, due to insufficient supply of water, such that normal physiological functions are inhibited (Dai, 2011; Barnabàs *et al.*, 2008; Boyer, 1982).

Owing to the role of water in plant physiology and biomass production, crops respond morphologically, physiologically and biochemically to water stress (Anjum *et al.*, 2011a; Barnabàs *et al.*, 2008; Araus *et al.*, 2002). When plants are exposed to water stress, stand establishment, plant height, leaf area index, and number of leaves are reduced and leaf senescence is accelerated (Khan *et al.*, 2001). These eventually restrict biomass accumulation and yield as radiation and nutrient capture are impaired (Anjum *et al.*, 2011a; Kamara *et al.*, 2003). Physiologically, water stress triggers root to shoot signals that induce stomatal closure, which minimizes further water loss (Kamara *et al.*, 2003; Araus *et al.*, 2002; Khan *et al.*, 2001). Abscisic acid (ABA) is the primary signal or cause of stomata closure although other factors can also contribute (Anjum *et al.*, 2011a; Pinheiro & Chaves, 2011; Araus *et al.*, 2002; Boyer 1982). Stomatal closure, together with leaf senescence, limits photosynthetic capacity and can reduce yield dramatically if prolonged (Anjum *et al.*, 2011a; Kamara *et al.*, 2003; Khan *et al.*, 2001). Anjum *et al.* (2011b) studied physiological response of maize to water stress and reported reductions in net photosynthesis (33.22%), transpiration rate (37.84%), stomatal conductance (25.54%),

water use efficiency (50.87%) and intercellular CO₂ (5.86%) relative to a well-watered control. Biochemically, water stress increases production of reactive oxygen species (ROS) which cause oxidative damage to lipids, proteins, DNA and ultimately cause cellular death (Anjum *et al.*, 2011a; Farooq *et al.*, 2009). The timing, duration and intensity of water stress can reduce overall crop performance and yield even though the extent might vary with species or genotypes, stage of development, and the type of organs or cells affected (Barnabàs *et al.*, 2008).

The dependence of crop production on the timely availability of sufficient water in the root zone makes food security vulnerable to the risk of water scarcity. Due to uncertainties in adaptive responses to anticipated global change, it is not easy to answer the question *how much water will be required to maintain food security at any point in future?* This is further complicated by the fact that future water requirement for food security will not be dictated only by hydro-climates and agronomic management practices, but also by dietary composition and lifestyles (Hanjra & Qureshi, 2010).

2.2 Water Availability for Future Food Security

2.2.1 Water Requirement for Future Food Security

Based on current estimates of water used to satisfy the dietary requirement per person, it is possible to estimate future food requirement and consequently water requirement for food security (Rockström *et al.*, 1999). Normally, a daily dietary energy intake of 2700 kcal of food is considered sufficient for a moderately active person (FAO, 2009; Molden, 2007). Rockström *et al.* (1999) estimated a global average of 1200 m³ cap⁻¹

year⁻¹ water was required to produce an adequate diet in the mid-90s. In 2050, however, 1300 m³ cap⁻¹ year⁻¹ water will be required to produce a projected average diet of 3000 kcal cap⁻¹ d⁻¹ in developing countries (assuming 20% meat content), while 1600 m³ cap⁻¹ year⁻¹ will be needed to produce a diet of 3300 kcal cap⁻¹ d⁻¹ (assuming no change in current food consumption levels, with 30% meat content) in industrialized countries (Falkenmark & Rockström, 2004; Rockström, 2003). This gives a global average of 1340 m³ cap⁻¹ year⁻¹ to produce adequate diets in 2050. The estimated global water required to produce an adequate diet increases crop water requirement from the current 6800 km³ year⁻¹ (with irrigation accounting for 1800 km³ year⁻¹) to a staggering 12,600 km³ year⁻¹ by 2050 (Rockström, 2003). The additional 5800 km³ year⁻¹ that will be required is more than threefold the volume of water currently used in irrigation (Rockström, 2003). Similarly, using a value of 3000 kcal cap⁻¹ d⁻¹, de Fraiture *et al.* (2007) estimated that additional 5600 km³ year⁻¹ of water will be required in 2050, with irrigation accounting for 800 km³ year⁻¹. They estimated that there will be a potential water supply gap of about 3300 km³ year⁻¹, with devastating consequences for stability of food security.

Additionally, to achieve a doubling of food production by 2050 (FAO, 2009), current global irrigated area will have to increase by almost twofold (Tilman *et al.*, 2001) and irrigation water supply by about 35% (Spring, 2009). Rockström *et al.* (2009) estimate that, at current irrigation efficiencies, about 8,500-11,000 km³ water will be required annually to achieve the required doubling of food production by 2050. It is noteworthy that the full extent of potential dietary shift to ‘western diets’ (rich in meat and dairy products) in developing countries, due to economic improvements, is not known accurately (Hanjra & Qureshi, 2010). This shift, as already observed in China, for

example, will have substantial effect on the overall water requirement for food production in the coming years (Hanjra & Qureshi, 2010). Production of meat and other animal food products makes significantly higher demands on water resources than the production of food-crop products (Chapagain & Hoekstra, 2008; Chapagain *et al.*, 2006; Beckett & Oltjen, 1993). The question therefore remains whether there will be sufficient water to satisfy this huge water requirement across the world, and whether this volume of water can be made available for food security without disturbing the tenuous balance of water supply to people, industry and ecosystem services.

2.2.2 Risk of Global Water Scarcity

Several definitions of water scarcity exist that reflect differences in the context and scale of application. According to Rijsberman (2006), an individual who is unable to access safe and affordable water to meet such personal basic requirements as drinking, washing, livelihood, hygiene, etc. is said to be *water insecure*; and an area is *water scarce* when a significant proportion of the population become water insecure for a prolonged period of time. Rockström *et al.* (2009) distinguish between water stress or water shortage (a temporary condition in which access to water is constrained) and water scarcity (a long-term condition in which supply lags behind demand). Other authors have used the term ‘water poverty’, defined as *a situation where a nation or region cannot afford the cost of supplying clean water to all people at all times* (Feitelson & Chenoweth, 2002). The European Environment Agency (EEA, 2010) defines water scarcity as the incidence of insufficient water resources to satisfy long-term average requirements. That is, long term

water imbalances, combining low water availability with a level of water demand exceeding the supply capacity of the natural system. This definition is adopted in this thesis. Water scarcity is already a global problem and could become acute in the next few decades (WRI, 2003).

Presently, 1.2 billion people in developing countries alone lack access to safe drinking water and about 2.6 billion people lack adequate water for basic sanitation (Vörösmarty *et al.*, 2010; Bartram, 2008; UNDP, 2006). Inadequate access to safe drinking water and sanitation accounts for 2.18 million deaths annually on a global scale, out of which 75% are children under five years old (Pruss *et al.*, 2002). It is also estimated that about 1.7 billion people depend on water-scarce catchments where water supply is less than $1000 \text{ m}^3 \text{ cap}^{-1}$ (WRI, 2003). At the end of the 20th century, global water withdrawal was more than twice the rate of population growth, resulting in several countries experiencing water stresses (see Figure 2-1). It is likely that the pattern of water stress in Figure 2-1 will continue into the future due to rising demand for water from all water use sectors, with adverse implications for food security.

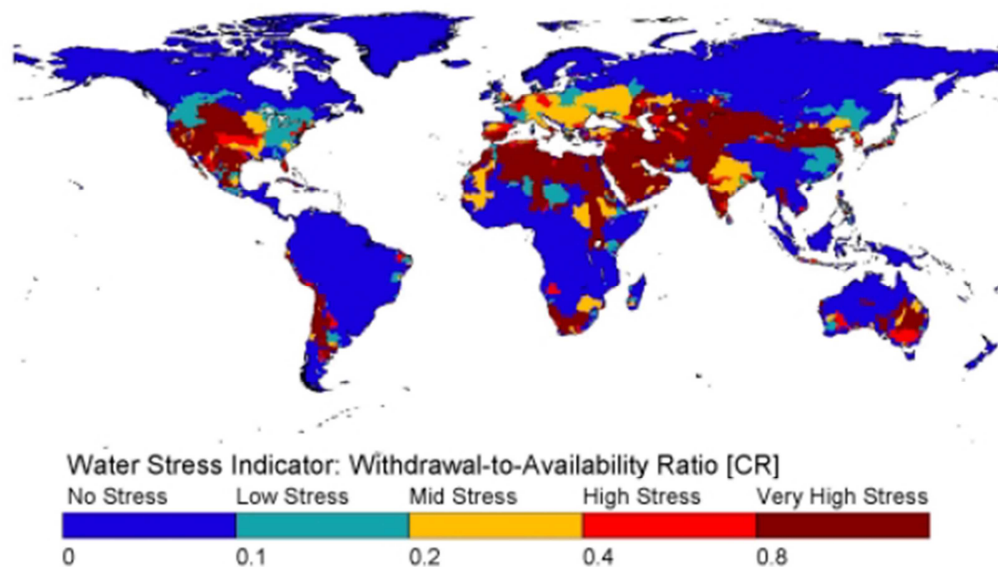


Figure 2-1: Global water stress indicated by the withdrawal to availability ratio (or the criticality ratio) for 1995, modelled using the WaterGap 2.0 model. Figure taken from Alcamo *et al.* (2000).

Global change factors such as population growth, urbanization and socio-economic development are likely to accelerate and amplify water scarcity through intensive competition among water use sectors. Reports on future water demand based on population projections alone indicate that, by 2025, about 3.5 billion people (48% of the world population) will likely live in overexploited river basins and 2.4 billion people under severe water-scarce conditions (WRI, 2003). By 2050 a third of the global population could live in water-scarce countries (Falkenmark *et al.*, 2009; Yang & Zehnder, 2007). The number of urban dwellers is projected to increase rapidly for the next four decades, accounting for two-thirds of the global population in 2050, with the greatest changes occurring in developing countries (Marcotullio *et al.*, 2008; UNDP, 2006). As a result, municipal water use could rise from 257 in 2000 to 536 billion m³ in 2050 for non-OECD countries (>100% increase), compared to an increase from 162 to 178 billion m³ (10%) in OECD countries (Hughes *et al.*, 2010). The pattern of increase in industrial

water allocation is projected to be similar to municipal water use for OECD and non-OECD countries (Strzepek & Boehlert, 2010). In Europe, the share of the energy sector is likely to be substantial. For example, as of 2010, the energy sector accounted for 45% of water allocation across Europe, having overtaken irrigation water use which has reduced to 22% of the total (EEA, 2010). Increases in the volume of water required for environmental flows (i.e. minimum volume of water required to sustain the normal functioning of the aquatic ecosystem) through legislative instruments (e.g. the EU Water Framework Directive) can substantially limit water withdrawals. Environmental flows can be as high as 30-50% of baseflows in some aquatic ecosystems (Revenga & Smakhtin, 2003). Indeed, some river basins and countries considered as not suffering water scarcity become water-scarce candidates when environmental flow requirements are considered (De Fraiture *et al.*, 2008; Revenga & Smakhtin, 2003). It has been reported that, even without climate change, increases in environmental flow requirements could have reduced water availability for agriculture by 9.7% of global mean agricultural water withdrawal in 2000 (Strzepek & Boehlert, 2010). Thus, there is considerable risk of increasing water scarcity in the next few decades, with a potential to reduce water allocation to food production (Ohlsson, 2000).

2.2.3 Limitations of Water Scarcity Perspectives to Food Security

2.2.3.1 Water Scarcity Perspectives

As reflected by the various definitions of water scarcity, perspectives on water scarcity differ depending on the context and the spatio-temporal scale considered. These

differences are captured by the conceptions of the causes or types of water scarcity and the attendant indicators. Molle and Mollinga (2003) distinguish between natural and induced water scarcity, where natural water scarcity is due to nature or biophysical factors limiting water availability as can be found in desert or arid areas, while induced water scarcity occurs from human activities that reduce availability or constrain access to water. Vörösmarty *et al.* (2005) used the same distinction when they referred to climate- and human-induced water scarcity. Ohlsson (2000) distinguishes three types of water scarcity: demand-induced, supply-induced and structurally-induced water scarcity. They defined demand-induced water scarcity as a situation where demand exceeds supply or natural renewal capacity of the system due to, for example, increase in population or requirement of other water use sectors. Supply-induced water scarcity occurs where water supply falls below a threshold or a long-term average requirement due to drought, lowering of water table, water depletion and deterioration of water quality. Structural water scarcity is where access to water is constrained by low economic capacity or other social, political, institutional and technical factors. Rijsberman (2006) suggested two main types of water scarcity: economic and physical water scarcity. Physical water scarcity refers to a situation in which there is higher water demand to supply ratio. Economic scarcity or social water scarcity relates to constrained access to sufficiently available water as a result of inadequate infrastructure and low investment potential in water resources development. Thus, economic water scarcity reflects a limited economic capacity to mobilize available water. In all, water scarcity is caused by natural or biophysical factors that limit availability (e.g. precipitation and reservoir characteristics) and human factors (e.g. poor water infrastructure, flow control, costs, institutional constraints, high demand, etc.) that

constrain ability to mobilize or access sufficient water (Rockström *et al.*, 2009; Rijsberman, 2006).

There are three common threads running through these perspectives. First, water scarcity denotes a condition in which available water is insufficient to meet average requirement or demand. Second, water scarcity is limited to water available for human use and, third, social access to water is the main concern. Hence, water scarcity is indicated in three main ways: (1) The withdrawal to availability ratio indicator, which compares total water withdrawal with the renewal capacity or total available water of the system and an area is normally considered water-scarce if it has a ratio of 0.4 (or 40%) and above (Oki & Kanae, 2006; Vörösmarty *et al.*, 2005; 2000; Alcamo *et al.*, 2003; 1997; Raskin *et al.*, 1997). (2) The per capita water availability indicator, which is the ratio of available water resources to a given population that depend on the water resource under consideration. This indicator therefore measures the amount of water potentially available to an individual in a given population. Here, water scarcity exists if per capita water availability is $1000 \text{ m}^3 \text{ year}^{-1}$ or less compared to the sufficient amount of $1,700 \text{ m}^3 \text{ cap}^{-1} \text{ year}^{-1}$ (Rockström, *et al.*, 2009; Rockström, 2003; Salameh, 2000; Shiklomanov, 1998; Falkenmark *et al.*, 1989). This indicator is widely used because it is intuitive and easy to measure. (3) A hybrid indicator combining the strengths and minimizing the weaknesses inherent in the previous indicators. Here, the physical available water is combined with a form of social adaptive capacity (society's capacity to optimally develop, exploit and manage water resources) to generate an index of water scarcity. Examples include the social water scarcity index (Ohlsson, 2000), water poverty index (Sullivan *et al.*, 2003;

Feitelson & Chenoweth, 2002), and the watershed sustainability index (Chaves & Alipaz, 2007).

2.2.3.2 Limitations of Current Water Scarcity Perspectives for Food Security

Current definitions and related indicators of water scarcity are focused on water availability for human populations and the socio-economics of water supply. They do not reflect an interest in integrating the hydrological cycle and water use in all sectors in the context of a unified sustainable water management framework (Brichieri-Colombi, 2004). The question therefore remains whether existing water scarcity perspectives adequately capture water availability and use in agro-ecosystems.

Water for crop production originates from two main sources: precipitation and irrigation. The fraction of precipitation that is retained in the unsaturated root zone for crop use has been classified as ‘green water’, while water introduced to the root zone through irrigation, using surface and groundwater, has been classified as ‘blue water’ (Hoff *et al.*, 2010; Chapagain & Orr, 2009; Rockström *et al.*, 2009; Rockström, 2003; 2001). These definitions arguably omit or mask the use of water harvested from rainfall by direct interception or by collecting runoff for crop production (Wisser *et al.*, 2010). Globally, two-thirds of precipitation recharges the green water pool while the remaining third recharges the blue water pool (Hoff *et al.*, 2010). A number of studies indicate that green water use in global crop production is about four- to five-fold greater than blue water use (e.g. Aldaya *et al.*, 2010a; Hanasaki *et al.*, 2010; Hoff *et al.*, 2010; Liu & Yang,

2010; Liu *et al.*, 2009; Rockström *et al.*, 2009). Unfortunately, green water use in agro-ecosystems is rarely measured (Hess, 2010).

Current water scarcity perspectives have limited use for crop production as they pay more attention to blue water supply and are, thus, only relevant for food security in the context of irrigation where competition among water use sectors is escalated. Current water scarcity perspectives neglect the role and value of green water in food production (Aldaya *et al.*, 2010a; Hoff *et al.*, 2010). Perhaps, this is because green water is of little value for direct human use (Yang *et al.*, 2006) but it is certainly critical for understanding the effect of water scarcity on food security, ecosystem services and blue water dynamics across varying scales (Rockström *et al.*, 2009; 2007). Accounting for green water availability in agro-ecosystems substantially modifies the perceived threat of water scarcity to food security and shows the importance of improving green water productivity to increase the resilience of current and future global food security (Hoff *et al.*, 2010; Rockström *et al.*, 2009; Falkenmark, 1997). It is therefore important to expand the current conception of water scarcity to include green water and to take an ecosystem-wide view in relation to the hydrological cycle. This is important to direct attention to the imperative to incorporate green water into water resources management frameworks in the context of adaptation planning to climate change and future food security needs (Brichieri-Colombi, 2004). Moreover, with respect to crops, water scarcity would not be limited to the mere physical presence of water in the root zone, but also the ability of crops to abstract the water. Thus, in terms of the water scarcity and food security relationship, there is the need to expand the concept of water scarcity from the perspective of meteorological drought to agricultural or physiological drought (Dai, 2011) which is more relevant to the seasonal

and intra-seasonal water availability and use by crops (Barnabàs *et al.*, 2008). Hence, in order to be relevant for food security, concepts of water scarcity should incorporate the soil-water-crop continuum over space and time.

2.3 Climate Change Complicates Water Availability for Food Security

Climate is the long-term pattern of weather of a place and is normally described by the average seasonal occurrence of temperature and precipitation over a 30-year period. Fluctuations in the average weather pattern over short time scales constitute climate variability. Climate change is *a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer* (IPCC, 2007). According to the UNFCCC (1994), “adverse effects of climate change” refers to harmful impacts of climate change on ecosystems, socio-economic systems and human and animal welfare. According to the 4th and 5th Assessment Reports (IPCC, 2007; 2013), warming of the climate system is “unequivocal” and is largely due to human activities. Since 1850, 11 out of the 12 warmest years occurred between 1995 and 2006 (IPCC, 2007). The IPCC (2007; 2013) has explained the scientific basis and presented evidence of global climate.

2.3.1 Projected Changes in Temperature and Precipitation

Projections suggest that the global temperature will rise between 1.8 and 4.0 °C (under the low, B1, and the high, A1FI emissions scenarios, respectively) by the end of this century (IPCC, 2007). Generally, warmer temperatures are projected and the greatest

increases in temperatures will occur over land and at higher latitudes in the Northern hemisphere and least over the Southern Ocean near Antarctica (Miraglia *et al.*, 2009; Meehl *et al.*, 2007). Outputs from the Special Report Emission Scenario (SRES) indicate that the climate will continue warming by 0.2 °C per decade for the next two decades or 0.1 °C per decade even if radiative forcing remains constant at the 2000 level; and projections of warming up to 2050 are not affected by different SRES scenarios (Meehl *et al.*, 2007). Moreover, warming in the first half of the century is irreversible due to prior emissions and will not be affected by mitigation policies (Solomon *et al.*, 2007). In the mid and high latitudes, frequent hot days and nights and heat waves are projected. Frost days are also expected to decrease. Europe will experience increases in annual mean temperature greater than the global mean. Summer and winter warming will be highest in the Mediterranean and northern Europe respectively while maximum summer temperatures in southern and central Europe are likely to go up (Christensen *et al.*, 2007).

Regarding precipitation, high latitudes and moist or humid tropical areas are very likely to experience increases in mean precipitation, while precipitation in the subtropics and mid-latitudes are likely to decrease by up to 20% by the end of the century (Solomon *et al.*, 2007). The frequency of heavy precipitation events will increase and create problems of flash flooding (IPCC, 2007). In the subtropics and mid-latitudes, there will be higher variability in precipitation events and significant potential for drought during summer. It is very likely that mean annual precipitation will decrease in southern Europe (especially in the Mediterranean region) and increase in northern Europe (Bates *et al.*, 2008). However, central Europe is likely to experience higher winter but lower summer mean precipitation (Christensen *et al.*, 2007), with greater variability and a high potential

for summer drought risk in central to southern Europe (Christensen *et al.*, 2007; EEA, 2005).

2.3.2 Implications of Projected Climate Change for Water Availability

The projected changes in precipitation and temperature will alter the long-term mean water supply and demand (Strzepek & Boehlert, 2010; Bates *et al.*, 2008; Solomon *et al.*, 2007). Spatio-temporal shifts and quantitative changes in precipitation, together with intense and more frequent extreme events will affect the quantity and quality of water available. Runoff is the major avenue to renewing a region's freshwater supplies. Runoff is likely to increase in regions where increased precipitation is projected (e.g. high latitudes and the moist tropics) but will be impaired in mid-latitudes and some areas of the dry tropics (Bates *et al.*, 2008). Figure 2-2 shows a projected effect of climate change on water availability.

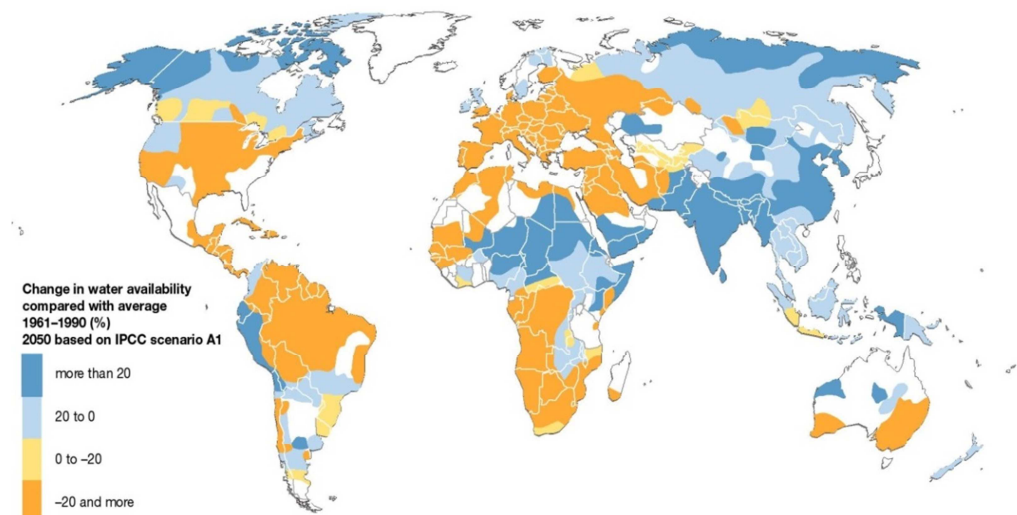


Figure 2-2: Projected change (%) in global water availability in 2050 from that of the baseline period (1961-1990) under the IPCC A1 emission scenario. Figure taken from UNEP GRID-A Vital Water Graphics 2, www.grida.no/publications/vg/water2/page/3294.aspx

Warmer temperatures will increase evapotranspiration (ET), dry up soils and reduce runoff. Simulations of the effects of climate change on European summer soil water content and ET between 2070 and 2080 show a sharp north-south gradient (Figure 2-3). Apart from northern Europe which is projected to have up to 2% increase in soil water content by 2080, a larger area of Europe is projected to have decreases of up to 7%, with the highest being in Mediterranean areas. Projected ET shows a similar pattern, with positive changes of 0.1-0.5 mm d⁻¹ in northern Europe and negative changes of the order of 0.5 mm d⁻¹ in southern Europe (Calanca *et al.*, 2006). Soil water content is projected to decrease in the UK but ET is projected to increase in the south-east of England and decrease slightly in western Scotland and Northern Ireland.

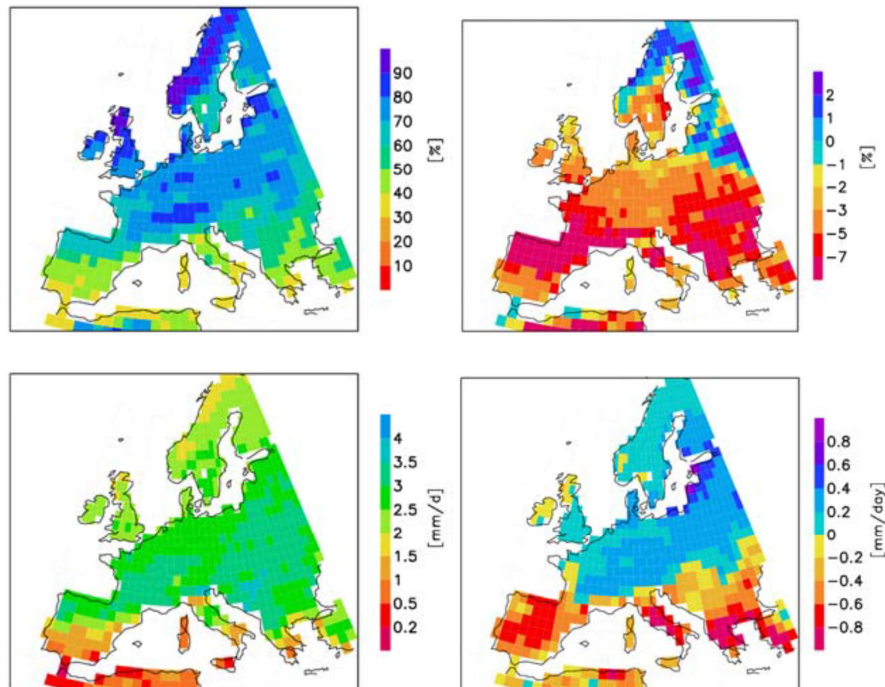


Figure 2-3: Projected changes in European summer mean soil water content (%) in the 2080s (upper right) relative to that of the baseline period (1961-1990, upper left) and projected changes in European summer mean ET (mm d⁻¹) in the 2080s (lower right) relative to that of the baseline period (lower left). Figure taken from Calanca *et al.* (2006).

Shifts in precipitation patterns can have adverse effects on crop production especially when peak water availability does not coincide with peak water demand by crops (Bates *et al.*, 2008). Agro-ecosystems are sensitive to changes in seasonal precipitation and its distribution, soil water storage, ET and runoff. Higher ET requirement and reduced precipitation can potentially increase net irrigation requirement. It is projected that climate change can increase global net irrigation requirements by as much as 45% by 2080 at current irrigation efficiency and by 20% with significantly improved irrigation efficiency (Fischer *et al.*, 2007). Warmer climate will also increase crop water demand per unit area and, therefore, irrigation water requirement substantially (Olesen & Bindi, 2002). Frequent and prolonged drought can increase physical water scarcity and irrigation requirement, while frequent flooding events can lower water quality, and severely overwhelm water management systems (Dai, 2011; Bates *et al.*, 2008), or reduce crop yields through waterlogging which can cause anoxia in plant roots and mineral toxicities by altering the redox state of the soil solution. Increased variability in precipitation will also raise the imperative for irrigation in rain-fed cropping systems. Finally, warmer temperatures can also increase competition for water by increasing demand in most water use sectors, particularly the domestic and energy sectors (Strzepek & Boehlert, 2010).

Apart from altering water balances, climate change will also affect crop yields, both directly and indirectly. Projected increases in atmospheric CO₂ concentration could stimulate increased stomatal conductance in C₃ crops and thereby increase yields, particularly in mid- and high-latitude regions where temperatures approach optimum for

crop growth (DaMatta *et al.*, 2010). However, this potential gain can be offset by other climate change effects such as warming and high water stress. The relatively higher capacity of C₄ crops to concentrate CO₂ and limit photorespiration makes them more productive than C₃ crops (DaMatta *et al.*, 2010; Easterling *et al.*, 2007). Because higher photorespiration tends to restrict CO₂ assimilation and gains from photosynthesis, there is a caveat that warmer temperatures can potentially increase photorespiration and offset gains from elevated atmospheric CO₂ concentration (Easterling *et al.*, 2007). Further, higher CO₂ uptake is invariably associated with higher transpiration (Kimball & Bernacchi, 2006). Under warmer conditions and decreased water supply, stomatal closure induced by water stress can potentially elevate leaf and canopy temperature and thereby reduce photosynthesis (Hanjra & Qureshi, 2010; Kimball & Bernacchi, 2006). Further, DaMatta *et al.* (2010) argue that since the effects of elevated atmospheric CO₂ concentration and warmer temperature are not known to be additive, it is probable that warmer temperatures can neutralize the potential gains from elevated atmospheric CO₂ concentration.

The source-sink relationship is an important determinant of dry matter production in crops (Dingkuhn *et al.*, 2007; Venkateswarlu & Visperas, 1987). The source refers to the potential capacity of the crop to synthesize food (or the organs or sites where food materials are synthesized), while the sink refers to its capacity to use or store photosynthetic products (Dingkuhn *et al.*, 2007; Venkateswarlu & Visperas, 1987). Ainsworth & Rogers (2007) have suggested that the relatively weak sink capacity of C₃ crops can cause carbohydrates saturation in source organs which will ultimately constrain further CO₂ assimilation and photosynthesis. In all, there are uncertainties regarding

estimates of cost and benefit of elevated atmospheric CO₂ for increased crop yields as the mechanisms of plant respiratory responses to CO₂ enrichment vis-à-vis warmer and water stress conditions remain unresolved (Hanjra & Qureshi, 2010).

Finally, under warmer temperatures, heat-stress can shorten crop phenology and reduce radiation capture, upset net carbon balance, reduce seed set and pollen viability, cause grain sterility and yield losses (DaMatta *et al.*, 2010; Porter & Semenov, 2005). Crops can senesce earlier and quicker than normal under warmer and water deficit conditions, with adverse effects on yield (Barnabàs *et al.*, 2008). Photosynthetic capacity is also sensitive to warmer temperatures due to the heat lability of Rubisco and the limitation of electron transport in chloroplasts (Ainsworth & Rogers, 2007). Ainsworth & Rogers (2007) report that, at 35 °C and above, photorespiration increases over photosynthesis resulting in lower net carbon gain. It is reported that a combination of warmer temperatures and reduced precipitation can decrease South Asian wheat production by 50% by 2050, which is equivalent to 7% of global crop production (De Fraiture *et al.*, 2008). Cline (2007) suggests that developing countries can potentially suffer a 10-25% overall decline in agricultural production due to climate change. However, with sufficient water supply, warmer temperatures could be beneficial to crop production. For example, it is projected that an increase in temperature between 1 and 3 °C could increase crop yields in high latitudes and moist tropical areas (Solomon *et al.*, 2007).

2.4 Maintaining Food Security under Water-Scarce Conditions: Key Options

Traditional options for maintaining food security include expanding croplands, using croplands more intensively, and bridging existing yield gaps (Gerbens-Leenes & Nonhebel, 2004). These depend on there being sufficient water availability to support crop production. In the context of future food security under water scarcity conditions, however, two key options can be considered. The first involves mechanisms to improve crop water use efficiency (WUE) or water productivity (WP) without incurring high yield penalties (Passioura, 2006). The second option involves measures to use available food efficiently in order to improve water use efficiency along the chain from post-harvest to food consumption. This goal can be achieved through effort to reduce food waste or losses from farm-to-fork (Smith, 2012; Gerbens-Leenes *et al.*, 2010). According to Smith (2012), measures to reduce food waste or losses should be complemented with efforts to manage food demand and reduce diversion of food from direct consumption to non-food uses such as raw material for biofuel, animal feed and other industrial and medicinal products. An important option that has not hitherto received the attention it deserves is virtual water which can be used as a complementary tool to reduce the effect of water scarcity on food security.

2.4.1 Improving Water Use Efficiency and Drought Tolerance

The imperative to increase crop WUE not only arises from increasing water scarcity but also the fact that over a third of the land in the world is located in semi-arid and arid hydro-climatic environments (Ali & Talukder, 2008). According to Morisson *et*

al. (2008), however, all agro-ecosystems are physiologically and physically ‘water-limited’ for plant growth to some extent. Hence, it is not helpful to make a distinction between ‘wet’ and ‘water-limited’ environments when thinking about addressing the urgent question of improving crop WUE or WP. It is therefore important, in the face of projected water scarcity, to take a global view of WUE improvement to assure food security (Zwart *et al.*, 2010).

Crop WUE has different meanings in different contexts and scales (Ali & Talukder, 2008; Parry *et al.*, 2005). For example, in an economic application, WUE can be equated to the ratio of the monetary value of crop yield to the volume of water input. To the crop physiologist, WUE might refer to the ratio of CO₂ gain per unit water transpired (i.e. leaf-scale efficiency, the so-called instantaneous WUE, WUE_{inst}) or net CO₂ assimilation relative to stomatal conductance (the so-called intrinsic WUE, WUE_{int}) (Ali & Talukder, 2008; Morisson *et al.*, 2008; Tambussi *et al.*, 2007). However, in the context of water scarcity and food security, WUE has been captured by the phrase ‘*more crop per drop*’, which is a call to produce more food with the same or reduced water input. This coincides with the agronomic or whole crop-level (yield-related) WUE. Consequently, WUE in this context refers to the ratio of the yield of harvested product to the volume or depth of water applied in irrigation or lost in evapotranspiration (Ali & Talukder, 2008; Morisson *et al.*, 2008; Tambussi *et al.*, 2007; Zwart & Bastiaanssen, 2004).

The need to improve crop WUE is already a topical issue in agriculture and substantial research effort has been devoted to the subject (Ali & Talukder, 2008; Condon *et al.*, 2004; Rockström, 2003; Araus *et al.*, 2002). Increasing WUE requires favourable manipulation of environmental, physiological and genetic factors that moderate crop water

consumption without decreasing yield. The employment of these manipulations to improve crop WUE can be regarded as successful if three main interlinked goals are achieved (Morisson *et al.*, 2008; Passioura 2006; Condon *et al.* 2004): (i) increased water availability for transpiration over unproductive water losses, (ii) increased effectiveness of CO₂ assimilation and biomass production per unit transpiration (i.e. increased transpiration efficiency) and (iii) high partitioning of biomass towards the harvested product (i.e. greater harvest index).

Studies on WUE of crops support the widely held belief that there is scope and opportunity for improving it, especially in tropical or developing countries where the interactions of high atmospheric evaporative demand, variability in rainfall and low external inputs increase crop water requirement or reduce yields (Tambussi *et al.*, 2007; Condon *et al.*, 2004). Cereals are the most water-intensive and widely cultivated crops. The WUE of well-managed cereal crops, free from disease and pests and without nutrient or water stress, is approximately 2 kg grain m⁻³ water (Passioura, 2006). Globally, the range of published WUE values from field experiments are large for wheat (0.6 – 1.7 kg grain m⁻³), rice (0.6 – 1.6 kg grain m⁻³) and maize (1.1 – 2.7 kg grain m⁻³), with averages of 1.09, 1.09 and 1.80 kg grain m⁻³, respectively (Zwart & Bastiaanssen, 2004). Zwart *et al.* (2010) used remote sensing and modeling approach to determine WUE of wheat on a global scale. They reported an average of 0.86 kg grain m⁻³, with a maximum value of 1.80 kg grain m⁻³ under irrigated conditions. The highest WUE values of rain-fed wheat (kg grain m⁻³) were found in temperate Europe in countries such as Ireland (1.45), France (1.42), UK (1.36) and Germany (1.35). Using more recent data, however, Liu *et al.*, (2007a) made similar observations but reported WUE values of wheat (kg grain m⁻³) as

1.89 (Ireland), 1.80 (UK), 1.47 (Germany) and 1.45 (France). The WUE of wheat in a number of major producing countries is below 1 kg grain m⁻³ (Figure 2-4). The WUE of cereals in developing countries are lower compared to those in developed countries (Ali & Talukder, 2008). The large range of WUE values indicates a potential for improvement, particularly in agro-ecosystems where other stresses such as limited nutrients supply exacerbate the effect of water deficits on yield (Ali & Talukder, 2008). However, vapour pressure deficit is inversely related to WUE but decreases with latitude (Zwart *et al.*, 2004). It is therefore expected that crop production located in higher latitudes will have higher WUE and is highly favourable to increasing crop WUE in the future (Zwart *et al.*, 2004; Araus *et al.*, 2002).

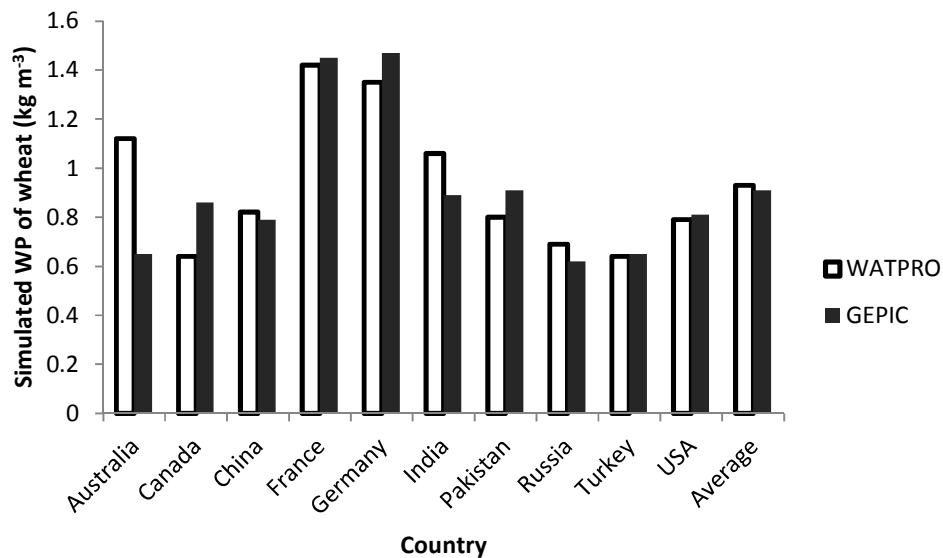


Figure 2-4: Water productivity (WP) of wheat in ten major producing countries, simulated with the WATPRO model and GEPIC model. WATPRO data taken from Zwart *et al.* (2010) and GEPIC data from Liu *et al.* (2007a).

2.4.1.1 Measures, Opportunities and Challenges to Improving Crop WUE

2.4.1.1.1 Agronomic Options

Agronomic practices are aimed at managing crop environments to optimize resource capture and use and, ultimately, to achieve high yields. All things being equal, improved agronomic practices could have substantial positive effect on improving crop WUE in future (Passioura, 2006). Several agronomic practices can be employed to shift evaporative losses to transpiration, save water, and retain more available water in the root zone for crop consumption (Rockström *et al.*, 2007; Passioura, 2006; Parry *et al.*, 2005). Examples include the employment of precision irrigation, quality seed, seed priming, timeliness and appropriate depth of sowing, as well as appropriate plant population density. These measures substantially influence seedling emergence, establishment, canopy development and competitiveness against weeds in resource capture (Passioura, 2006; Parry *et al.*, 2005). *Sustainable intensification* is now being promoted, in both research and policy arenas, as a potentially effective route to increasing food production (Smith, 2012; Firbank *et al.*, 2008); and this also raises the question of land use efficiency. However, the efficacy of sustainable intensification in increasing productivity and its full implications for water resources, biodiversity, ecosystem services and overall environmental sustainability remain to be identified (Smith, 2012; Firbank *et al.*, 2008; Matson *et al.*, 1997).

Soil and water conservation practices, combined with soil fertility and organic matter management will improve water availability and WUE by improving soil structure, infiltration and water retention in the root zone, as well as reducing erosion and

evaporation by modifying surface energy (Hatfield *et al.*, 2001). A review by Hatfield *et al.* (2001) clarifies the soil management practices and the extent to which they contribute to WUE. Examples of such practices include mulching, appropriate tillage, organic matter management and soil fertility management. As Hatfield *et al.* (2001) indicate, there is huge scope for improvement in soil management with the view to improving crop WUE. For example, conservation tillage holds much promise for WUE and yield improvement in Europe, but more work remains to be done to strengthen the evidence for wider adoption (Holland, 2004). Equally important is the management of irrigation scheduling, the volume of water applied and technical efficiency to improve irrigation effectiveness (Ali & Talukder, 2008). Deficit irrigation (application of water below the amount required to satisfy a crop's maximum ET needs) and water harvesting are gaining practical and research attention (Wisser *et al.*, 2010; Fereres & Soriano, 2007). This is because of their demonstrated superior ability to save water and improve WUE over conventional full irrigation (Wisser *et al.*, 2010; Fereres & Soriano, 2007). However, to reduce uncertainties and risks (such as yield penalties) associated with deficit irrigation, it has been suggested that thresholds of yield response to deficit irrigation by different crops in different agro-ecosystems need to be established (Fereres & Soriano, 2007; Tambussi *et al.*, 2007). This might also highlight the need to revise traditional guidelines on irrigation in response to changing soil water availability (Ali & Talukder, 2008). Access to non-conventional water (such as desalinated seawater and highly brackish surface and groundwater) and marginal quality water resources (such as domestic, municipal and industrial wastewater and agricultural drainage) will help increase water availability for crop production (Qadir *et al.*, 2007).

As observed by Passioura (2006), soil-crop-water management is a primary lever for improving soil water availability for crop use and crop WUE under future water scarcity conditions. For example, Rockström *et al.* (2007) show that by shifting evaporative losses to transpiration in developing countries, cereal yields can be increased from the current 1.5 – 2 t ha⁻¹ to 3.5 – 4 t ha⁻¹ by 2030 – 2050, with corresponding reductions in water requirement for food production by 28% (1,150 km³ year⁻¹) in 2030 and 45% (2,300 km³ year⁻¹) in 2050. Thus, not only will such measures, if adopted, lead to improvement in WUE but also significantly bridge the yield gap in under-performing agro-ecosystems (Falkenmark *et al.*, 2009; Rockström *et al.*, 2007; 1999).

2.4.1.1.2 Physiological and Breeding Options

Selecting for traits or manipulating physiological processes that influence crop water consumption, biomass production and yield presents both opportunities and challenges for improving crop WUE and yield simultaneously (Araus *et al.*, 2002). The WUE at the leaf-scale (WUE_{int}) can be improved by either increasing photosynthetic capacity or lowering transpiration (and for that matter, stomatal conductance) or both simultaneously (Morisson *et al.*, 2008). Due to the relationship between photosynthesis and stomatal conductance (see explanation under Figure 2-5), achieving higher photosynthetic capacity and WUE remains a huge breeding challenge (Tambussi *et al.*, 2007; Parry *et al.*, 2005; Araus *et al.*, 2002). To achieve genotype 4 (G4, Figure 2-5), more work is required to improve understanding of the genetic basis for the required anatomical and physiological alterations (Morisson *et al.*, 2008; Tambussi *et al.*, 2007).

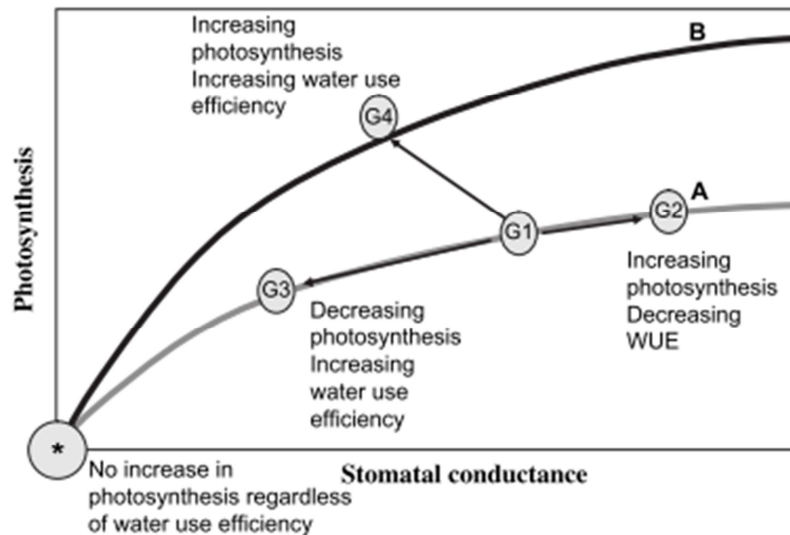


Figure 2-5: A generalized relationship between photosynthesis and stomatal conductance. Converting a genotype G1 into G2 will increase photosynthesis but decrease WUE. Conversely, converting a genotype G1 into G3 will increase WUE but decrease photosynthesis. Achieving higher photosynthesis and WUE requires shifting curve A towards curve B. This can only be achieved through (a) CO₂ concentrating mechanisms, (b) increased mesophyll conductance to CO₂ or (c) increased Rubisco specificity factor. Figure taken from Parry *et al.* (2005).

Results on the effect of the relationship between transpiration efficiency, stomata conductance and growth rate are mixed (Tambussi *et al.*, 2007; Parry *et al.*, 2005). Nevertheless, it has been reported that increase in transpiration efficiency correlates with reductions in stomatal conductance, leading to reduced growth rate and potential yield reductions (Parry *et al.*, 2005). This indicates (as observed also in Figure 2-5) that selecting or breeding for high leaf-level WUE could be counterproductive due to potential yield penalties and, thus, a scope for further work to translate improved relationships to increased yield (Parry *et al.*, 2005). There is the need, therefore, to determine an acceptable tradeoff between WUE and yield penalty. Passioura (2006) warns that breeding for high yields under water-scarce conditions could be risky due to the high input

requirement for fertilizer and water. Where severe drought is frequent, yields can also be reduced substantially, or there might even be total crop failure, regardless of gains made through breeding.

Moreover, leaf-level WUE (WUE_{inst}) does not translate to whole crop-level or yield-level WUE (WUE_{yield}) and this connection should be explored further (Morisson *et al.*, 2008). For example, carbon isotope discrimination ($\Delta^{13}C$) has been shown to be a key potential breeding target to be manipulated for increasing transpiration efficiency. Low $\Delta^{13}C$ is associated with high CO_2 assimilation and transpiration ratio (Morisson *et al.*, 2008; Condon *et al.*, 2004; Araus *et al.*, 2002). Unfortunately, this relationship observed in leaves or individual plants in pot studies does not translate into field-scale or yield WUE (Condon *et al.*, 2004). Reasons that have been advanced for the variable relationship between $\Delta^{13}C$ and yield include differences in flowering dates, plant height and, most importantly, that the low $\Delta^{13}C$ -high transpiration efficiency relationship is a conservative trait in cereals in terms of water use and, possibly, growth rate (Condon *et al.*, 2004). To improve yield-level WUE, breeding for early vigour to reduce surface evaporation is a better target for Mediterranean type of environments where seasonal rainfall distribution is skewed to early growth stage (Condon *et al.*, 2004). On the other hand, breeding for high transpiration efficiency is appropriate for environments where good rainfall events coincide with the reproductive phase (Tambussi *et al.*, 2007; Condon *et al.*, 2004). Overall, matching cultivars and crop phenology (especially flowering time) to ecological and water supply conditions will have huge impact on crop WUE and attaining acceptable yields (Ali & Talukder, 2008; Morisson *et al.*, 2008; Passioura, 2006). In all, there is

always a trade a tradeoff between crop WUE and productivity due to the stomata being the gateway for atmospheric CO₂ conductance and transpiration.

Furthermore, the discovery that the gene called ERECTA plays a role in both transpiration and photosynthesis constitutes a huge opportunity for exploring molecular tools to improve WUE and photosynthesis simultaneously (Masle *et al.*, 2005). Advances in genetic and genomics tools (e.g., quantitative trait loci [QTL] mapping, microarray techniques for genotyping and transcriptional analyses and the generation of transgenic crops) will be of enormous help in screening large numbers of breeding lines for relevant traits (Fleury *et al.*, 2010). From a breeding perspective, increase in harvest index, quicker development and improved canopy structure, as well as early flowering have been linked to improved WUE_{yield} in modern cultivars (Morisson *et al.*, 2008; Tambussi *et al.*, 2007). Further improvements in cultivars are required in the future to modify crop morphological and physiological characteristics that allow dehydration avoidance or tolerance in the context of climate change (Barnabàs *et al.*, 2008). Particularly, early vigour, optimal flowering time, transpiration efficiency and high harvest index will be worth considering in tandem, taking into account local ecological and climatic conditions. This requires a multi-disciplinary approach. It remains unclear, however, if cultivar improvements in WUE and dehydration avoidance or tolerance will substantially reduce the need for irrigation without incurring yield penalties under projected warmer climates with higher variability in precipitation.

2.4.2 Reducing Food Waste and Losses

“Food waste is composed of raw or cooked food materials and includes food loss before, during or after meal preparation in the household, as well as food discarded in the process of manufacturing, distribution, retail and food service activities. It comprises materials such as vegetable peelings, meat trimmings, and spoiled or excess ingredients or prepared food as well as bones, carcasses and organs” (European Commission, 2010). Food loss, on the other hand, is the qualitative or quantitative decrease in edible food mass in the supply chain preceding the retail and consumer levels (i.e. from farm to processing stages) (Parfitt *et al.*, 2010). Thus, food waste occurs at the retail and consumer levels (Gustavsson *et al.*, 2011; Parfitt *et al.*, 2010). Globally, the magnitude of food loss and waste from farm to fork is staggering (Figure 2-6).

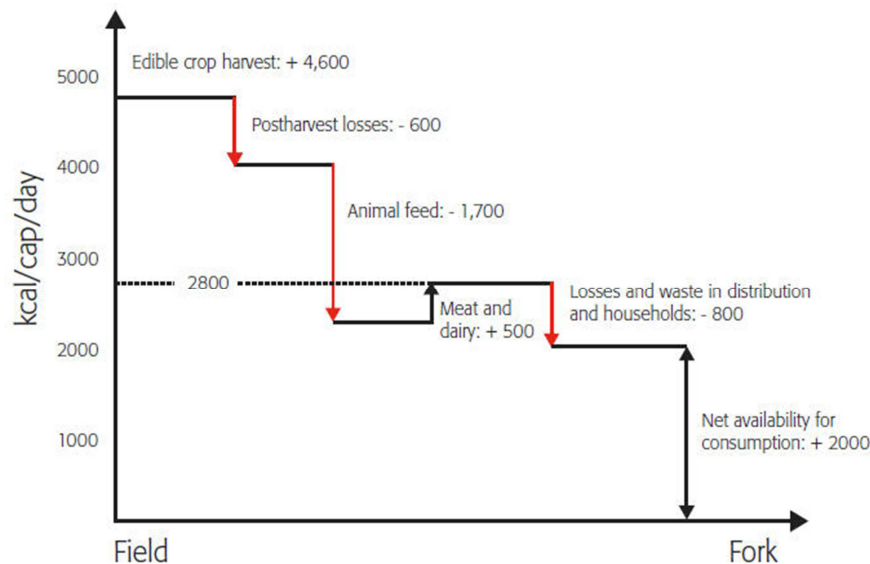


Figure 2-6: Schematic representation of global per capita food production, conversions and losses along the chain from farm to fork. Figure taken from Lundqvist *et al.* (2008).

Although post-harvest losses are high, food waste at the retail and household levels are higher, and losses to animal feed are highest (Figure 2-6). At the global scale, food waste and losses can account for as much as 30-40% (Godfray *et al.*, 2010) or 50% of total food produced (Lundqvist *et al.*, 2008). Even neglecting ‘planned’ allocation to non-food uses, Gustavsson *et al.* (2011) suggests annual food losses and waste amount to as much as 1.3 billion tons of total food produced. In low income countries, food losses are greater than food waste. The reverse is true for high income countries, such as USA and the UK (Gustavsson *et al.*, 2011; Godfray *et al.*, 2010). On average, 95 – 115 kg cap⁻¹ year⁻¹ of food is wasted in industrialized countries, contrasted with 6 – 11 kg cap⁻¹ year⁻¹ in low income countries (Gustavsson *et al.*, 2011). For example, about 7.2 million tonnes of food are wasted annually in the UK, with 4.4 million tonnes classified as ‘avoidable’ food waste (WRAP, 2011). Regionally, total food losses and waste are greatest in North America and Europe and lowest in South and South-East Asia (Buzby & Hyman, 2012; Nahman *et al.*, 2012; FAO, 2011; Gustavsson *et al.*, 2011; WRI, 1999). For example, in the EU-27, over 89 million tonnes of food is wasted annually (European Commission, 2010).

Food loss or waste represents a waste of money and scarce resources invested in producing, transforming and transporting food along the supply chain to consumer level. Food waste also raises the moral or ethical questions of over-consumption, negative attitudes, such as undervaluing food, and diversion of food to non-food uses such as biofuel and animal feed (Parfitt *et al.*, 2010; Lundqvist *et al.*, 2008; FAO, 2006b). It has been suggested that shifting food losses and waste to poor households can reduce global food insecurity and greenhouse gas emissions significantly (Buzby & Hyman, 2012;

Nahman *et al.*, 2012; WRAP, 2012; European Commission, 2010; Parfitt *et al.*, 2010; Lundqvist *et al.*, 2008). Thus, in the context of anticipated water scarcity, food demand and pressures on food production, reducing food losses and waste represents a huge opportunity for reducing future food insecurity.

2.5 Virtual Water: The Missing Piece

An equally important option worthy of consideration in the discourse on paths to food security under future water-scarce conditions is the virtual water concept. Introduced by Allan (1999; 1997), virtual water refers to the volume of water used in producing a unit food commodity that is traded. This definition implies that for virtual water to exist, trade must bridge food production and consumption between two spatially distinct economies (e.g. national or regional). Earlier, Allan had used the term “embedded water” (Allan, 2003), derived from a suggestion by an Israeli economist in the 80s that it was not ‘economically sensible’ for arid Israel to export scarce water embedded in oranges and avocados. In his own words (Allan, 2003), the term “*embedded water was underwhelming in its impact*”, but the response of the water policy community to the ‘virtual water metaphor’ was overwhelming.

The role of virtual water in ensuring food security under water-scarce conditions derives from the proposition that through the importation of water-intensive crop commodities from a water-rich country, a water-scarce economy can save water and offset food insecurity (Dalin *et al.*, 2012; El-Sadek, 2011; Aldaya *et al.*, 2010b; Hoekstra, 2010; Chapagain & Hoekstra, 2008; Chapagain *et al.*, 2006; Yang *et al.*, 2006; Hoekstra &

Hung, 2005; 2002; Allan, 2003; 2001; 1997). It has been shown that virtual water is a useful tool for arid and semi-arid regions (El-Sadek, 2011; Faramarzi *et al.*, 2010b; Allan, 2001) or Mediterranean countries (Yang & Zehnder, 2002) to save water and maintain food security.

Food trade is an old practice. Trade in food commodities has played a crucial role in ensuring global food security by increasing economic, physical, nutritional and socio-cultural access to a wide range of foods (Defra, 2009; 2008). Food trade can contribute to efficient use of global resources such as land, water, energy and technology by distributing surplus food from producing countries to countries that have deficits (Chapagain & Orr, 2009; Defra, 2009; 2008; Chapagain *et al.*, 2006). While water scarcity might not be a new phenomenon (Kummu *et al.*, 2010), the projected increase in its scale and complexity suggests a need for new responses. Therefore, in the context of projected climate change or anticipated water scarcity, it is important to improve understanding on the potential usefulness of the virtual water concept, as a complementary tool, in informing policy and management decisions on water and food security in the future.

2.5.1 Virtual Water Content, Flows and Savings

2.5.1.1 Estimating Virtual Water Content of Crops

For primary crop commodities, virtual water content (VWC) is the ratio of total crop evapotranspiration (ET_c) to yield. The VWC has been referred to variously as the specific water demand (SWD) (Hoekstra & Hung, 2005; 2002), water use intensity (Hoekstra, 1998), virtual water value (Zimmer & Renault, 2003) and unit water

requirement (Oki *et al.*, 2003). However, the calculation procedure is the same. In the virtual water literature, the VWC ($\text{m}^3 \text{ton}^{-1}$) of a given crop c is calculated as (Chapagain & Orr, 2009; Yang *et al.*, 2006; Hoekstra & Hung, 2002):

$$\text{VWC}_c = \frac{\sum_{i=1}^n \text{ET}_c}{Y_c} \quad \text{Equation 2- 1}$$

where Y denotes yield (tons ha^{-1}); ET_c denotes crop evapotranspiration (mm day^{-1}) under specified conditions; and n denotes the number of days in the growing period. But:

$$\text{ET}_c = \text{ET}_o(\text{Kc}) \quad \text{Equation 2- 2}$$

where ET_o denotes reference evapotranspiration; and Kc denotes a crop-specific coefficient (Shahin, 2003; Allen *et al.*, 1998).

This means VWC of crops excludes the minute amount of water retained in the plant cells during growth or in the harvested product (Hess, 2010), water used in background processes such as dissolution of chemical amendments applied to soil or plants (Berger & Finkbeiner, 2010; Ridoutt & Pfister, 2010), and water used in farm operations such as cleaning implements, washing produce or used by workers (Hess, 2010).

Reference evapotranspiration (ET_o) refers to the ET from a hypothetical, short, well-watered, uniformly growing reference crop (e.g. alfalfa or grass) that is disease-free and growing in a large field with non-limiting soil fertility and reaching full production potential (Shahin, 2003; Allen *et al.*, 1998; Doorenbos & Pruitt, 1977). It represents the evaporative demand of the atmosphere at a given location and time, independent of crop type or management (Sumner & Jacobs, 2005; Shahin, 2003; Allen *et al.*, 1998). The crop-specific coefficient (Kc) relates to the crop's soil water depletion potential (Allen *et al.*,

1998). Allen *et al.* (1998) provide a procedure for estimating ETo and Kc as well as give Kc values for a number of crops.

Thus, the energy balance approach is widely used to quantify crop VWC which is justified by the fact that direct measurement of actual crop water use (ETc) can be laborious, expensive and difficult to scale up and is therefore rarely done (Hess, 2010; Ali & Talukder, 2008). In the energy balance approach, weather or climate data is used to compute ETo, which is then used together with Kc to estimate the ETc of a given crop-type at a particular place and time and under specific conditions of production (which may not be optimal). Commonly used energy balance methods are grouped into temperature-based methods, radiation-based methods and combination methods (Shahin, 2003). Most popular and commonly used temperature-based methods include the Blaney-Criddle, Hargreaves and Thornthwaite equations (Yawson *et al.*, 2011; Shahin, 2003; Doorenbos & Pruitt, 1977). The Blaney-Criddle equation is still useful for estimating ETo particularly where there is limited meteorological data (Yawson *et al.*, 2011). Even though a number of radiation-based methods have been developed, they are not commonly used as it is cumbersome to meet their data and computational requirements and they tend to overestimate ETo (Shahin, 2003). A popular radiation-based method is the Jensen-Haise method (Shahin, 2003). The combination methods basically combine energy and aerodynamic terms and are mostly modifications of equations that were originally developed to estimate evaporation from free water surface. Popular examples include the Priestley-Taylor equation, FAO-Penman and the FAO Penman-Monteith (FAO P-M) methods (Tabari *et al.*, 2011; Sumner & Jacobs, 2005; Shahin, 2003; Allen *et al.*, 2006; 1998). The Penman-Monteith method is the standard, most popular and widely used

method for estimating ETo due to its excellent performance against other methods (Tabari *et al.*, 2011; Hess, 2010; Sumner & Jacobs, 2005; Shahin, 2003; Allen *et al.*, 2006; 1998). It is expressed as (Allen *et al.*, 1998):

$$ET_0 = 0.408\Delta(R_n - G) + [900\gamma u_2(e_s - e_a)/(T_k)] \div [\Delta + \gamma(1 + 0.34u_2)] \quad \text{Equation 2- 3}$$

where Δ is the slope of the saturation vapour pressure curve at a given temperature T (kPa °C⁻¹); R_n and G are respectively net radiation and soil heat flux density (MJ m⁻² day⁻¹); γ denotes the psychrometric constant (kPa °C⁻¹); u_2 denotes wind speed at 2 m height (m s⁻¹); e_s and e_a are respectively saturation and actual vapour pressure (kPa); $e_s - e_a$ is the saturation vapour pressure deficit (kPa); T_k denotes absolute temperature in degrees Kelvin.

Alternatively, ETc can be estimated by the water balance approach which is laborious and difficult to scale up over large spatial scales. Here, ETc is estimated as (Shahin, 2003):

$$ETc = (I + Pe) - (R + D) \pm \Delta SM \pm (GWr) \quad \text{Equation 2- 4}$$

where I and Pe denote irrigation and effective precipitation respectively; R and D denote surface runoff and drainage respectively; ΔSM denotes change in soil water content and GWr denotes groundwater recharge. When I and R are reduced to zero, the water balance equation becomes:

$$ETc = Pe + \Delta SM - D \pm (GWr) \quad \text{Equation 2- 5}$$

In this special case equation, Pe represents effective rainfall plus irrigation. This equation is applicable under conditions where the water-table is very low and far below the root zone and soil moisture content is determined gravimetrically or volumetrically at

specific time intervals before and after water input. Alternatively, ET_c can be estimated as the depth (D , mm) of soil water depleted from the root zone (Israelsen, 1956):

$$D = \sum \frac{(\theta_{fc} - \theta_r) \rho_s h}{100}$$

Equation 2- 6

where θ_{fc} denotes water content at field capacity (%); θ_r is the measured soil water content (%); ρ_s is the apparent specific gravity of soil; and h is the thickness of soil layer (mm). Due to differences in agronomic practices, crop cultivars, method used to estimate ETo, and spatio-temporal variations in environmental conditions, the VWC of the same crop can vary considerably over space and time.

2.5.1.2 Virtual Water Flows and Balances in Food Trade

Between any two economies, the virtual water flow for a particular food commodity is calculated as (Chapagain & Hoekstra, 2011; 2008; Chapagain & Orr, 2009; Yang *et al.*, 2006; Hoekstra & Hung, 2005):

$$VWF [e, i, c, t] = Q_c [e, i, c, t] \times VWC_c [e, c, t]$$

Equation 2- 7

where VWF denotes virtual water flow ($\text{m}^3 \text{ year}^{-1}$) from an exporting country e to an importing country i in year t due to the quantity Q_c (tons year^{-1}) of trade and virtual water content VWC_c of commodity c in the exporting country. The net virtual water flow ($NVWF$), or virtual water balance, is the difference between the total virtual water import and export for any given commodity and time period. The water saved by an importing nation is conceptually equivalent to the volume of water that would have been used domestically to produce the quantity of the food commodity imported (Chapagain & Hoekstra, 2011; 2008). This has been referred to as theoretical virtual water (Hoekstra,

2003) or virtual water savings (e.g. Chapagain & Hoekstra, 2008; Chapagain *et al.*, 2006; Yang *et al.*, 2006) or exogenous water (Haddadin, 2003). Yang *et al.* (2006) suggest that virtual water savings should be considered to exist when NVWF is positive and the water productivity or availability of the importing region(s) for the same commodity is lower than that of the exporting region(s). Otherwise, water losses occur.

Hoekstra & Hung (2002) estimated global virtual water flows associated with food commodity trade in 2000 to be $1031 \text{ Gm}^3 \text{ year}^{-1}$, with crops accounting for $695 \text{ Gm}^3 \text{ year}^{-1}$ while trade in livestock and livestock products accounted for $336 \text{ Gm}^3 \text{ year}^{-1}$. Hoekstra & Hung (2005) estimated the total global virtual water flows for 33 crops for the period 1995-1999 to be $694 \text{ Gm}^3 \text{ year}^{-1}$, with the top ten crops (Figure 2-7) accounting for 92.12%. Wheat and soybean were the largest contributors to the global virtual water flows, accounting for 30% and 17%, respectively. Regarding water savings, Chapagain *et al.* (2006) estimated that trade in cereals for the period 1999-2001 resulted in global water savings of $222 \text{ km}^3 \text{ year}^{-1}$ (Figure 2-8). Subsequent to these pioneering works, there have been several estimates of virtual water flows and savings at different spatio-temporal scales for different commodities, reflecting diverse methodological efforts to improve spatio-temporal resolution, water use accounting or to capture impacts on water resources (e.g. Dalin *et al.*, 2012; El-Sadek, 2011; Faramarzi *et al.*, 2010b; Mekonnen & Hoekstra, 2010a; 2010b; Siebert & Döll, 2010; Dabrowski *et al.*, 2009a; 2009b; Dietzenbacher & Velázquez, 2007; Yang *et al.*, 2006). All the global scale studies indicate that the proportion of green water far exceeds blue water in global virtual water flows, indicating that global trade in primary food crops could help offset blue water scarcity.

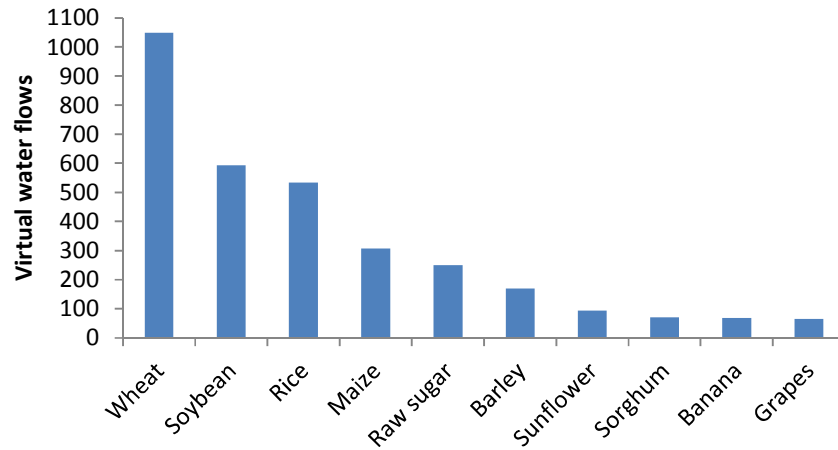


Figure 2-7: Contributions of top 10 crops to global virtual water flows (Gm³) for the period 1995 – 1999. Data taken from Hoekstra & Hung (2005).

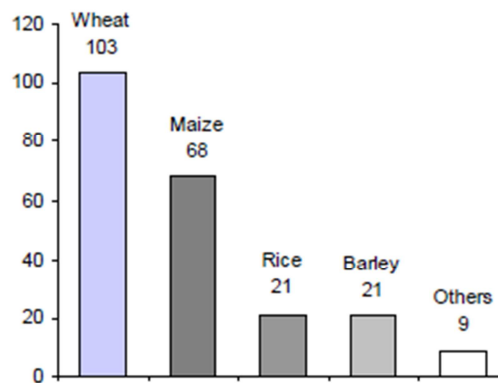


Figure 2- 8: Global average water savings (km³ year⁻¹) from cereal trade (1999-2001). Data taken from Chapagain *et al.* (2006).

For the UK, Yu *et al.* (2010) studied the regional and total water footprints of 28 sectors in South-East, North-East England and the UK. Agriculture was found to be the most water-intensive sector, consuming approximately 2104, 2131 and 2116 m³ water per £1000 of output for the whole UK, the South-East region and the North-East region, respectively. They reported that 55% of UK national water footprint was external. In a

similar study for 28 sectors, Feng *et al.* (2010) observed that agriculture was the most water-intensive sector, with a total production water footprint of $86 \text{ Gm}^3 \text{ year}^{-1}$, of which $77 \text{ Gm}^3 \text{ year}^{-1}$ was internal. Approximately 74% of UK's total water footprint ($86 \text{ Gm}^3 \text{ year}^{-1}$) was external. It was found that the food products sector is the largest consumer of external water and 55% of its water consumption originates from non-OECD countries while 28% comes from EU-OECD countries. These few studies show that the UK depends heavily on external virtual water and there is scope for more research to understand the role of virtual water in UK food security, especially in the context of climate change and anticipated increase in global water scarcity.

2.5.2 Incorporating Virtual Water into Policy: Opportunities and Challenges

A debate on the usefulness of virtual water for policy is still ongoing. Neubert & Horlemann (2008) have discussed the key arguments, assumptions and requirements of the opposing sides of the debate. The pro-virtual water argument is that importation of water-intensive food commodities is motivated by water deficit and that water savings resulting from food import helps mitigate the effects of water scarcity (e.g. Chapagain *et al.*, 2006; Yang *et al.*, 2006; Hoekstra & Hung, 2005; Allan, 2003; 1999; 1997). Some studies using the Middle East and North Africa (MENA) region or Mediterranean countries (e.g. Novo *et al.*, 2009; Yang *et al.*, 2003; Haddadin, 2003; Hakimian, 2003; Yang & Zehnder, 2002) have been used to support this argument. Hence, given the projected changes in climate, demographics, food demand and supply, virtual water will play an important role in food trade strategies of water deficit countries in the future.

Here, strategies based on virtual water will be insurance against water and food insecurity due to occasional and progressive drought or worsening aridity in a manner that is effective, politically silent and economically invisible (Allan, 2003; 2001; 1999; 1997). Hence, adjustments in international trade and resource governance, as well as national water resources management are necessary to minimize disruptions, unfair competition and risks (Hoekstra, 2009; 2006). It is also argued that virtual water reveals interdependencies between nations and consumers and natural resources such as water and thereby promotes ethical consumption, diplomacy and peace (Chapagain *et al.*, 2006; Hoekstra, 2006).

The opposing argument is that virtual water has analytical value but not sufficient instrumental value for policy due to certain conceptual or theoretical limitations and that policy proposals based on virtual water can even be potentially dangerous (Wichelns, 2010a; 2010b; Frontier Economics, 2008). This argument is based on claims that the virtual water concept is inconsistent with the structure and pattern of virtual water flows, the supposed water savings are inaccurate and irrelevant for reducing water deficits, virtual water estimates are not linked to any environmental target to guide policy or management decisions, lack of consideration of policy failures and opportunities to improve water resources development and productivity, as well as socio-economic and political impacts on importing nations (Ansink, 2010; Ridoutt & Pfister, 2010; Wichelns, 2010a; 2010b; Frontier Economics, 2008). There are arguments that the relevance of virtual water for policy can be enhanced by considering comparative advantage or opportunity cost of water in food production (Wichelns, 2010a; 2010b; 2004; 2001; Lant, 2003; Earle, 2001), or by considering other environmental, socio-economic and political

factors (Aldaya *et al.*, 2010b; Wichelns, 2010a; 2010b; Kumar & Singh, 2005; Lant, 2003; Earle, 2001). As suggested by Frontier Economics (2008), research in this direction, instead of estimates of virtual water flows, can improve the utility of virtual water for policy.

The idea that international commodity trade is an indirect trade of factors of production and that relative endowments in such factors dictate the structure and pattern of trade is rooted in the Heckscher-Ohlin theorem of trade which builds on classical Ricardian comparative advantage (Hakimian, 2003). Because the virtual water concept seems to be about differences in water resource endowments and indirect trading of a productive resource (water) between trading nations, it is believed that the structure and pattern of virtual water flows can be explained with the Heckscher-Ohlin theory (Ansink, 2010; Wichelns, 2010a; 2010b; Hakimian, 2003; Allan, 1999). The two central assumptions of the Heckscher-Ohlin theory are that (i) countries differ in their relative abundance of productive resources (e.g. water, land, labour and capital) which determines factor prices and comparative advantages; and (ii) different proportions of these input factors are used to produce goods (Krugman & Obstfeld, 1991). Countries are therefore expected to import goods which require intensive use of their scarce resources to produce and *vice versa* (Ansink, 2010; Hakimian, 2003).

Classical applications of the Heckscher-Ohlin theory to trade in industrial commodities have often revealed the opposite, a situation called the 'Leontief Paradox' (Hakimian, 2003; Krugman & Obstfeld, 1991). Similarly, in the virtual water literature, the application of comparative advantage (based on relative water resources endowment) has largely exhibited the Leontief Paradox where water-rich nations import water-

intensive food commodities even from water-deficit countries, or where no relation was found between water deficit and food import (e.g. Seekell *et al.*, 2011; Ansink, 2010; Ramirez-vallejo & Rogers, 2010; Verma *et al.*, 2009; Kumar & Singh, 2005; Lant, 2003; Earle, 2001). These studies attributed the structure of virtual water flows largely to factors other than water endowment, such as arable land, labour, and trade liberalization policies. These findings are not surprising. From the calculations of virtual water flows, it is natural that large food importers and exporters will have large virtual water imports and export respectively and trade structure is not dictated entirely by water resources but also by political, economic and socio-cultural considerations (Youkhana & Laube, 2009; Neubert & Horlemann, 2008; Roth & Warner, 2007; Kumar & Singh, 2005; Hakimian, 2003; Warner, 2003). Crop productivity differences among trading nations might also contribute as observed in certain studies (Dabrowski *et al.*, 2009b; Neubert & Horlemann, 2008; Yang & Zehnder, 2007).

It has also been argued that the global water savings and distribution of water scarcity associated with virtual water are questionable and irrelevant as global virtual water flows is a fraction of the total water used in crop production and there is no guarantee that the supposed water saved will be applied to agriculture (Wichelns, 2010a; Frontier Economics, 2008). What is important to note, though, is that water endowment alone cannot explain the structure of food trade but can contribute to understanding the patterns in certain jurisdictions (Hakimian, 2003). Hakimian (2003) reported that his results, while supporting the virtual water hypothesis, were sensitive to the definition and measurement of water used in the analysis. He reported that using 'total annual water withdrawal' yielded a result consistent with the virtual water proposition, whereas using

‘internal renewable water resources’ or ‘annual agricultural withdrawals’ gave poor results. This raises the need for (1) better assessment of water endowment and (2) compatibility between the definition of water scarcity and crop water use.

The need to study the implications of adopting virtual water as a policy prescription for national security, economic growth, employment, institutional adjustments and poverty reduction in different countries has been suggested (Wichelns, 2010b; 2003; 2001). There are even arguments evoking the political risk of losing sovereignty through high reliance on food import (Wichelns, 2010a; Verma *et al.*, 2009; Kumar & Singh, 2005; Lant, 2003; Earle, 2001). These are genuine concerns worthy of consideration for optimal water management and food security decisions. The food crisis (2007-2009) revealed the volatility of the global food market and the dangers inherent in a widely connected global food system (Essex, 2010). The crisis re-ignited the old debate about self-sufficiency, food security and food dependency through trade. Joachim von Braun (Director General, IFPRI) stated that “*a world confronted with more scarcity of food needs to trade more – not less – to spread opportunities fairly*” (von Braun, 2008). In the UK, while there were calls for a return to the self-sufficiency paradigm, Peter Kendall (President of National Farmers Union) suggested that “*food security cannot be uniquely tackled at the national level, but that should not preclude British farming from playing a crucial part in addressing this global issue*” (Defra, 2008). On the contrary, Russia banned grains export in 2009 due to severe drought, suggesting that countries can reduce food export during periods of domestic low production or food scarcity.

There are important elements missing in the debate on the utility of virtual water for policy. The question is ‘what policy?’ Is it water policy, food security policy or water-

food security policy? A shift in focus might help the debate. Food is imported primarily to augment domestic food capacity to achieve food security. Hence, food import will be more consistent with food security goals. Moreover, water is only one of the factors of crop production and the true economic cost of both water and food is not transferred to the consumer (Allan, 2003) and thus distort the food market and trade (Hakimian, 2003). Hence, a hydrocentric view is not sufficient for water and food security policy (Brichieri-Colombi, 2004). Virtual water links water consumption in crop production, on the agronomy side, to food trade and consumption, on the economy side (Neubert & Horlemann, 2008; Allan, 2003; Yang & Zehnder, 2002). The role of virtual water in food security can therefore be better assessed through a combined analysis of the agricultural and economic structure, resource endowment and food security needs of a country (Aldaya *et al.*, 2010b). Food production serves multiple purposes, including cultural, political, and socio-economic purposes (Neubert & Horlemann, 2008). Each country will therefore strive to produce as much food as these purposes and resources will allow; hence, food production and trade might not always make sense in only one domain. Consequently, caution should be exercised when giving prescriptions on food production and consumption based on water endowment or virtual water analysis alone as this might easily lead to a theoretical overstretch.

As noted by Roth & Warner (2007), for nations faced with acute food insecurity induced by water scarcity, virtual water is a key component of a wider palette of policy choices. No policy prescription, however, will be effective if it is based on a single strategy such as virtual water (Aldaya *et al.*, 2010b; Roth & Warner, 2007). Therefore, the extent to which a policy directed at water and food security should directly incorporate

virtual water 'trade' is a matter of national circumstances. An informed answer would consider a range of factors, including dynamics of water availability and uses, agricultural capacity and structure, asymmetries in power and international commodity trade, political and economic structure, market signals and risks, maturity of food supply chains and environmental costs. There is the need, therefore, for more studies on the role and usefulness of the virtual water concept in ensuring water-food security in different jurisdictions.

CHAPTER 3**EVALUATION OF MODELS FOR ESTIMATING WATER USE OF BARLEY****3.1 Introduction**

Estimates of crop water use are central to quantifying virtual water flows through crop commodity trade. In-field monitoring or direct measurement of daily crop water consumption over the crop growing season and over large spatio-temporal scales is extremely difficult. As a result, dynamic models for simulating crop growth have become a preferred tool for indirectly and rapidly estimating crop water use as they are also scalable over space and time (Todorovic *et al.*, 2009). Such models are also useful in assessing the occurrence and effects of intra-seasonal water stress on crop growth and yield to support irrigation and agronomic management decisions (Brouwer & van Ittersum, 2010; Hess, 2010). Compared to irrigated crops, however, the water use of crops under rain-fed conditions (green water use, Chapagain & Orr, 2009) is only occasionally measured (Hess, 2010) and normally for academic purposes. Estimating crop water use under rain-fed conditions is important not only because green water dominates global crop production and virtual water flows (Aldaya *et al.*, 2010a; Hanasaki *et al.*, 2010; Hoff *et al.*, 2010; Liu & Yang, 2010; Rockström *et al.*, 2009; Chapagain *et al.*, 2006; Yang *et al.*, 2006) but also because green water use of crops affects potential groundwater recharge (Holman *et al.*, 2011; 2009).

Several models are available for simulating the dynamics of crop growth and/or soil water content, as well as the effects of climate change on these parameters (Hunink *et*

al., 2011; Rivington & Koo, 2011; UNFCCC, 2008; Steduto, 2003; van Ittersum *et al.*, 2003). These models differ in their complexities and data requirements depending chiefly on whether their core crop growth sub-model is mainly driven by carbon, radiation or water (Hunink *et al.*, 2011; Steduto, 2003; van Ittersum *et al.*, 2003; De Wit *et al.*, 1970). Carbon-driven models (e.g. WOFOST, SWACROP and CROPGRO) are the most complex and have the most extensive data requirements. Crop growth in these models is mainly driven by photosynthetic assimilation of carbon from the atmosphere. Radiation-oriented models (e.g. CERES, CropSyst and EPIC) are next in complexity and in these models crop growth is driven by intercepted solar radiation and radiation use efficiency of the crop. By contrast, water-driven models or agrohydrological models (e.g. AquaCrop and CropWat) present a far less complex architecture and fewer data requirements. In these models, crop growth is largely driven or limited by soil water balance (SWB) which is linked to transpiration through a water productivity function that can be normalized for different climates (Steduto *et al.*, 2009; Todorovic *et al.*, 2009). Because of their simplicity, and because they are based on soil water dynamics, water-driven models are the most widely used models in studies of crop water use and the effects of water stress on yields (van Ittersum *et al.*, 2003). While radiation or carbon-driven models can be better for simulating crop yields due to the canopy-atmosphere interaction in yield formation, van Ittersum *et al.* (2003) suggested that water-driven models perform better and are more suitable for irrigation and water-use assessments than carbon- and radiation-driven models.

In the virtual water literature, CropWat is commonly used to estimate crop virtual water content and consequently virtual water flows even at a global scale (Hess, 2010;

Chapagain & Orr, 2009; Chapagain *et al.*, 2006). For a model to be applicable to several crops under different management and environmental conditions, its ability to predict a target parameter accurately should be proven through multi-site and multi-year testing (Raes *et al.*, 2009; Todorovic *et al.*, 2009; Steduto, 2003). Some studies have shown that, compared to other models, CropWat performs poorly in predicting crop water use in certain environments. For example, Hess (2010) reported that WaSim is better than CropWat for estimating pasture water use under English conditions. George *et al.* (2000) reported that, compared to the Irrigation Scheduling Model, CropWat slightly underestimated the ET_c of beans in Davis, California (USA). Kang *et al.* (2009) reported that CropWat, just like CERES-Wheat and MODWht, predicted daily ET_c of winter wheat in China and USA poorly. Therefore, in the interest of improving the accuracy of the estimates of crop virtual water content and flows, there is the need to compare the abilities of CropWat and other water-driven models for predicting crop water use and the effects of soil water stress on yields. Previously, CropWat has been compared with WaSim (Hess, 2010) and AquaCrop has been compared with other models such as CropSyst and WOFOST (Todorovic *et al.*, 2009). No study, however, has yet compared the abilities of AquaCrop, CropWat and WaSim for simulating crop water use. AquaCrop is the latest FAO crop water productivity model, with capacity for climate change simulations (Raes *et al.*, 2009). It has been used to simulate the growth, yield and response to soil water dynamics of different crops and in different locations, including West and South Africa, Near East and Asia, with satisfactory results (Steduto *et al.*, 2011). WaSim has been shown to be suitable for English environmental conditions (Hess, 2010) and, therefore, the UK. The objective of this chapter is to compare the abilities of AquaCrop, CropWat and

WaSim to predict the water use and effect of water stress on yields of 10 barley genotypes grown in the field in Scotland.

3.2 Description of the Models

3.2.1 AquaCrop

AquaCrop, released in 2009, is a crop water productivity model for simulating biomass and yield response to soil water dynamics (Raes *et al.*, 2009; Steduto *et al.*, 2009). The model is targeted at a broad range of users at varying scales. It can be used as a planning tool or to assist in management decisions. It incorporates current knowledge of crop physiological responses to predict attainable yield of a crop based on water availability. It is designed to offer a balance between accuracy, simplicity and robustness. The architecture and algorithms of AquaCrop have been reported by Raes *et al.* (2009) while the conceptual framework, underlying principles, and distinctive components and features have been reported by Steduto *et al.* (2009).

The soil sub-model is designed as a dispersed system permitting the user to define up to five layers of varying textures and depths in the soil profile. This sub-model contains default values of hydraulic properties (e.g. saturated hydraulic conductivity, saturated water content, field capacity and wilting point), generated using a pedotransfer function, for all the soil textural classes defined in the USDA soil texture triangle. However, user-defined soil type and or values of hydraulic characteristics are also permitted. The available soil water in the root zone is tracked from water input by performing a daily water balance that includes the processes of runoff, infiltration, redistribution, deep

percolation, capillary rise, uptake, evaporation and transpiration. In performing soil water balance, AquaCrop separates soil evaporation from crop transpiration.

The crop-growth sub-model relies on the conservative behavior of water productivity. Thus, biomass production in AquaCrop is a function of water productivity and crop transpiration relative to the extent of canopy cover. The canopy cover (expressed as a fraction of green canopy ground cover) is crucial as it determines the scale of transpiration and biomass production through its expansion, ageing, stomatal conductance and senescence. Under unstressed conditions, canopy expansion from emergence to full cover follows an exponential growth function while the phase from full canopy to senescence follows a decay function. Subsequent to full canopy cover, the canopy can have a variable duration period prior to senescence. Intermediary processes of biomass accumulation are not simulated but synthetically incorporated into a single coefficient defined as biomass water productivity (WP), which is normalized for reference ET (ET₀) and CO₂ concentration of the bulk atmosphere. This normalization makes the model applicable to varied locations and seasons, including climate change scenarios. Even though the final yield is a product of biomass and harvest index (HI), AquaCrop separates final yield into biomass and HI and, thus, allows a distinction of environmental effects on biomass production and harvest index (Raes *et al.*, 2009; Geerts *et al.*, 2009). The crop-growth sub-model has five main components and related dynamic responses to environmental conditions (phenology, canopy cover, rooting depth, biomass production and harvest index). Crop responses to water stress occur through three main conservative, plant-based parameters: reduced rate of canopy expansion, stomatal control of transpiration, and accelerated canopy senescence (Andarzian *et al.*, 2011; Raes *et al.*,

2009). Through these pathways, the WP and HI are adjusted. Other water stresses (e.g. waterlogging) can also affect the WP and HI. The stress functions of the crop responses are considered conservative with respect to management or geographical location, but the onset and intensity of stresses are strongly dependent on management, time, climate and soil conditions (Raes *et al.*, 2009). Simulations can be run in either growing degree days or calendar days depending on data availability and user preference. A recent literature review on the performance of AquaCrop shows that AquaCrop is able to simulate crop water use, biomass production and yield and crop responses to soil water deficits satisfactorily (Steduto *et al.*, 2011).

3.2.2 CropWat

The FAO CropWat model (Smith, 1992) was developed as a simple tool for estimating crop water requirement (CWR), generating irrigation schedules and water supply schemes for different agronomic management scenarios (Stancalie *et al.*, 2010). CWR is simulated as the product of ETo and crop coefficient (Kc) relative to effective rainfall over four crop development stages: *initial*, *development*, *mid-* and *late-seasons* (Doorenbos & Pruitt, 1977). The initial period is between sowing to 10% canopy cover and the development stage is the period from 10% canopy cover to maximum canopy cover (normally initiation of flowering). Mid-season covers the period from maximum canopy cover to start of maturity (beginning of ageing, yellowing or senescence). The late season is marked by the start of maturity to harvest. Different Kc input values are required for the different growth stages. However, within a given growth stage, the daily Kc values

applied can be a proportion of the input value in response to the extent of soil wetness or dryness. Maximum K_c is assumed to be reached at the end of mid-season (Doorenbos & Pruitt, 1977). CropWat has been used in various studies on CWR and irrigation optimization with varied results (e.g. Kang *et al.*, 2009; Mimi & Jamous, 2010; Smith & Kivumbi, 2002; George *et al.*, 2000). The common use of CropWat in the virtual water literature might be due to the availability of generic K_c values and length of development stages of several crops, the accompanying climate data generation software (Climwat), the minimal data and calibration requirements and the relative ease of use (Smith & Kivumbi, 2002).

3.2.3 WaSim

WaSim is a one-dimensional soil water balance simulation model developed by HR Wallingford and Cranfield University (UK). A general description of WaSim is given by Hess & Counsell (2000) and details of the model structure, sub-models and algorithms are published in the technical manual (Hess *et al.*, 2012). WaSim is designed to simulate daily soil water balance in response to agronomic management practices and environmental conditions, such as weather, soil and crop growth (Hess & Counsell, 2000). In WaSim, soil water is stored between an upper boundary (the soil surface) and a lower boundary (the impermeable layer) divided into five compartments. The first two compartments (0-0.15 m and 0.15 m - root depth) constitute plant available soil water. Soil water depletion through ET occurs mainly in the top layer and subsoil water abstraction occurs when water in the topsoil is depleted. ET is modelled separately for crop cover,

bare soil and mulch. Crop cover fraction is linearly interpolated between the dates of emergence, 20% canopy cover, maximum cover, maturity and harvest, while senescence is captured as a linear reduction in canopy cover between maximum cover and zero cover at maturity (Hess & Counsell, 2000). Even though WaSim was originally designed for educational training in drainage, irrigation and salinity management (Hess & Counsell, 2000), it has been used in simulating subsurface drainage system performance (Hirekhan, 2007), water use of pasture (Hess, 2010), total volumetric irrigation water requirements (Knox *et al.*, 1997), catchment runoff (Hess *et al.*, 2010) and groundwater recharge (Holman *et al.*, 2009) with satisfactory results.

3.3 Materials and Methods

3.3.1 Site Description and Crop Husbandry

A field experiment was conducted at The James Hutton Institute (Dundee, 56.27N, 3.40W) in 2011. The soil of the site belongs to the Balrownie series, a Stagnic Cambisol in the FAO classification, with a sandy loam texture derived from red sandstone sediments (Bell and Hipkin, 1988; McKenzie *et al.*, 2009). The soil is freely drained, with saturated water content of 45.8%, field capacity of 23%, permanent wilting point of 9.5% and total available soil moisture of 135 mm/m. The pH (CaCl₂) ranges from 5.1 in the surface to 5.6 in the subsoil.

The soil was ploughed and harrowed to a depth of 0.4 m. The field was divided into 10 plots (each 6 m long, 10 m wide), with a distance of 2 m between plots. Each plot was divided into five rows, each row measuring 6 m long and 1.2 m wide with a distance

of 1 m between rows. Each row was further divided into 6 subplots of 1 m length for different root restriction treatments. Ten spring barley genotypes (B83-12/21/5, Bowman, Derkado, Golden Promise, Morex, NJSS106, Optic, Triumph, Westminster, and Zephyr) were assigned randomly to the rows of a plot. These genotypes were selected because seeds were available at The James Hutton Institute and they were on the list of spring barley genotypes recommended by the Home Grown Cereals Authority (HGCA). Seed was sown on 8th April 2011 in the 6 m long rows to a target density of 365 plants m⁻². A single fertilizer application was made at sowing at a rate of 110 kg ha⁻¹ N, 20 kg ha⁻¹ P₂O₅ and 70 kg ha⁻¹ K₂O. Weeds were controlled chemically. Harvesting took place on 15th September 2011. The data collected for this study were from the control subplots.

3.3.2 Data Collection

3.3.2.1 Weather Data

Weather data (daily maximum and minimum temperature, sunshine hours, humidity, rainfall and wind speed) were collected from an onsite meteorological station (UK Station No. 339299) located 50 m from the experiment plot at an altitude of 30 m above sea level. The weather data were used to compute daily reference evapotranspiration (ET_o), using the FAO Penman-Monteith equation (Allen et al., 1998) in the FAO ET_o Calculator software (Raes, 2009). The computed ET_o data were exported as a text file and converted to compatible formats for the crop models.

3.3.2.2 *Canopy Cover and Canopy Temperature*

The growth stages and durations of developmental stages of the crops were monitored in the field using the Zadoks Scale and the HGCA Barley Growth Guide (HGCA, 2006). Canopy cover was calculated from digital true colour images taken with an 8.2 megapixels SONY CYBERSHOT digital camera (SONY™, TOKYO), operating in the visible region of the electromagnetic spectrum. For each genotype, three subplots were selected for imaging at a 3-day interval except when weather conditions did not permit. For each subplot, two images were taken each time. The images were taken by pointing the lens of the camera perpendicularly to the canopy surface of a subplot. The images were always taken when the sun was overhead to ensure that canopy shadows were visible. The edges of a subplot were marked out with four bamboo sticks fixed at the corners of the subplot but are sometimes visible in the image. The images were imported in FIJI ImageJ software, cropped to cut out edge-effect and then converted to binary format (using *Process>Binary>Make Binary*), with a pixel inclusion probability threshold of 55%. A histogram of the binary image was saved (Figure 3-1a, b) in order to obtain the count of pixels representing the background soil (pixel value of 0) and the vegetation fraction (pixel value of 255). Per cent canopy cover (% CC) was calculated as:

$$\% CC = \frac{Vg}{T} \times 100 \qquad \text{Equation 3-1}$$

where Vg is the total count of pixels representing vegetation and T is the total number of pixels.



Figure 3-1a: Sample colour image of barley in the field for canopy cover calculation.

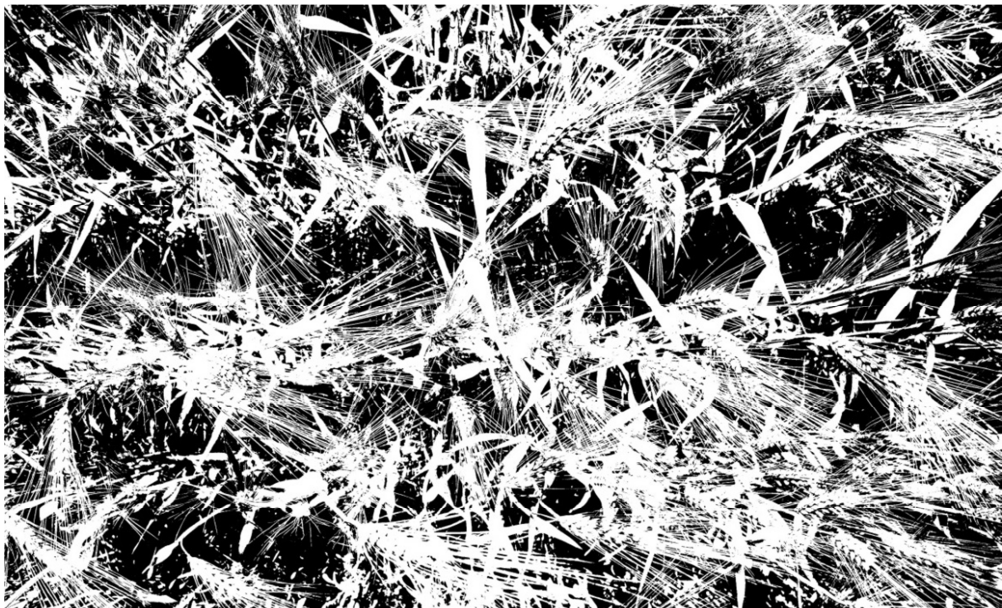


Figure 3-1b: Corresponding binary image of Figure 3-1a.

The calculated canopy cover values were used in the simulations using AquaCrop and WaSim. Results of canopy cover calculated using this method do not differ significantly from those obtained by other methods such as the ocular estimation, digital

square grid and polygon methods (Avsar and Ayyildiz, 2010), or the USDA point sampling method (Crawley, 2011). Also, Campillo *et al.* (2008) reported that canopy cover calculated using this method in ImageJ showed a linear relationship with light interception measured with line quantum sensor at solar noon.

Canopy temperature was retrieved from thermal images of the canopy captured with a ThermaCAM™ P25 thermal camera (FLIR SYSTEMS, Sweden), with the following settings: *emissivity* (0.97), *humidity* (60%), *ambient temperature* (20 °C), *distance* (1.6 m), *Trefl* (28), *Tatm.* (20) and *FOV* (23). The camera was used in autofocus mode but each image was frozen first before saving. Images were captured every other day. On each day, unless the weather conditions did not permit, two imaging events were undertaken, one in the late morning (between 10:00 and 11:00 a.m.) and the second in the afternoon (between 13:30 and 14:30 p.m.). The procedure and number of subplots are similar to those described for canopy cover imaging. Thermal imaging was done from 1st June to 15th August, 2011.

The thermal images were imported into ThermaCAM Researcher Pro 2.8 software (FLIR SYSTEMS, Sweden) to generate canopy temperature values. Temperature statistics of each image were derived by drawing a rectangular box of fixed size over the centre of the image. No major processing or image enhancement was applied. However, when high soil temperature pixels were present at the edge of an image, they were considered as artefacts (or noise) and therefore removed. This was normally due to the effects of uncovered soil surface between subplots. When such pixels exist across the image or cover a substantial part of the image, they were included in the analysis because they were due to openings in the canopy.

3.3.2.3 Soil Water Content

Volumetric soil water content (θ_v , $\text{m}^3 \text{m}^{-3}$) was measured at 4-hour intervals from 24th April to 9th August 2011, using ML2X Theta-Probes connected to DL6 dataloggers (Delta-T Ltd., Cambridge, UK) placed at a depth (d) of 30 cm. The average of each 24-hour volumetric soil water content measurement was converted to an equivalent depth of water (D , mm) using equation 3-2 (White, 2006):

$$D = 1000(\theta_v d) \quad \text{Equation 3-2}$$

3.3.3 Simulation and Validation of Water Use of Barley Genotypes

3.3.3.1 Simulation of Water Use of Barley Genotypes

Water use of the 10 barley genotypes was simulated using AquaCrop (version 3.1+), CropWat (version 8.0) and WaSim (version 1.8.17). Robust calibration and parameterization of crop models require multi-year and multi-site studies for greater accuracy. However, conservative parameters from such calibration studies can be applied in other simulation studies, with minimal local calibration, to assess the performance and applicability of the model under different environmental conditions (Steduto *et al.*, 2011). In all the simulations, maximum rooting depth was assumed to be reached at the same time as maximum canopy cover (Allen *et al.*, 1998) and a value of 0.70 m was used. Initial soil water content was set to field capacity as soil water content was not measured at sowing. Surface runoff was assumed to be insignificant as the plot has an almost flat surface. Default drainage characteristic values generated by the models, based on input

values of key soil hydraulic properties values (i.e. saturated water content, field capacity, permanent wilting point), were used.

With simulations using AquaCrop, the choice of conservative parameter values (Table 3-1) was based on reported barley calibration information (Araya *et al.*, 2010a; Raes *et al.*, 2011), with minimal adjustments based on personal communications with scientists at The James Hutton Institute. Because CropWat and WaSim simulations are in calendar mode, AquaCrop parameters reported here are in calendar days to ease comparison with the other models. Information on growing degree days for key parameters is reported in Chapter 4.

Table 3-1: Conservative parameter values adopted in simulations using AquaCrop.

Symbol	Parameter Description	Value
1. Crop Phenology		
1.1 Development of green canopy cover (CC)		
CC ₀	Initial canopy cover (%)	3.6
	Time from sowing to emergence (days)	15
CGC	Canopy growth coefficient (fraction per day, % day ⁻¹)	10
CC _x	Maximum canopy cover (%)	85
CDC	Canopy decline coefficient (fraction per day, % day ⁻¹)	8
1.2 Development of root zone		
Z _n	Minimum effective rooting depth (m)	0.30
Z _x	Maximum effective rooting depth (m)	0.70
	Shape factor describing root zone expansion	1.5
2. Crop Transpiration		
K _{C_{Tr,x}}	Crop coefficient at maximum CC	1.15
	Decline of crop coefficient (% day ⁻¹) due to ageing	0.15
	Effect of canopy shelter on surface evaporation in late season stage (%)	50
3. Biomass production and yield formation		
3.1 Crop water productivity		
WP*	Water productivity normalized for ET ₀ and CO ₂ (g m ⁻²)	15
	Water productivity normalized for ET ₀ and CO ₂ during yield formation (as % WP* before yield formation)	100
3.2 Harvest index		
HI ₀	Reference harvest index	0.49
	Upper threshold for water stress during flowering on HI	0.82
	Possible increase (%) of HI due to water stress before flowering	12 (strong)
	Coefficient describing positive effect of restricted vegetative growth during yield formation on HI	Moderate
	Coefficient describing negative effect of stomatal	Moderate

	closure during yield formation on HI	
	Excess of potential fruits	Moderate
	Allowable maximum increase (%) of specified HI	15
4. Stresses		
4.1 Soil water stress		
P _{exp,lower}	Lower threshold of water stress for triggering inhibited canopy expansion	0.60
P _{exp,upper}	Upper threshold for canopy expansion (canopy expansion ceases)	0.27
	Shape factor for water stress coefficient for canopy expansion	3.5
P _{sto}	Upper threshold for stomata closure	0.60
	Shape factor for water stress coefficient for stomatal control	3.0
P _{sen}	Upper threshold for early senescence due to water stress	0.60
	Shape factor for water stress coefficient for canopy senescence	3.5
P _{pol}	Upper threshold of soil water depletion for failure of pollination	0.80
	Vol.% at anaerobic point (with reference to saturation)	15

Table 3-2: Duration (in days) of crop developmental stages for simulations using AquaCrop. Data from crop monitoring in 2011.

Genotype	Sowing to max. canopy cover	Sowing to start of canopy senescence	Sowing to start of flowering	Harvest index build-up	Flowering period
B83-12/21/5	71	115	83	44	12
Bowman	56	90	68	34	12
Derkado	68	120	79	52	11
G. Promise	68	102	78	34	10
Morex	62	120	72	58	10
NJSS106	58	115	69	57	11
Optic	69	120	79	51	10
Triumph	68	115	81	47	13
Westminster	68	115	80	47	12
Zephyr	68	122	80	54	12

With simulations using CropWat, the default FAO values for barley for K_c, rooting depth, depletion and yield response fractions were used (Allen *et al.* 1998; Smith 1992). Values for K_c were 0.30, 1.15 and 0.25 for *initial*, *mid* and *late* season, respectively. For rooting depth, the values were 0.30 and 0.70 m for *initial* and *mid*-

seasons, respectively. For depletion fraction, the values were 0.55, 0.55 and 0.65 for *initial*, *mid* and *late* season, respectively, and for yield response factor the values were 0.20, 0.60, 0.50, 0.40 and 1.00 for *initial*, *development*, *mid*, *late* seasons and total yield response factor, respectively. The durations of crop developmental stages are presented in Table 3-3.

Table 3-3: Duration (in days) of crop developmental stages for simulations using CropWat. Data from crop monitoring in 2011.

Genotype	Initial	Development	Mid-season	Late season
B83-12/21/5	31	40	44	45
Bowman	23	33	34	70
Derkado	31	37	52	40
G. Promise	25	43	34	58
Morex	31	31	58	40
NJSS106	31	27	57	45
Optic	30	39	51	40
Triumph	28	40	47	45
Westminster	30	38	47	45
Zephyr	28	40	54	38

WaSim has not been calibrated for any particular crop. Therefore, conservative crop parameters used here (e.g. maximum Kc) were based on values used for simulations using CropWat. A value of 1.15 for maximum Kc, a value of 0.5 for p-fraction (equivalent to the depletion fraction) and a value of 1 for yield response factor were used. Durations of crop developmental stages for simulations using WaSim are presented in Table 3-4.

Table 3-4: Duration (in days) of crop developmental stages for simulations using WaSim. Data from crop monitoring in 2011.

Genotype	20% Cover	Full Cover	Maturity
B83-12/21/5	53	71	110
Bowman	36	56	85
Derkado	30	68	115
G. Promise	40	68	97
Morex	53	62	115
NJSS106	53	58	110
Optic	50	69	115
Triumph	46	68	110
Westminster	50	68	110
Zephyr	46	68	117

3.3.3.2 Validation of Simulated Water Use of Barley Genotypes

To validate the simulations, the measured soil water content (SWC) was compared with the predicted soil water balance (SWB) in the top-soil for AquaCrop and WaSim or the difference between available water and depletion in the root zone for CropWat. This is reasonable as the crops would be expected to exploit sub-soil water only when the top-soil water is depleted and, therefore, evapotranspiration can be restricted to the top-soil under adequate soil water supply conditions (Passioura, 2006). Furthermore, McKenzie *et al.* (2009) showed that the barley genotypes studied did not require sub-soil water, provided rainfall was adequate. AquaCrop allows the user to define depth of soil layers but these are predetermined as 0 – 15 cm, 15 – 30 cm and >30 cm in WaSim. Thus, depth of 0-30 cm and 30-60 cm for first two soil layers were defined for simulations using AquaCrop. In CropWat, however, the SWB is simulated only in relation to root depth and the soil is not layered. Hence, for CropWat, the measured soil water content was compared with the difference between available soil water and depletion in the root zone. In addition, yields

predicted by AquaCrop were compared with observed yields for the years 2009, 2010 and 2011. Yields from 2009 and 2010 were obtained from previous experiments.

The performances of AquaCrop, CropWat and WaSim were assessed using the normalized root mean square error (RMSE; Loague & Green, 1991) and D-Statistic (D-Stat), also known as index of agreement (Wilmot, 1982).

$$RMSE (\%) = \sum_{i=1}^n \sqrt{\left[\frac{P_i - O_i}{n} \right]^2} \times \frac{100}{m} \quad \text{Equation 3-3}$$

$$D - Stat = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i - m| + |O_i - m|)^2} \quad \text{Equation 3-4}$$

where P_i is the predicted value, O_i is the observed (measured) value, and m is the mean of the observed variable.

The RMSE indicates the overall model uncertainty and model performance improves as the RMSE approaches the lower limit of zero (Loague & Green, 1991). The D-Stat is a descriptive value, bounded between 0 and 1, which indicates the extent of agreement between the observed and predicted values. A value of 1 indicates excellent agreement (Wilmot, 1982).

3.4 Results

3.4.1 Weather

Total and mean daily rainfall over the season (8th April – 15th September, 2011) was 418.9 and 17.5 mm, respectively, with a range from 0.0 to 36.1 mm and standard deviation of 5.98. There was no rain on the days of sowing and harvesting and it was relatively dry during the first few days after sowing (DAS, Figure 3-2a). There was

relatively less rainfall during crop establishment and canopy expansion (from sowing to mid-June) than during anthesis, grain filling and the late stage or canopy senescence of the crop (from mid-June to mid-August). However, in-between the peaks, several minor rainfall events probably helped sustained the crops.

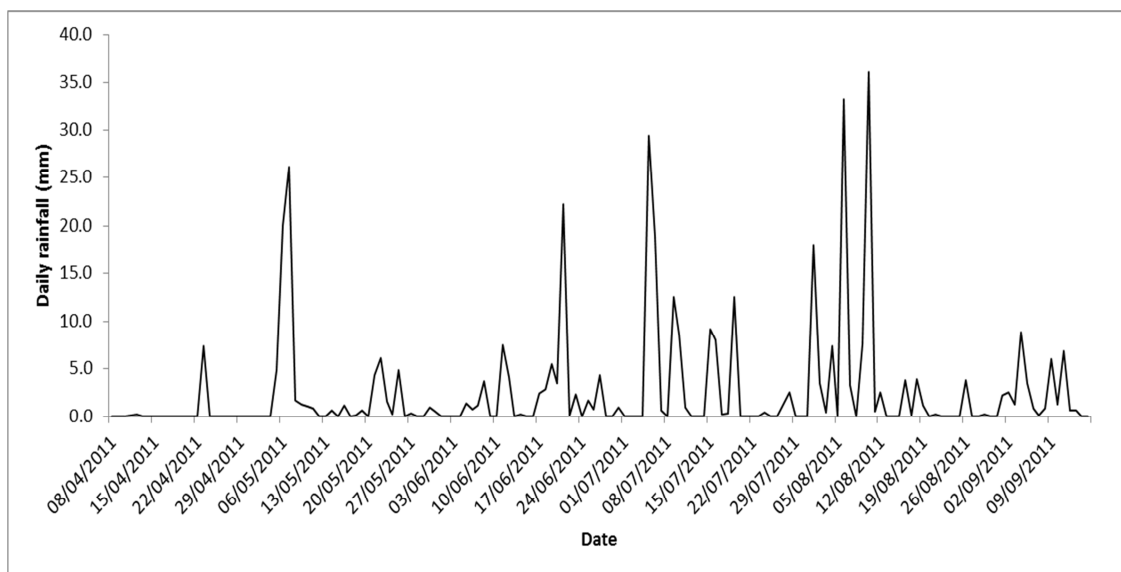


Figure 3-2a: Daily rainfall at the study site from sowing to the date of harvest (8th April – 15th September 2011).

Daily maximum temperatures over the growing season ranged from 12.3 to 23.6 °C, with a mean of 16.9 °C and a standard deviation of 2.33 °C. Temperature did not vary substantially during the growing season (Figure 3-2b). The highest daily maximum temperatures recorded were observed around sowing and early June, as well as in the early part of July. Daily reference evapotranspiration (ET_o) over the crop growing season ranged from 1.0 to 4.2 mm, with a mean of 2.16 mm and a standard deviation of 0.68 mm. Just as with temperature, daily ET_o was higher between early June and early July compared to other times (Figure 3-2b). Daily ET_o increased gradually from 5 DAS to late July but decreased thereafter until harvest. Apart from the few peaks in early June and

July, due to higher temperatures, daily ETo did not vary substantially over the growing season.

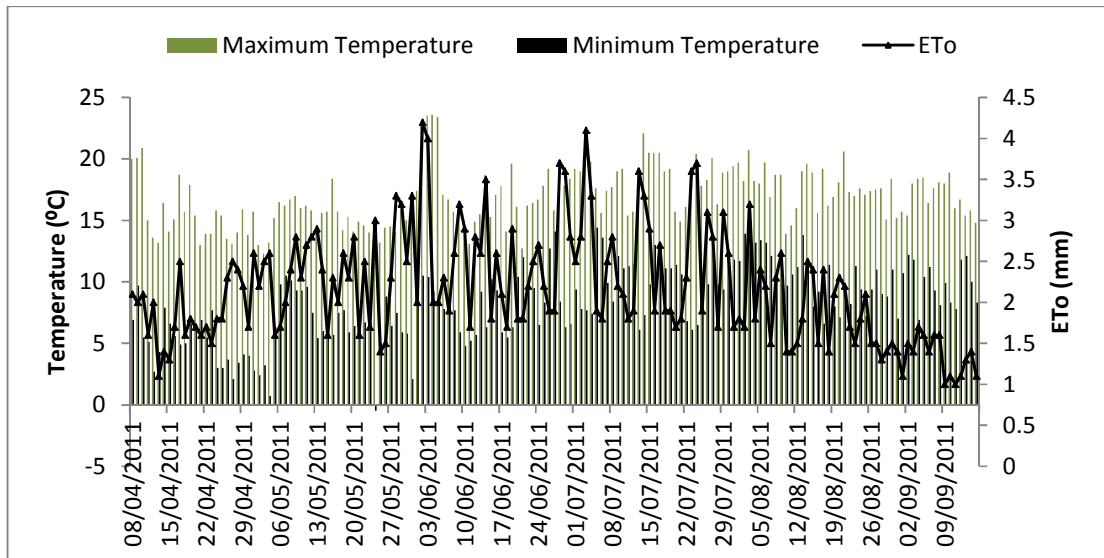


Figure 3-2b: Mean daily maximum and minimum temperatures and ETo at the study site from sowing to the date of harvest.

3.4.2 Daily and Seasonal Crop Water Use

The daily crop evapotranspiration (ET_c) of the barley genotypes simulated using AquaCrop ranged between 0.4 and 4.1 mm. The genotypes showed no substantial differences in their daily water use (Figure 3-3a). Daily ET_c increased slightly from mid-May to late July and declined thereafter, indicating the periods of canopy development and senescence respectively. However, during the late stage (from late July through August) the decline in daily ET_c of Bowman was steeper than that of the other genotypes, followed by Golden Promise (G. Promise). Apart from this, only slight differences in daily ET_c were observed among the genotypes during canopy senescence stage in the season.

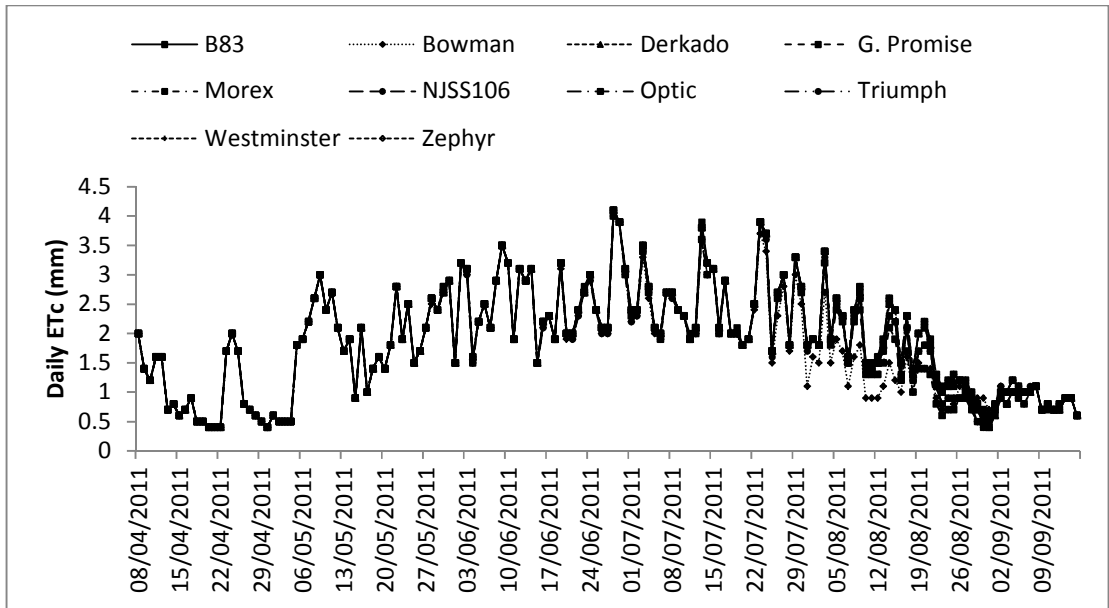


Figure 3-3a: Daily crop evapotranspiration (ETc) of barley genotypes simulated using AquaCrop.

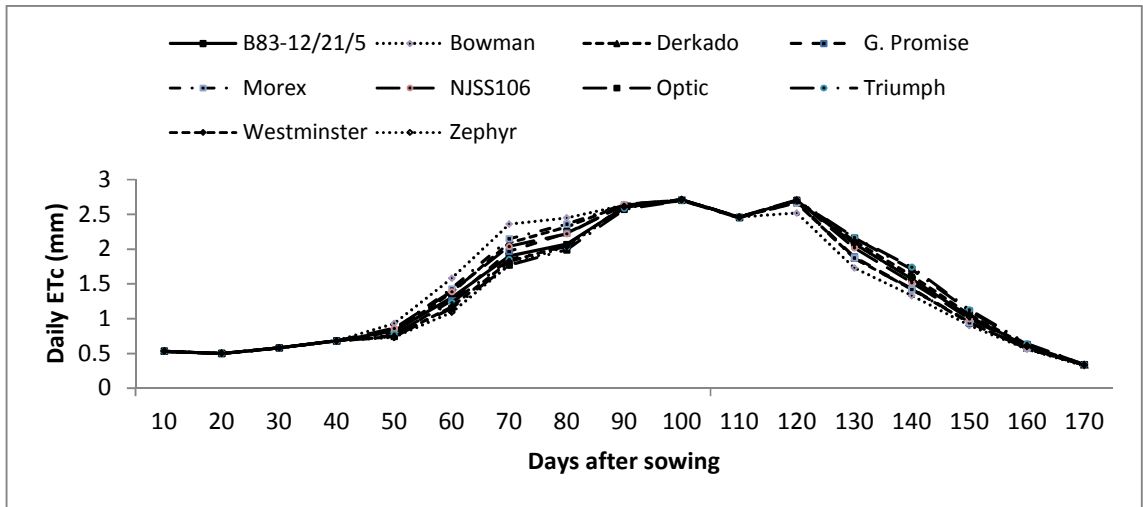


Figure 3-3b: Daily ETc (averaged over 10-day period) of barley genotypes simulated using CropWat.

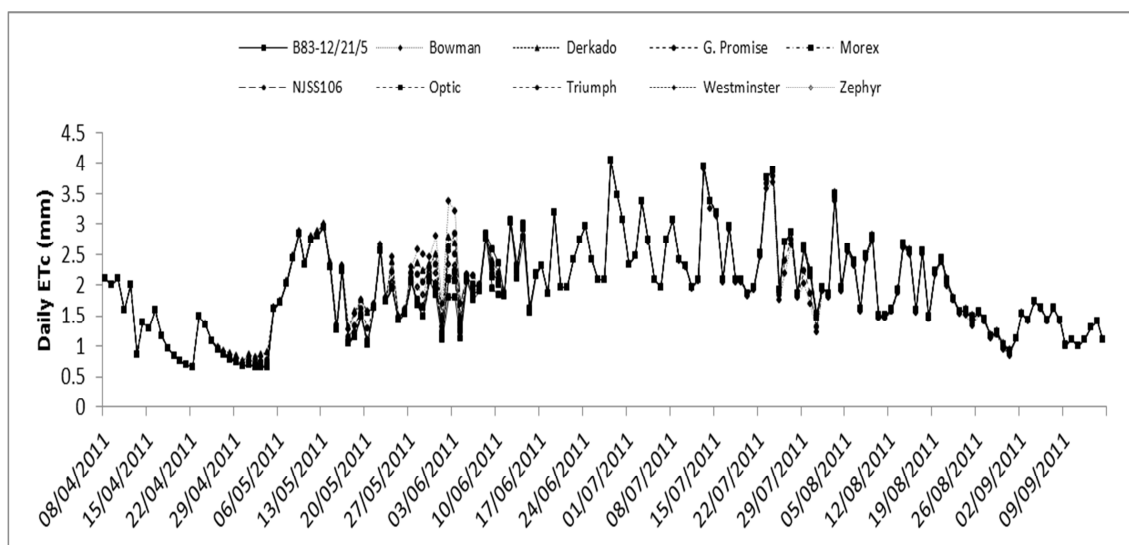


Figure 3-3c: Daily ETc of barley genotypes simulated using WaSim.

For simulations using CropWat, the output of daily ETc was given as averages of 10-day periods from sowing to harvesting (Figure 3-3b). The genotypes did not show substantial differences in daily ETc during the initial period (up to 40 DAS) and mid-season (between 90 and 120 DAS). However, slight differences between genotypes were observable during the development phase (50 to 90 DAS) and part of the late season (120 to 150 DAS), with Bowman showing the highest increase and decrease in daily ETc at these periods respectively. Daily ETc ranged between 0.62 and 2.71 mm. Similarly, the genotypes did not show substantial differences in their daily water use simulated using WaSim (Figure 3-3c). Only slight differences in daily water use between the genotypes were observed from mid-May to mid-June, with Bowman showing the greatest difference due to its rapid vegetative growth, which was also observed in the field. At this stage, B83-12/21/5 had the least daily ETc. Daily ETc for all the genotypes, simulated using WaSim, ranged from 0.65 to 4.06 mm.

Figure 3-4 shows the seasonal (cumulative) ET_c of the barley genotypes from the simulations using all the three models. For simulations using AquaCrop, Optic had the highest seasonal ET_c of 303.1 mm, followed by Zephyr (302.9 mm), with Bowman having the least value of 283.3 mm. The ET_c of Bowman was substantially lower than that of the other genotypes. With simulations using CropWat, the seasonal ET_c values ranged from 241.5 to 249.8 mm for Zephyr and Bowman respectively. The ET_c of Zephyr was substantially lower than that of the other genotypes. For simulations using WaSim, Derkado had the highest seasonal ET_c (319.2 mm), followed by Bowman, with B83-12/21/5 having the lowest value of 307.4 mm. Generally, seasonal ET_c of the genotypes simulated using WaSim are slightly higher than those from simulations using AquaCrop which are in turn higher than those simulated using CropWat. In all, the barley genotypes do not vary substantially in their daily or seasonal ET_c simulated using AquaCrop, CropWat or WaSim.

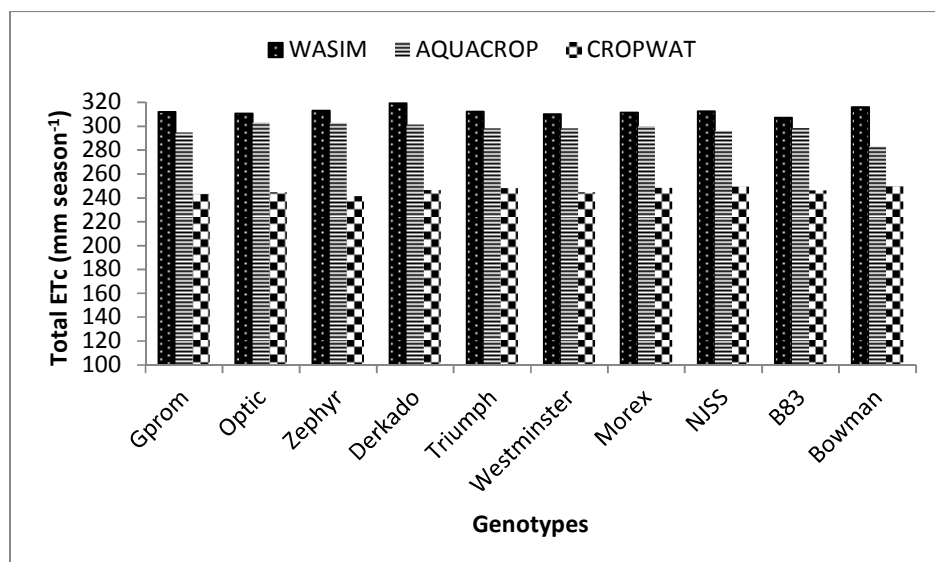


Figure 3-4: Comparison of the seasonal ET_c of the genotypes from the three models.

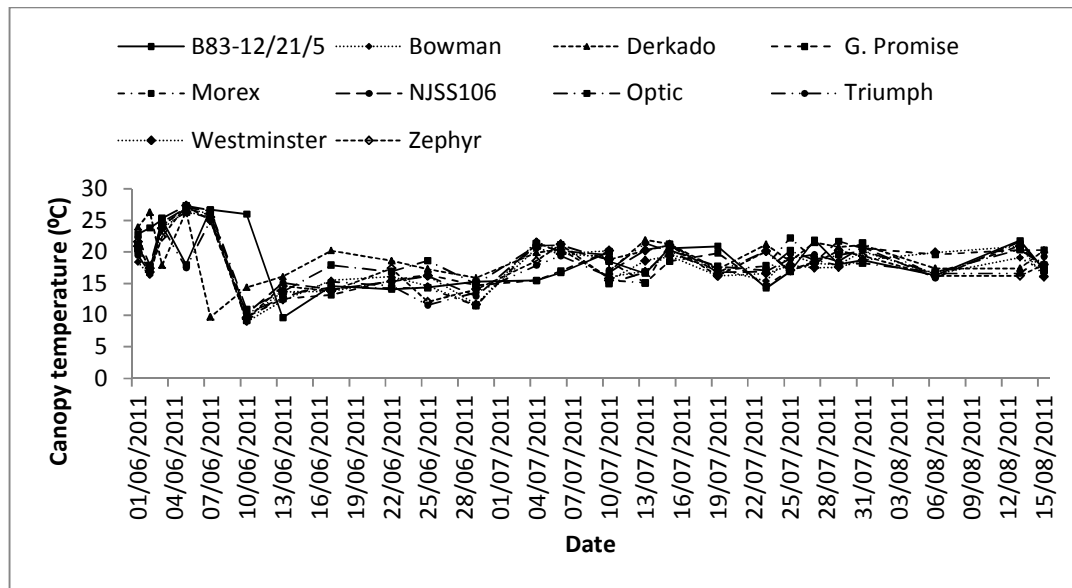


Figure 3-5: Average canopy temperatures of barley genotypes measured from 1st June to 15th August, 2011.

Average canopy temperatures of the barley genotypes also did not show substantial variations (Figure 3-5), partly confirming the similarity in pattern of water use. Even though the high temperatures in early June were largely reflected by the canopy temperatures, there was also high soil background noise in those images. Canopy temperatures also did not vary substantially over time (Figure 3-5). However, no relationship was found between canopy temperature and any of the weather variables or ETc.

The genotypes did not show substantial differences in canopy cover (from sowing to maximum cover) simulated using AquaCrop (Figure 3-6a). Differences were observable between the genotypes from maximum canopy cover to harvest, indicating that these differences (and for that matter ETc) depends on the extent of maximum canopy cover, its duration and rate at which the canopy declined after maximum development was reached. For simulations using WaSim, however, the canopy rose steeply from emergence to 20%

cover and then even more steeper from 20% cover to maximum canopy cover (Figure 3-6b). Between maximum cover and maturity, the canopy cover of the genotypes neither varied nor showed differences between the genotypes. After maturity, the canopy declined linearly until harvest.

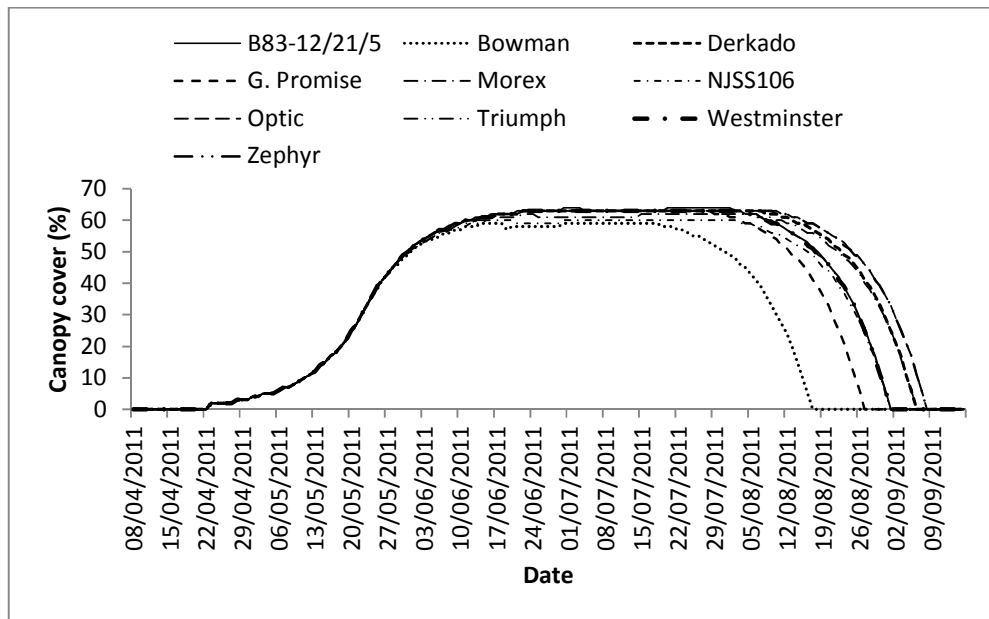


Figure 3-6a: Canopy cover of ten barley genotypes simulated using AquaCrop.

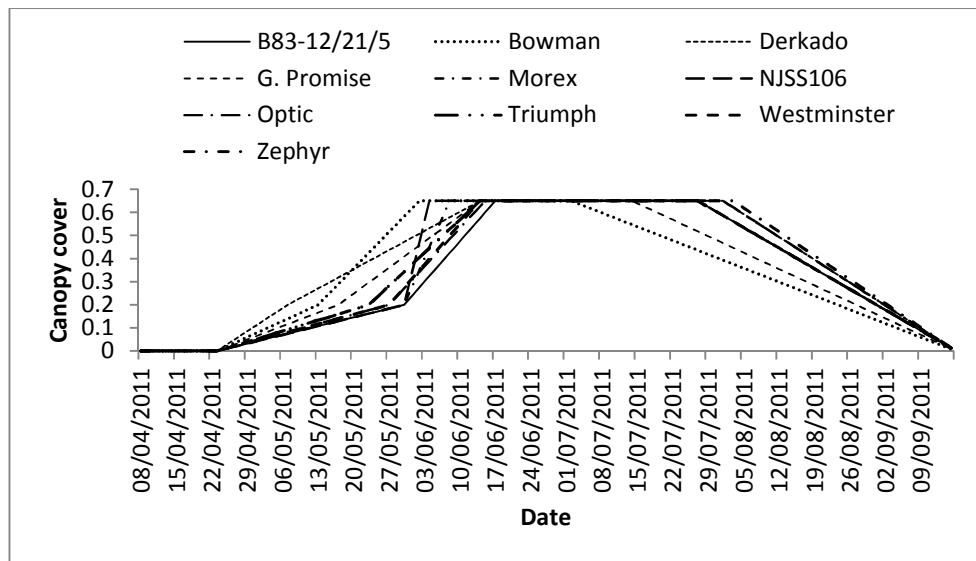


Figure 3-6b: Canopy cover of ten barley genotypes simulated using WaSim.

Spearman's rank correlation (r) was used to assess the agreement between the models on the order of the genotypes in terms of their simulated water use. Negative but significant rank correlation was found between AquaCrop and CropWat ($r = -0.73$, at 5% significance level) and between CropWat and WaSim ($r = -0.76$, at 5% significance level). However, a positive but weak relationship ($r = 0.43$) was found between AquaCrop and WaSim.

3.4.3 Performance Assessment of Models

Generally, for simulations using each of the three models, both the RMSE and D-Stat of the genotypes did not vary substantially but the general performance of the models to predict SWB followed the order WaSim > AquaCrop > CropWat (Table 3-5). For simulations using AquaCrop, the RMSE and D-Stat for all genotypes were approximately 8.1% and 0.65, respectively. The D-Stat value could be improved to approximately 0.80 if predicted SWB values higher than 100 mm (7 out of 107 data points, Figure 3-6a) were replaced with the average of all predicted values. For simulations using CropWat, the RMSE values ranged from 19.56% (Morex) to 24.56% (G. Promise), while D-Stat ranged from 0.14 (Bowman) to 0.25 (Morex). For simulations using WaSim, the RMSE and D-Stat values for all genotypes (except Bowman) were approximately 5.6% and 0.81 respectively (Table 3-5). The RMSE and D-Stat for Bowman were 2.96% and 0.94 respectively (Table 3-5).

Table 3-5: The RMSE and D-Stat as indicators of the ability of AquaCrop, CropWat and WaSim to predict soil water content under ten barley genotypes.

Genotypes	AquaCrop		WaSim		CropWat	
	RMSE (%)	D-STAT	RMSE (%)	D-STAT	RMSE (%)	D-STAT
B83-12/21/5	8.1046	0.6497	5.641	0.8079	22.5086	0.1933
Bowman	8.1097	0.6500	2.960	0.9355	24.0293	0.1429
Derkado	8.1019	0.6491	5.616	0.8091	23.2603	0.1930
G. Promise	8.0966	0.6491	5.6496	0.8076	24.5646	0.1875
Morex	8.1183	0.6512	5.6366	0.8079	19.5649	0.2494
NJSS106	8.1410	0.6496	5.6372	0.8079	23.8474	0.1836
Optic	8.1021	0.6490	5.6359	0.8081	22.4917	0.2245
Triumph	8.1784	0.6449	5.6328	0.8083	22.4487	0.2003
Westminster	8.1030	0.6489	5.6383	0.8080	20.8910	0.2008
Zephyr	8.1022	0.6491	5.6286	0.8084	23.3488	0.2087

The agreement between the measured soil water content and that predicted by AquaCrop, CropWat and WaSim can be graphically illustrated with reference to Bowman (Figures 3-7a, 3-7b and 3-7c). As indicated by the RMSE and D-Stat (Table 3-5), generally, WaSim predicted SWC better than AquaCrop, which in turn predicted SWC better than CropWat (Figure 3-7). It can be seen that the measured soil water content did not vary substantially over time.

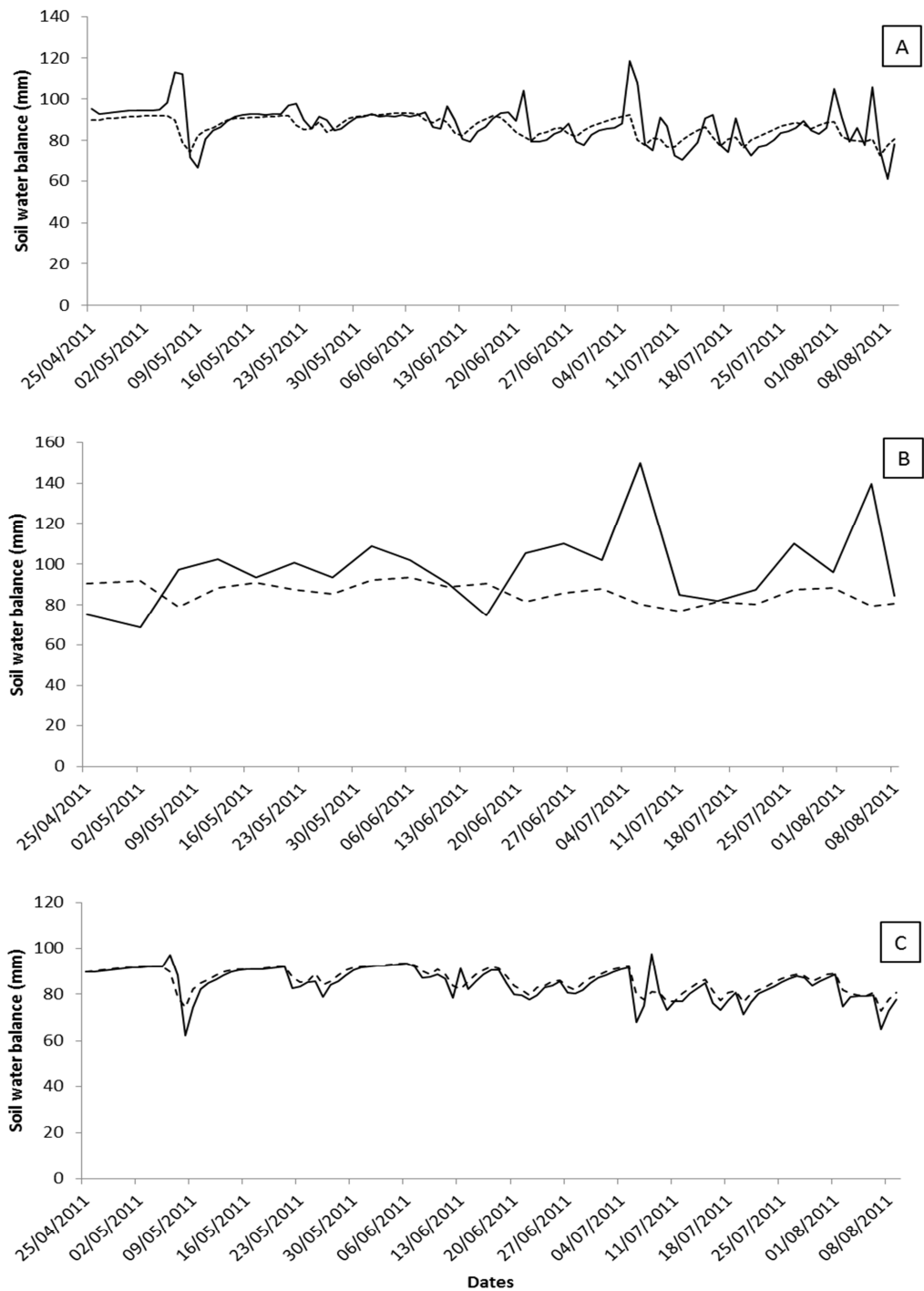


Figure 3-7: Graphical illustration of the agreement between the measured soil water content (---) and the soil water content predicted by (A) AquaCrop, (B) CropWat and (C) WaSim (—) for Bowman during the period 25th April to 8th August 2011.

AquaCrop generally predicted temporal variations in SWC accurately, although it occasionally predicted far higher SWCs than were actually observed (Figure 3-7a). The greatest deviations can be observed in early May and July. CropWat showed the greatest deviation from the measured SWC. CropWat consistently overestimated the SWC and also occasionally predicted far higher SWCs than were measured (Figure 3-7b). Predictions using WaSim showed the closest agreement with the measured SWC, although it often slightly underestimated the SWC (Figure 3-7c).

3.4.4 Comparison of Actual and Predicted Yields

The ability of AquaCrop was further tested by comparing yields predicted by AquaCrop with observed yields for barley genotypes grown in 2009, 2010 and 2011 (Table 3-6). The yields predicted by AquaCrop in 2009 and 2010 were generally lower than the observed yields. The observed yields in 2009 ranged from 4.71 (NJSS106) to 11.39 t ha⁻¹ (Derkado) while the predicted yields ranged from 5.15 to 8.94 t ha⁻¹, with differences between observed and predicted yields for individual genotypes ranging from -0.44 to 2.4 tons ha⁻¹. Only three genotypes, out of the ten studied, recorded yield differences over 1.0 t ha⁻¹. In 2010, the observed yields ranged from 4.75 (NJSS106) to 8.60 t ha⁻¹ (Westminster) and the predicted values ranged from 5.01 to 7.69 t ha⁻¹. The differences between observed and predicted yields for individual genotypes ranged from -0.95 to 0.91 t ha⁻¹. Bowman had the lowest observed yield (3.47 t ha⁻¹) while Derkado had the highest yield (6.76 t ha⁻¹) in 2011, with the predicted yields ranging from 4.07 to 6.50 t ha⁻¹. The differences between observed and predicted yields for individual genotypes

ranged from -1.61 to 0.47 t ha⁻¹. Only Bowman had absolute yield difference over 1.0 ton ha⁻¹. Thus, with the exception of B83-12/21/5, Derkado and Westminster in 2009 and Bowman in 2011, the absolute differences between yields predicted by AquaCrop and the observed yields were less than 1.0 ton ha⁻¹. Derkado and Westminster showed the highest yields while NJSS106 was the lowest yielding genotype. In general, yields in 2009 were highest and 2011 had the lowest yields. Spearman's rank correlation (r) was used to assess the agreement between the order of observed and predicted yields for each of 2009, 2010 and 2011. A strong, positive rank correlation was found for the year 2009 (r = 0.90 at 1% significance level) but negative relationships were found for the years 2010 (r = -0.61) and 2011 (r = -0.56).

Table 3-6: Differences (ΔY , tons ha⁻¹) between observed yields (Y_o , tons ha⁻¹) and yields predicted by AquaCrop (Y_p , tons ha⁻¹) of ten barley genotypes grown in 2009, 2010 and 2011.

Genotype	2009			2010			2011		
	Y _o	Y _p	ΔY	Y _o	Y _p	ΔY	Y _o	Y _p	ΔY
B83-12/21/5	8.29	7.00	1.29	6.65	6.65	0.00	6.47	6.08	0.39
Bowman	-	-	-	6.62	5.95	0.67	3.47	5.08	-1.61
Derkado	11.39	8.90	2.4	6.84	6.75	0.09	6.76	6.36	0.40
G. Promise	7.80	6.87	0.93	6.81	6.00	0.81	6.44	5.97	0.47
Morex	8.00	7.22	0.78	5.55	6.50	-0.95	4.76	5.25	-0.49
NJSS106	4.71	5.15	-0.44	4.75	5.01	-0.26	3.52	4.07	-0.55
Optic	7.52	7.15	0.37	6.00	6.51	-0.51	6.00	6.50	-0.50
Triumph	8.78	7.90	0.88	6.78	6.63	0.15	5.58	6.05	-0.47
Westminster	10.67	8.94	1.73	8.60	7.69	0.91	6.64	6.50	0.14
Zephyr	6.56	6.24	0.32	6.86	6.78	0.08	5.31	6.11	-0.8

3.5 Discussion

3.5.1 Water Availability and Crop Growth

Three water-driven crop simulation models were used to simulate the growth of 10 barley genotypes grown in 2011. In water-driven crop growth simulation models, soil water deficit is the main cause of reduction in biomass production and yield (Raes *et al.*, 2009; Todorovic *et al.*, 2009). However, in the current study, no symptoms of water stress were observed in barley growing in the field in 2011, and none of the simulation models used indicated any yield reduction due to water stress. This suggests that soil water content was sufficient for crop growth throughout the 2011 growing season. Indeed, 2011 was the wettest year recorded for Scotland (Centre for Ecology and Hydrology, 2012).

The relatively dry conditions 1-14 DAS could be responsible for the slight delay in emergence (Figure 3-2a) but the observations of González and Ayerbe (2011) suggest that even though short-term water deficit slows coleoptile growth in barley, the coleoptile is able to recover and resume rapid growth when water supply is restored. They reported further that the ability of barley coleoptile to grow, in spite of water deficit, corresponded with a greater capacity for osmotic adjustment even in the later stage of development, a trait that can be explored in breeding for drought tolerance. It is probable that residual soil water content between sowing and emergence sustained coleoptile growth. The ability of barley to recover quickly from temporary water-stress has been observed previously (González, *et al.*, 1999; Shone & Flood, 1983). However, water stress during early crop establishment can affect yield adversely when tillering is limited, as barley has a low ability to compensate for poor tillering at later stage (HGCA, 2006; González, *et al.*,

1999). In the experiment reported here, sufficient rainfall after the first two weeks of sowing enabled the crops to grow rapidly and become established. Even though warmer temperatures and high ETo occurred in late May to early June (Figure 3-2b), the distribution of rainfall suggests that soil water content would be sufficient during anthesis and grain-filling which are the most sensitive periods to water stress (Alderfasi, 2009). However, high water potential in the root zone of barley can potentially increase the vegetative growth period and delay the reproductive phase (if nutrients are not limiting) due to excessive uptake and translocation of water and nutrients to shoots (Alderfasi, 2009; Shone & Flood, 1983). This might account for the low yields observed in 2011 compared to 2009 and 2010.

3.5.2 Crop Water Use

There are very few estimates (empirical or simulated) of barley water use under rain-fed conditions (Rötter *et al.* 2012). In the current study, the simulated seasonal ETc using the three models for all barley genotypes ranged from 241.5 to 319.2 mm season⁻¹ (Figure 3-4). These values are lower than those reported for Alberta, Canada (390-430 mm season⁻¹, Government of Alberta, 2008), south-east England (490 mm season⁻¹, Chatterton *et al.*, 2010), northern Ethiopia (375 mm season⁻¹, Araya and Fantahun, 2010), and FAO generic values (450-650 mm season⁻¹, FAO, 1986). This can be attributed to differences in the method of estimation or climate and weather conditions which influence ETo and consequently ETc. For example, Araya and Fantahun (2010) used lysimeters to measure ETc which is indirectly estimated in the current study. The peculiar wet conditions

experienced in 2011 might also partly account for the lower ET_c observed in the current study as rainfall is likely to increase the moisture content of the air surrounding the canopy and reduce irradiance. Obviously, the period of canopy expansion up to maximum canopy cover when ET_c is expected to rise steadily coincided with frequent rainfall (Figure 3-2a) and low ET_o (Figure 3-2b), resulting in reduced and less variable daily ET_c (Figure 3-3).

Results from the simulations using each of the models show that neither the daily nor the seasonal ET_c varied substantially among the genotypes studied. Similarly, canopy temperatures of the genotypes did not vary substantially (Figure 3-5) and canopy temperature is known to be directly related to ET_c (Leinonen & Jones, 2004). The observed similarity in water use of the barley genotypes can be attributed to adequate soil water availability throughout the growing season. This finding is in agreement with Alderfasi (2009) who reported that two barley genotypes (Jesto and Sahrawe) did not differ in their water use when soil water supply was adequate. Normally, differences in water use among crop genotypes are often observed under conditions of soil water deficit (González & Ayerbe, 2011). This suggests that small differences in the timing of phenological stages between the genotypes did not affect overall crop water use. This observation is in agreement with Alderfasi (2009). Thus, to capture or examine differences in water use among the genotypes, experiments under both water-stressed and unstressed conditions are necessary.

Moreover, the observed similarity in water use among the different genotypes can also be due to similarities in their ability to acquire water from the soil. A root restriction experiment was performed by McKenzie *et al.* (2009) at the site where the current study was conducted to examine the abilities of B83-12/21/5, Derkado, G. Promise, Morex and

Optic to acquire water from the subsoil. They found that, even though the genotypes differed in some above-ground parameters (such as plant height, tiller number and normalized difference vegetation index), they did not differ in their ability to acquire water from the topsoil or to exploit pores in a restrictive mesh to acquire water from the subsoil. Similar observations have been made by Alderfasi (2009). It is likely that the use of the same root length value for all the genotypes in the simulations for the current study might have also contributed to the similarity in ET_c. Nonetheless, this finding in the current study suggests that barley genotypes grown in temperate northern Europe might not differ substantially in their water use if there is adequate soil water supply. Under such condition, differences in yield become the only criterion for selecting water-efficient barley genotypes.

3.5.3 Statistical Performance of the Models

The direct relationship between SWB and ET_c (Kirnak *et al.*, 2002) makes SWB a good route for directly estimating ET_c. In this study, ET_c was estimated indirectly and validated through a comparison of simulated SWB and empirically measured soil water content. The hypothesis is that a model that is able to simulate SWB with acceptable accuracy will likely simulate ET_c with good accuracy. Technically, a Theta Probe measures the water content of a smaller volume of soil compared to neutron probe or even gravimetric measurement (Campi *et al.*, 2008; Schmutz, 2007). However, assuming that the ratio of soil:water volume is constant in the layer under consideration (i.e. assuming conditions of uniform distribution of water in a homogenous layer of soil), then it could be

argued that the volume of soil measured for water content by the Theta Probe is inconsequential. Moreover, the study by Schmutz (2007) showed that the sensitivity of Theta Probe to variations in soil moisture content weakened when the length of the sensor rod was reduced but the accuracy of Theta Probe in measuring moisture content was not affected by sediment size. Campi *et al.* (2008) reported that Theta Probe sensor gave accurate measurements of surface soil water content in a Mediterranean environment.

Seasonal ET_c predicted by WaSim were slightly higher than the predictions by AquaCrop but both were substantially higher than the seasonal ET_c predicted by CropWat (Figure 3-4). These differences can result from differences in (a) the assumptions underlying the partitioning of water input between ET, drainage, surface runoff and soil storage (b) the relationships among sub-models and crop growth parameters, or (c) contrasting sensitivities to crop development stages (Rötter *et al.* 2012; Raes *et al.*, 2009; Todorovic *et al.*, 2009). It can be deduced from Figure 3-3 that AquaCrop is more sensitive to the onset of senescence when water use declines sharply. This might explain why Bowman and G. Promise had relatively lower water use as they showed aggressive vegetative growth in the field but were also the first to senesce and therefore had a longer period of senescence (Figure 3-6a). CropWat is more sensitive to the lengths of the development and late stages (Figure 3-3b). Compared to AquaCrop and WaSim, the low ET_c estimated by CropWat can be attributed to the fact that CropWat uses a fixed rate of change in crop coefficient (K_c) with time even though ET_c actually varies over short time scales with weather, canopy cover and wetting and drying of the soil surface (Hess, 2010; Shahin, 2003). WaSim can be said to be more sensitive to the transition from development to mid-stages (i.e. between 20% canopy cover to full cover) but only slightly sensitive to

the senescence stage (Figure 3-4a, 3-6b) so that Bowman which had rapid canopy development could have higher ETC. The faster canopy expansion and slightly higher maximum canopy covers estimated by WaSim could account for the higher ETC predicted by WaSim than AquaCrop. Thus, WaSim largely uses Kc in a way similar to CropWat (Figure 3-6b), except that WaSim applies different Kc values to different phenophases using linear interpolation and in relation to canopy cover. These sensitivities might be worth exploring in future studies but, in all, AquaCrop simulates canopy expansion more realistically than the other models.

According to Jamieson *et al.* (1991) the performance of a model is considered excellent when normalized RMSE is <10%, good if it is between 10 and 20%, fair if it is between 20 and 30% and poor if it is > 30%. Therefore, the performance of WaSim and AquaCrop can be considered excellent compared to CropWat which was fair (Table 3-5). However, when considering D-Stat, CropWat predicted SWB poorly and disagrees substantially with the observed SWC.

In AquaCrop, the pattern of soil water depletion by crops is more realistic and largely agrees with current knowledge (Raes *et al.*, 2009). Hence, depending on root growth, soil water depletion can occur simultaneously in both upper and lower layers. This can result in overestimation of the SWB of the upper layer as observed in the current study, especially when barley is capable of restricting water acquisition to the upper layer under conditions of sufficient water supply (McKenzie *et al.*, 2009). A tendency of AquaCrop to overestimate the water balance of surface soil has been reported previously (Farahani *et al.*, 2009), even though in this study there were instances of over- and under-estimation. Moreover, there have been instances in which AquaCrop has been reported to

perform better with non-water stressed conditions than with irrigated conditions in which water stress is imposed (e.g. Stricevic *et al.*, 2011; Hussein *et al.*, 2011; Patel *et al.*, 2011; Heng *et al.*, 2009; Farahani *et al.*, 2009; Salemi *et al.*, 2011). Thus, the better performance of AquaCrop in this study could be partly due to the absence of water stress. Few studies have validated SWB or used it as a proxy for validating ETc in simulation studies. The better performance of AquaCrop is in agreement with the findings of Hussein *et al.* (2011), Araya *et al.* (2010a; 2010b), Farahani *et al.* (2009) and Geerts *et al.* (2009) although the performance values in the current study are lower compared to these previous studies. In addition to simulating ETc and SWB, AquaCrop also provides information on biomass production and yield. Yields predicted by AquaCrop did not deviate greatly from the observed yields for the years 2009, 2010 and 2011 for most of the genotypes studied (Table 3-6), although it often underestimated the yield. AquaCrop seems conservative in estimating yields, that is, it estimates extreme yields poorly (overestimate low yields and underestimate high yields, Table 3-6). However, the range of deviations of predicted yields from actual yields of barley in this study compares well with the range of deviations of predicted yields from actual yields of barley reported for Ethiopia (Araya *et al.*, 2010a). The experiment in 2009 was conducted under relatively drier conditions (McKenzie *et al.*, 2009) compared to 2010 and 2011, and this might account for the relatively higher yields observed in 2009. This suggests that wet conditions can substantially reduce barley yields and influence inter-annual variations in yields.

The relatively poor performance of CropWat compared to AquaCrop and WaSim can be attributed to limitations associated with the use of the effective rainfall method and its inability to separate water depletion at different depths in the soil (Hess, 2010).

CropWat uses a single soil layer and water deficit is balanced when it rains. In the event of rainfall, it is likely that topsoil will be filled first (even to field capacity) whereas the subsoil might remain unsaturated or even dry. Since CropWat precludes this possibility due to its use of a single soil layer, soil water depletion pattern will likely be inconsistent with measured SWB of the topsoil. Because WaSim is a one-dimensional model and water in an upper soil layer is depleted before water in a sub-layer is used, rapid depletion of water from the upper layer could result in relatively higher ET_c and lowered SWB. This might explain why WaSim predicted higher ET_c and often underestimated SWB in the upper soil layer. The better performance of WaSim in terms of predicting SWB might also be due to the fact that it was designed basically for water balance studies while AquaCrop is focused around crop sensitivity to water stress and realistic pattern of water depletion by crops. Moreover, the difference could also arise from the use of default drainage characteristic values of the models. A few studies have investigated the ability of WaSim to simulate crop water use, with good agreement between simulated and observed data (Hess, 2010; Fasinmirin *et al.*, 2008; Abbot *et al.*, 2001). They all concluded that WaSim has potential for ET and water balance studies. In general, some crop parameters used (such as K_c) were adapted from other sources which can give rise to model uncertainties as these parameters have not been calibrated for Scottish conditions. However, considering the possibility of such uncertainties in relation to the performance of the models, it can therefore be concluded that both AquaCrop and WaSim have potential for simulating barley growth and water use under the environmental conditions prevalent in temperate northern Europe.

In general, the findings are also in agreement with similar studies in other environments. Todorovic *et al.* (2009) reported that AquaCrop, CropSyst and WOFOST all predicted final biomass, yield and ET of sunflower in Southern Italy satisfactorily, although AquaCrop was slightly better than the other two models. Hess (2010) compared WaSim and CropWat in simulating the water use of pasture in England and reported that WaSim performed better than CropWat and that CropWat's effective rainfall method, commonly used in the virtual water literature, underestimated pasture water use and might not be suitable for English conditions. George *et al.* (2000) simulated soil water content with CropWat and Irrigation Scheduling Model and showed that even though the models gave comparable results, CropWat slightly underestimated ET_c of beans. By contrast, Kang *et al.* (2009) reported that neither CropWat nor CERES-Wheat nor MODWht predicted daily ET_c of winter wheat in Zenghou (China) or Bushland (Texas, USA) satisfactorily.

3.6 Conclusions

1. Simulations using AquaCrop, CropWat and WaSim indicated that the 10 barley genotypes studied did not differ substantially in either their daily or seasonal ET_c.
2. The seasonal ET_c simulated using WaSim was greater than that of AquaCrop, which was greater than that of CropWat.
3. Differences in the sensitivities of the models to water use at different crop development stages might account for the observed differences in seasonal ET_c predicted by each model for each genotype.

4. Model performance evaluated with normalised RMSE and D-Statistic values indicated that AquaCrop and WaSim performed excellently, while CropWat's performance was fair.

5. AquaCrop and WaSim are better for estimating barley water use in Scotland than CropWat.

6. The yields predicted by AquaCrop compared satisfactorily with the observed yields.

7. The results show that local level studies of multi-model comparisons can improve the accuracy of quantifying crop water use or virtual water content.

CHAPTER 4**EFFECT OF CLIMATE CHANGE ON UK BARLEY YIELDS****4.1 Introduction**

Generally, precipitation in the UK decreases from west to east and north to south while the reverse is true for temperature (Figure 4-1a, 4-1b). Long-term trends show that Scotland is becoming wetter while England and Wales are experiencing drier summers and wetter winters (Jenkins *et al.*, 2009; 2008). The UK Climate Projections 2009 (UKCP09; <http://ukclimateprojections.defra.gov.uk>) presents the most current and widely used evidence and projections of climate change for the UK (Jenkins *et al.*, 2009; Murphy *et al.*, 2009). By the 2050s and under the high emission scenario (HES), projected changes in summer mean precipitation of the baseline period (1961-1990) for all UK regions (Figure 4-1a) ranges from -45% to +9% (Table 4-1a). A wider range of uncertainty (defined as the range from the lowest to highest value of change for all three emissions scenarios and all three probability levels – 10, 50 and 90%, – Murphy *et al.*, 2009) is from -45% to +16%. Projected changes in summer mean precipitation under the medium emissions scenario (MES) and the HES are not substantially different (Table 4-1a). Winter precipitation is projected to increase in all UK regions (Jenkins *et al.*, 2009; Murphy *et al.*, 2009). Projected changes in precipitation exhibit greater uncertainty than temperature (Hawkins & Sutton, 2011; 2009; Murphy *et al.*, 2009).

Table 4-1a: Projected changes (%) in summer mean precipitation of UK regions in the 2050s relative to the climate of the baseline period (1961-1990). Data taken from UKCP09.

Region	Probability Levels (HES)			Probability Levels (MES)			Probability Levels (LES)			WR
	10%	50%	90%	10%	50%	90%	10%	50%	90%	
EE	-40	-18	+8	-38	-17	+6	-34	-13	+14	-40 +14
EM	-38	-17	+7	-36	-16	+6	-33	-12	+13	-38 +13
NI	-28	-12	+4	-27	-13	+3	-24	-9	+8	-28 +8
NEE	-31	-15	+2	-30	-15	+1	-28	-12	+7	-31 +7
NES	-28	-13	+2	-27	-13	+1	-26	-11	+6	-28 +6
NWE	-37	-18	+2	-36	-18	+1	-34	-14	+8	-37 +8
NWS	-24	-10	+3	-24	-11	+2	-21	-8	+6	-24 +6
SEE	-43	-19	+9	-41	-19	+7	-37	-14	+9	-43 +16
SES	-28	-13	+2	-27	-13	+1	-26	-11	+6	-28 +6
SWE	-45	-20	+8	-42	-20	+7	-39	-14	+16	-45 +16
SWS	-28	-13	+2	-27	-13	+1	-25	-10	+6	-28 +6
WA	-38	-17	+7	-36	-17	+6	-33	-12	+13	-38 +13
WM	-39	-17	+7	-37	-17	+6	-33	-12	+14	-39 +14
YH	-38	-18	+3	-36	-19	+1	-34	-15	+9	-38 +9

Key: *HES*, *MES*, and *LES* are High, Medium and Low Emissions Scenarios respectively. *WR* denotes Wider Range; *EE* denotes East of England; *EM* denotes East Midlands; *NI* denotes Northern Ireland; *NEE* denotes North East England; *NES* denotes North East Scotland; *NWE* denotes North West England; *NWS* denotes North West Scotland; *SEE* denotes South East England; *SES* denotes South East Scotland; *SWE* denotes South West England; *SWS* denotes South West Scotland; *WA* denotes Wales; *WM* denotes West Midlands; *YH* denotes Yorkshire and Humber. *Probability* refers to the extent to which a projected climatic variable is supported by currently available evidence (Murphy *et al.*, 2009).

Table 4-1b: Projected changes (°C) in summer mean temperature of UK regions in the 2050s relative to the climate of the baseline period (1961-1990). Data taken from UKCP09.

Region	Probability Levels (HES)			Probability Levels (MES)			Probability Levels (LES)			WR
	10%	50%	90%	10%	50%	90%	10%	50%	90%	
EE	1.3	2.9	4.8	1.2	2.5	4.3	1.0	2.4	4.0	1.0-4.8
EM	1.3	2.8	4.7	1.2	2.5	4.2	1.0	2.3	3.9	1.1-4.7
NI	1.1	2.4	4.0	1.0	2.2	3.5	0.8	1.9	3.2	0.8-4.0
NEE	1.4	2.9	4.7	1.2	2.5	4.1	1.1	2.4	3.8	1.1-4.7
NES	1.3	2.7	4.5	1.1	2.3	3.9	1.0	2.2	3.6	1.0-4.5
NWE	1.5	3.0	4.7	1.2	2.6	4.1	1.1	2.4	3.8	1.1-4.7
NWS	1.1	2.4	3.9	0.9	2.0	3.4	0.9	1.9	3.1	0.9-3.9
SEE	1.4	3.1	5.2	1.3	2.8	4.6	1.4	2.6	4.3	1.1-5.2
SES	1.3	2.7	4.5	1.1	2.3	3.9	1.0	2.2	3.6	1.0-4.5
SWE	1.4	3.1	5.1	1.3	2.7	4.6	1.1	2.5	4.1	1.1-5.1
SWS	1.3	2.8	4.4	1.1	2.4	3.8	1.0	2.2	3.6	1.0-4.4
WA	1.3	2.8	4.6	1.2	2.5	4.1	1.0	2.2	3.7	1.0-4.6
WM	1.4	2.9	4.8	1.2	2.6	4.4	1.0	2.3	3.9	1.0-4.8
YH	1.2	2.6	4.4	1.1	2.3	3.9	0.9	2.2	3.6	0.9-4.4

By the 2050s, the projected changes in summer mean temperatures for all UK regions, relative to the climate of the baseline period (Figure 4-1b), range from 0.8 °C to 5.2 °C (Table 4-1b). Correspondingly, projected changes in winter mean temperatures range from 0.6 °C to 3.8 °C (Murphy *et al.*, 2009). Generally, warmer and wetter winters, hotter and drier summers with frequent hot spells are projected (Jenkins *et al.*, 2009; Murphy *et al.*, 2009). Central estimates under the medium emission scenario (MES) show that the number of days with heavy rain events (rainfall greater than 25 mm) will increase by a factor of between 2 and 3.5 in winter, and 1 to 2 in summer over most of the lowland UK in the 2080s (Jenkins *et al.*, 2009; Murphy *et al.*, 2009). More information on climate change projections for the UK regions can be found in Murphy *et al.* (2009).

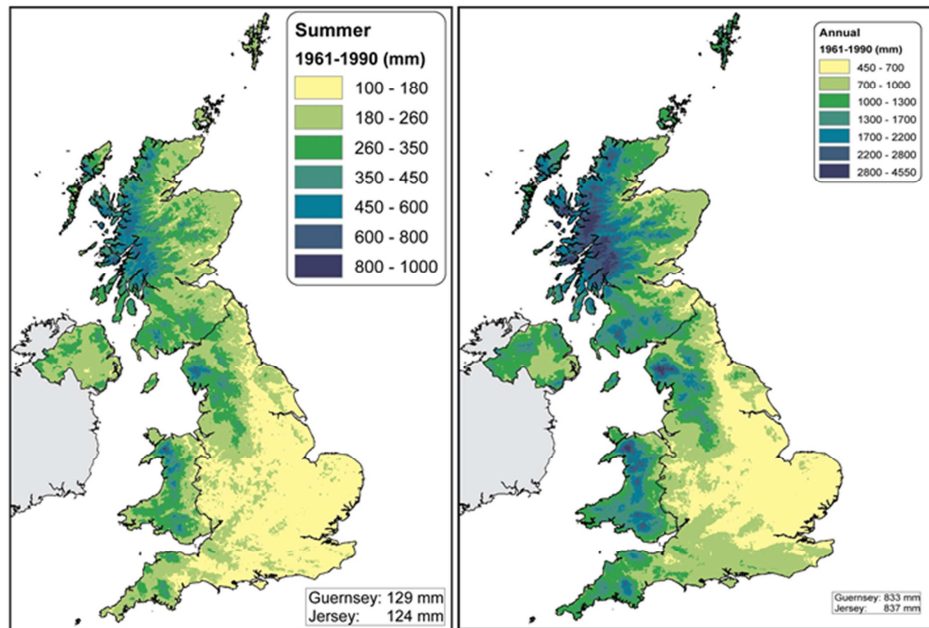


Figure 4-1a: Summer mean (left) and annual (right) precipitation in the UK for the baseline period (1961-1990). Figure taken from Jenkins *et al.* (2008).

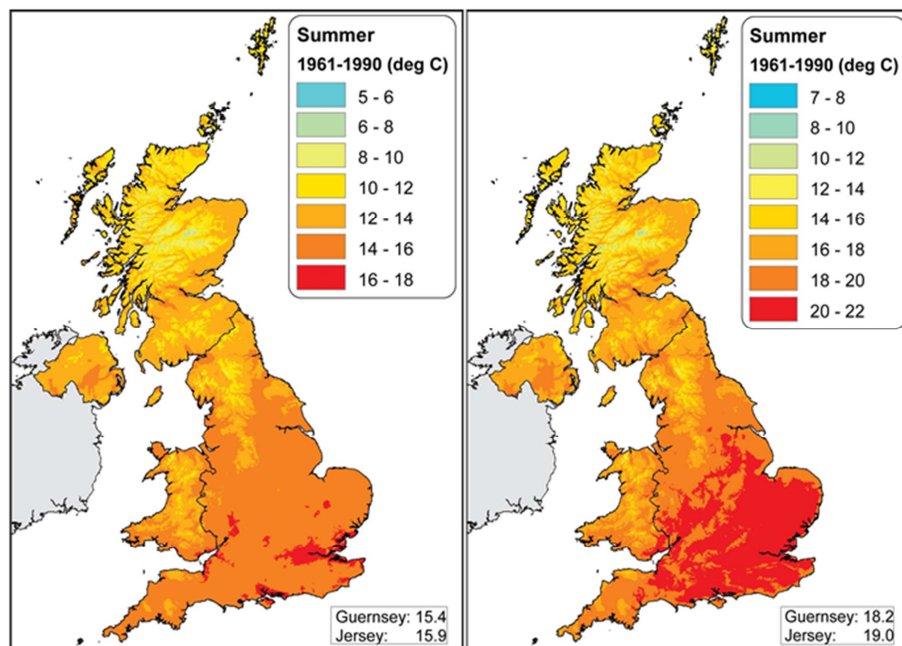


Figure 4-1b: Summer mean (left) and maximum (right) temperatures in the UK for the baseline period (1961-1990). Figure taken from Jenkins *et al.* (2008).

Globally, barley (*Hordeum vulgare* L.) is the 4th most important cereal crop (in terms of quantity of grain produced) with a wide spatial distribution due to its tolerance of a wide range of growing conditions (Newton *et al.* 2011). About 53% of barley grains produced globally is used as feed for animals; the remainder goes into malting and, to a lesser extent, food for human consumption (Newton *et al.*, 2011). The straw is also used as animal bedding and feed. In the UK, where cereals cover 50% of cultivated land, barley is the second most important arable crop after wheat and the number one crop in Scotland in terms of area cultivated and quantity produced (Defra, 2011). In 2011, barley production occupied 970,000 ha of cultivated land in the UK, with a national production of 5.5 million tonnes at a value of £860 million, excluding contributions from the barley-based industrial and commercial sectors (Defra, 2011). Current UK average yield (2000–2010) is approximately 5.3 tons ha⁻¹. Over 60% of barley produced in the UK is used as animal feed while a little over 30% is used in the malting industry (Defra, 2011). Premium whiskey and malt barley production confers a cultural significance to barley in the UK. Thus, barley production is economically, politically and socio-culturally important to the UK.

Projected climate change presents both opportunities and threats to barley production in all countries where it is grown. In northern temperate environments such as the UK, elevated atmospheric CO₂, together with moderate warming and adequate soil water supply, is likely to be beneficial to C₃ cereal crops such as barley (Rötter *et al.*, 2011; DaMatta *et al.*, 2010; Richter & Semenov, 2005; Fuhrer, 2003). Such conditions could increase photosynthetic capacity through radiation and water use efficiency and thereby increase biomass production and harvest index of barley (Claesson & Nycander

2013; Clausen *et al.*, 2011; Robredo *et al.*, 2011; 2007; Wall *et al.* 2011; Manderscheid *et al.*, 2009; Barnabàs *et al.*, 2008; Richter & Semenov, 2005; Holden *et al.*, 2003; Fangmeier *et al.*, 2000; Sæbø & Mortensen, 1996). Conversely, projected climate change also threatens to escalate abiotic stresses in barley production. Barley, like all cereals, is particularly sensitive to soil water dynamics and temperature around establishment, anthesis and grain filling (Anjum *et al.*, 2011a; Semenov & Shewry, 2011). Barley is widely known as being moderately tolerant to soil water deficits due to its capacity for osmotic adjustment and recovery from short-term water stress (González & Ayerbe, 2011; González *et al.*, 1999; Shone & Flood 1983). However, it is also sensitive to anoxic conditions (caused by waterlogging) and heat stress, and compensates poorly for reduced tillering at early stages. Projected warming and frequent heat waves, in combination with reductions and greater spatio-temporal variability in precipitation can potentially increase the evaporative demand of the atmosphere, rapidly dry soils and cause heat stress in barley, resulting in reduced biomass production and grain yield (Rötter *et al.*, 2011; Semenov & Shewry, 2011; Richter & Semenov, 2005). Holden *et al.* (2003) reported that even though barley production will remain viable in Ireland, water deficits within the growing season in some years in the 2050s could cause reductions in grain yield of up to 4.5 t ha⁻¹. Warmer conditions can also significantly hasten phenophases and senescence of barley and thereby reduce harvest index (Semenov & Shewry, 2011; Ainsworth & Rogers, 2007). Clearly, regardless of the magnitude, the projected climate change has implications for barley production in the UK. Yet, in spite of the importance of barley to the UK economy, there is scant information on the possible effects of projected climate change on barley yields in the UK and much less at a more detailed scale of administrative regions.

Such information is relevant for planning adaptation through breeding, agronomic adjustments, policy design and management decisions. Therefore, the objective of this chapter is to simulate (using the AquaCrop model) the effect of projected climate change on barley yields across 14 UK administrative regions in the 2030s, 2040s and 2050s.

4.2 Materials and Methods

4.2.1 Data Sources

4.2.1.1 Climate Data

Two main approaches are used to obtain a numerical description of future climatic variables required to model the effect of climate change on crop yields (Roudier *et al.* 2011). In the first approach, assumptions about uniform increase or decrease (e.g., 2 % decrease and 1 °C increase in precipitation and temperature respectively) are applied to the baseline climate data to obtain the climate variables of a given future time slice. While this is easy to compute, the main disadvantage is that the fundamental physical relationships among the future climate variables are not preserved (Roudier *et al.* 2011). The second approach employs radiative forcing (based on scenarios of greenhouse gas emissions) using an ensemble of Global Climate Models (GCMs) to generate future climate variables. This is now the most widely used approach in climate change studies (Roudier *et al.* 2011). To enable consistency in the use of this approach, the Intergovernmental Panel on Climate Change (IPCC) has defined four main families of emission scenarios that, as captured in the Special Report on Emission Scenarios (SRES), are narratives of potential

trajectories of greenhouse gas (GHG) emissions as a result of certain assumptions on different socio-economic conditions and development pathways over the course of the 21st century (Nakićenović & Swart, 2000). The four main emission scenario families are termed A1, A2, B1 and B2. Each emission scenario narrative, however, has subdivisions. Future climate variables generated from GCMs can be downscaled to regional levels using Regional Climate Models (RCMs). The main advantage of this approach is that it is physically-based and therefore the sets of future climate variables generated are physically consistent (Hawkins & Sutton, 2011; 2009; Roudier *et al.*, 2011; Holden *et al.*, 2003).

The UKCP09 is a publicly accessible online database that provides data on projected climate change (relative to a baseline period of 1961-1990) over the UK (Murphy *et al.*, 2009). The UKCP09 is based on the radiative forcing of GCMs to generate future climate variables. The UKCP09 incorporates three SRES emission scenarios (A1FI, A1B, and B1; otherwise known as high, medium and low emission scenarios, respectively). Generally, the A1 narrative represents a future world characterized by very rapid economic growth, rapid availability of new and efficient technologies, fast decline in regional economic disparities and with global population peaking at 8.7 billion in 2050 and declining thereafter to 7.1 billion by the end of this century. The three subdivisions in the A1 narrative represent intensive use of fossil fuels (A1FI), intensive use of non-fossil energy sources (A1T) and an intermediate situation (A1B). On the other hand, the B1 narrative portrays a future world inclined towards global equity and sustainable solutions to economic, social and environmental challenges. It also assumes rapid structural shifts towards service and information oriented economies, as well as clean and efficient

technologies with less intensive material use. The B1 narrative has the same population scenario as the A1 narrative (Nakićenović & Swart, 2000).

The projected climate change data in the UKCP09 has a grid resolution of 25 km and are averaged over seven overlapping 30-year time periods or time slices (Murphy *et al.*, 2009). Probabilities (indicative of the extent to which each climate outcome is backed by current evidence) are attached to the different levels of the UKCP09 projections to minimize uncertainties. It is noteworthy that probabilities cannot be assigned to emission scenarios themselves (Murphy *et al.*, 2009). In this study, future climate variables for the three emission scenarios and three time slices (30-year means centered on the 2030s, 2040s and 2050s) were obtained from the UKCP09 database for each of the 14 UK regions (see Appendix 1). The time slices ended at 2050 because global population is projected to reach a peak by mid-century and decline thereafter (UN, 2004), meaning increase in demand for food and other resources will be highest in the first half of the century. The uncertainties associated with climate change projections and their impacts are much higher beyond 2050 (Murphy *et al.*, 2009; IPCC, 2007; Corfee-Morlot & Höhne, 2003). Prior commitment of GHGs and current trends in emissions to the atmosphere suggest that the full effects of mitigation (stabilization) measures might not be realized before the 2050s due to transient climate change before an equilibrium climate is attained (IPCC, 2007; Corfee-Morlot & Höhne, 2003). These, together with the high cost of adaptation, render adaptation measures less motivating beyond 2050 (World Bank, 2010; Adger *et al.*, 2007). The current study did not consider a ‘future without climate change’ scenario. This is because it is difficult to imagine a future without climate change considering, as stated earlier, the medium-term warming effect of GHGs already emitted

to the atmosphere, the current rate of GHG emissions, and the observed climate change due to anthropogenic activities (IPCC, 2007; 2013; Alexandratos & Bruinsma, 2012; Corfee-Morlot & Höhne, 2003).

The Weather Generator (WG, version 2, Jones *et al.*, 2009) embedded in the UKCP09 was used to generate future daily climate variables for the simulations. The WG randomly samples a specified number of model variants from the probabilistic projections and uses a stochastic process to generate statistically credible future climate variables at 5 km grid resolution at daily or hourly scales (Jones *et al.*, 2009). The WG preserves the internal consistency among the variables and inherits the statistical properties of the underlying probabilistic projections (Jones *et al.*, 2009). For each emissions scenario, time slice and region, daily data on weather variables were generated by submitting a new request for standard WG variables at the UKCP09 user interface (<http://ukclimateprojections-ui.defra.gov.uk/ui/start/start.php>). For each request, 40 contiguous cells (maximum allowed) were selected in the region of interest based on the arable areas in the UK land cover map (LCM2007, Centre for Ecology and Hydrology). Since cereals (mainly wheat and barley) account for 50% of cultivated land and are the most widely distributed arable crops in the UK, it was assumed that selection of cells of arable areas is likely to coincide with an area of cereal production. The duration of each WG run was 30 years and 100 random samples were requested from the 10,000 randomly sampled model variants. The result was 100 climate data files generated for each request, each file containing a variant of the future climate data. The weather data required for the simulations (minimum and maximum temperature, precipitation and reference evapotranspiration) were extracted from the downloaded WG data into separate text files

using a Python code (programming language). This resulted in 300 files per time slice, emission scenario and region. These files were then formatted to make them readable or usable for the simulations.

The use of the WG was necessitated by practical considerations. First, simulations of crop yield response to climate change are sensitive to the temporal changes of weather variables which fluctuate greatly and rapidly within hours and days (Brouwer & van Ittersum, 2010; Raes *et al.*, 2009; Todorovic *et al.*, 2009). Hence, data at a finer spatio-temporal resolution minimizes errors in predicted yields. While the UKCP09 probabilistic projections are averaged over monthly, seasonal and annual scales, the WG uses a stochastic process to generate statistically credible future climate variables at spatial and temporal resolutions appropriate for crop growth simulations (Jones *et al.*, 2009). Second, the probabilistic projections are suitable when assessing an impact of interest that is triggered in a given system when a particular climatic threshold is exceeded (Jones *et al.*, 2009; Murphy *et al.*, 2009). Hence, the probabilistic projections were not compatible with the objective of this study as the study is not aimed at assessing climate change effect on yields when specific climatic thresholds are exceeded or not exceeded. Moreover, using the probabilistic projections would have resulted in complicated analysis, more work and uncertainties to deal with than time and resources would permit. The structure of the UKCP09 WG, how it works and its advantages and limitations are presented by Jones *et al.* (2009). Similar studies used weather generators to obtain synthetic future daily weather variables (e.g. Meza *et al.* 2008; Abraha and Savage, 2006; Richter & Semenov 2005; Holden *et al.* 2003; Guereña *et al.* 2001).

The projected atmospheric CO₂ concentrations files for the medium (A1B), low (B1), A2 and B2 emission scenarios were available in AquaCrop (Raes *et al.*, 2009). The projected atmospheric CO₂ concentration file for the high (A1FI) emission scenario was created using data from the IPCC data distribution centre (<http://www.ipcc-data.org/ancillary/tar-isam.txt>) (see Figure 4-2).

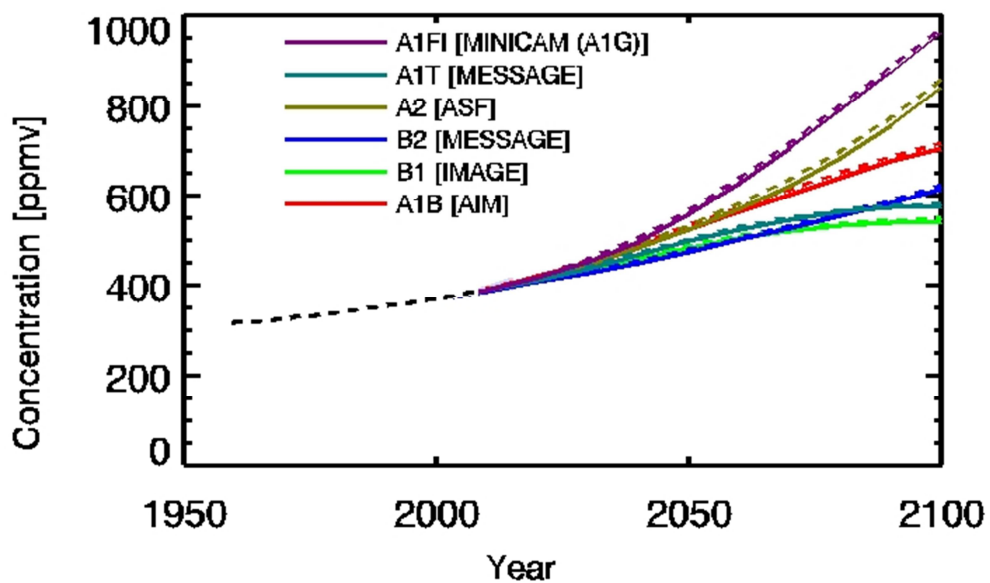


Figure 4-2: Atmospheric CO₂ concentrations observed at Mauna Loa from 1958-2008 (black dashed line) and projected under 6 SRES scenarios from 2008 to 2100. Two carbon cycle models are used for each scenario: BERN (solid lines) and ISAM (dashed lines). Figure taken from IPCC Data Distribution Centre, http://www.ipcc-data.org/ddc_co2.html (accessed February 10, 2013).

4.2.1.2 Soil Data

Detailed soil data for the UK (1:250,000 HOST data) were available but not free. The fact that Scotland uses a different soil classification system (described as “typological”) from England and Wales (which are “hierarchical”) also complicate soil data integration. Hence, soil hydraulic data was obtained from the Crop Growth

Monitoring System (CGMS) database in the new Soil Information System (SINFO), which is part of the Monitoring Agriculture with Remote Sensing (MARS) Crop Yield Forecasting System (MCYFS) for the European Union (Baruth *et al.*, 2006). It is worth mentioning that, for mapping purposes, soil classification relies on spatially coherent, homogenous soil groups that are recognizable within the landscape. Since soils show continuous variation, the scale of mapping profoundly influences the classification scheme used to produce a soil map (Nussbaum *et al.*, 2011). At a coarse resolution, therefore, each map unit (i.e. polygon on the final map) will normally contain more than one type of soil that might have different properties.

The SINFO database has a scale of 1:1,000,000. In this database, Europe is divided into Soil Mapping Unit (SMU) polygons. Each SMU is made up of several Soil Typological Units (STUs) with attributes describing the properties of the soils. Soil texture and bulk density are the key physical properties used in determining the water retention properties of the soils. The potential rooting depth and soil water retention properties are mainly used to define the hydraulic properties of the soil groups used in crop modeling in the CGMS. For each soil physical group, available water capacity (AWC, a static soil characteristic which indicates the amount of water that can be held between field capacity and wilting point per unit rooting depth) is defined (Baruth *et al.*, 2006). The product of AWC and rooting depth gives the maximum available water a soil can supply to a plant.

The SINFO data was imported in ArcGIS version 9.1 (ESRI™, USA) for further processing. The UK was clipped from the map. The attribute tables in the CGMS database were joined based on common fields. The soil polygon attribute table was joined to the

soil typological unit (STU) table via the common field 'smu no.' The resulting table was in turn joined to the soil physical group table via the common field 'soil group no.' to build one attribute table that contains all the attributes for the soil polygons. This map, together with its attribute table, was exported to represent the UK soils. The UK had 5 soil texture classes out of the 8 main classes in the CGMS, with the dominant textural class being 'medium'.

The UK soils map was then intersected with the UK regions map to obtain the distribution of soil in each region. Because soil hydraulic properties in the CGMS were derived mainly from texture and bulk density, the selection of dominant soil in arable areas was also based on the soil texture. For each region, the most widely spatially distributed soil was taken as the dominant soil and the weighted averages of the attributes of the dominant soil polygons were taken as representative hydraulic properties of the soil for that region (Table 4-2). Where peat was dominant, the next dominant soil was used.

Table 4-2: Soil hydraulic properties from the SINFO database used in the simulations. Data taken from the SINFO database (Baruth *et al.*, 2006).

Admin. Sub-region	Dominant Soil	θ_{sat}	θ_{pwp}	θ_{fc}	Rooting Depth (m)	θ_{asw} (mm/m)
EE	Medium	0.42	0.18	0.33	7	150
EM	Fine	0.49	0.29	0.43	6.8	140
NI	Medium	0.41	0.16	0.31	6.6	150
NEE	Medium	0.42	0.18	0.34	6.6	160
NES	Medium	0.41	0.15	0.30	6.1	150
NWE	Medium	0.43	0.19	0.34	6.4	150
NWS	Medium	0.40	0.15	0.29	7.0	140
SEE	Medium fine	0.55	0.14	0.49	5.9	350
SES	Medium	0.41	0.15	0.32	6.2	170
SWE	Medium fine	0.58	0.15	0.50	4.4	350
SWS	Medium	0.41	0.15	0.31	6.4	160
WA	Medium	0.45	0.22	0.37	6.9	150
WM	Medium	0.45	0.22	0.37	6.7	150
YH	Medium	0.43	0.19	0.35	6.5	160

Key: θ_{sat} is saturated water content; θ_{pwp} is water content at permanent wilting point; θ_{fc} is water content at field capacity; θ_{asw} is total available soil water.

The soil data was used to create the required soil files in AquaCrop. AquaCrop-generated values for drainage characteristics such as drainage coefficient (τ), saturated hydraulic conductivity and curve number for surface runoff using the input values of saturated water content, field capacity and permanent wilting point, were used. It is recognized that saturated hydraulic conductivity is highly variable in space and time. However, due to lack of data, these AquaCrop-generated drainage characteristic values were used in the simulations to estimate water losses to drainage or potential groundwater recharge.

4.2.1.3 Crop Data

The crop file was created using information for the genotype 'Westminster'. The HGCA Recommended List shows that the genotype 'Westminster' is widely grown in the UK both as spring and winter barley crop, feed and malt barley and is high-yielding. The model parameters were based mainly on the calibration reported previously (see Chapter 3) and information from Raes *et al.* (2012), and personal communications with scientists at The James Hutton Institute, Dundee. Thermal time information not available in the crop parameters in Chapter 3 are reported here (Table 4-3).

Table 4-3: Crop parameters in growing degree days (GDD).

Symbol	Description	Value
Threshold air temperatures		
T _{base}	Base temperature (°C)	0
T _{upper}	Upper temperature (°C)	18
Development of green canopy cover		
	Time from sowing to emergence (GDD)	135
CGC	Canopy growth coefficient (fraction per GDD)	0.813
	Time from sowing to start senescence (GDD)	1315
CDC	Canopy decline coefficient (fraction per GDD)	0.602
	Time from sowing to maturity	1675
Flowering		
	Time from sowing to flowering (GDD)	950
	Length of flowering stage (GDD)	215
Air temperature stress		
	Minimum air temperature below which pollination starts to fail (cold stress, °C)	5
	Maximum air temperature above which pollination starts to fail (heat stress, °C)	30
	Minimum growing degrees required for full biomass production (°C - day)	15

Average barley yields for the baseline period (1961-1990) were obtained from the respective National Agricultural Statistics Departments. In some cases, yields were reported as 100 weight acre⁻¹ (*cwt acre⁻¹*) and these were converted to tons ha⁻¹. For England, the regional yield data were available for the period 1999 to 2010. However, UK national average yield data for the baseline period (1961-1990) were available. Therefore, regression equations (4th order polynomial) were developed using the sub-regional and UK yields as dependent and independent variables respectively for 1999 to 2010. While good R² values were obtained, these equations could not satisfactorily predict the regional yields for the baseline period. Consequently, averages of the differences between the UK and each English regional yield (1999-2010) were computed. The averages were then subtracted from the UK baseline yield for each year to obtain the baseline yields for English regions. Northern Ireland had two blocks of missing data in the

baseline yield data (from 1961 to 1966 and from 1974 to 1980). The missing data were filled using the same approach as for the English regions.

The search for an appropriate sowing date for each UK region was restricted to the range of optimum sowing period (± 1 week) recommended by the (HGCA) (http://www.hgca.com/publications/documents/cropresearch/spring_barley.pdf). The HGCA indicates that the optimum sowing dates for spring barley ranges from late January to end February in the south and east of England and from late February to the end of March in Scotland. The HGCA warns that sowing outside the optimum period can result in grain quality impairment and yield losses of up to $30\text{-}50 \text{ kg ha}^{-1} \text{ day}^{-1}$.

To obtain the sowing date for each region, the AquaCrop model was forced to the 1990 regional yields by changing only the sowing date until the simulated yield approximated the observed yield. The first date that gave the closest match between the simulated and observed yields was selected as the sowing date for that particular region. It is noteworthy that the sowing date so obtained could differ substantially in practice as the phenology of the crop is assumed to be the same for all the regions. However, it is assumed that, during the simulations, differences in phenology will largely depend on the respective weather conditions and the speed with which the required total thermal time is accumulated. To compensate for yield increase due to, for example, genetic improvement, the reference harvest index (H_{Io}) was reduced to 0.46 when the model was being forced to the 1990 baseline. This is because using a H_{Io} of 0.49 gave yields substantially higher than the actual yields. The H_{Io} was restored to 0.49 for the climate change simulations. To test or validate the goodness of the sowing dates and the model setup, the prediction error of the model was assessed by comparing simulated and observed yields for the baseline

period (1980-1989) using the root mean square error (RMSE). It is noteworthy that the regional average yields are a mix of different genotypes under different management practices and it was not always clear if they represented only spring barley yields or both winter and spring barley yields. This is a likely confounding factor to the simulated yields.

4.2.1.4 Simulations Using AquaCrop

Once the sowing dates had been established, simulations of future yields were performed. All simulations were made for rain-fed conditions (i.e. irrigation was not considered), using AquaCrop version 4.0. For all simulations, no field management was specified, fertility stress was not considered and the initial soil water content was set to field capacity. Multiple run project (.PRM) files were created in AquaCrop for each region, time slice and emission scenario with the relevant climate, soil, and crop files. Thus, for each region, time slice and emission scenario, 100 multiple run project files were created, representing the 100 climate model variants. The multiple run project files (100 at a time) were transferred to the AquaCrop plug-in program version 3.1+ (Raes *et al.* 2009) in which the simulations were executed.

4.2.2 Data Analysis

The output text files of the simulations for each of the 100 model variants for each region, time slice and emission scenario were imported singly to separate worksheets in a Microsoft Excel 2010 workbook. Mean values of the model output variables were then generated for each of the 30 years in a given time slice, emission scenario and region.

Descriptive statistics and percentiles were then generated for that particular time slice, using the Data Analysis tool. Descriptive statistics and percentiles were also generated for the baseline yield. Differences between the baseline yields and the simulated yields were calculated for time slices and emission scenarios.

Relationships between simulated yields and rainfall and CO₂ were explored using scatterplots fitted with linear regression trend-lines. Where necessary, points that were clearly isolated from the dense cluster of the data points were treated as outliers and removed if doing this improved the explanatory power (R²) of the relationship substantially. In all such cases, not more than four points (out of 30) were removed. Thus, if there were more than four isolated points, they were not removed regardless of the magnitude of improvement in the R². In most cases, however, a maximum of three points were removed.

The projected virtual water content (VWC, m³ ton⁻¹) of simulated UK barley grains was calculated as:

$$VWC = 10 \cdot \frac{ETc}{Yield} \quad \text{Equation 4-1}$$

Where *ETc* is the total crop water use (mm); and 10 is a scalar to ensure consistent units (Chatterton *et al.*, 2010). The averages of simulated water use and yields of barley for the 14 UK regions were calculated for the high, medium and low emissions scenarios (HES, MES and LES, respectively) and for the 2030s, 2040s and 2050s.

4.3 Results

4.3.1 Sowing Dates and Descriptive Statistics of Baseline Yield

Sowing dates ranged from 13th February (Eastern England, EE) to 24th March (North West Scotland, NWS) (Table 4-4) which was within the HGCA recommended window (see Appendix 1 for a map of the 14 UK regions). The observed and simulated yields for 1990 ranged from 4.52 to 5.72 and 4.00 to 5.51 respectively. The differences between the observed and simulated yields ranged between ± 0.14 and 0.59 tons ha⁻¹. In absolute terms, South East England (SEE) showed the least difference between the observed and simulated yields. The RMSE values for the baseline period 1980-1989 (Table 4-4) ranged from 0.44 (EE) to 1.15 tons ha⁻¹ (WA) and 0.35 tons ha⁻¹ for the UK. Thus, except for WA, the RMSE values for all regions were under 1 ton ha⁻¹.

Table 4-4: Sowing dates, differences between observed and simulated yields for 1990 (ΔY , tons ha⁻¹), and root mean square error (RMSE, tons ha⁻¹) for simulated and observed yields for baseline period (1980-1989).

Region	Sowing Date	Observed Yield (1990)	Simulated Yield (1990)	ΔY	RMSE
EE	13 th February	5.32	4.73	0.59	0.44
EM	27 th February	5.32	5.22	0.10	0.79
NI	8 th March	4.53	4.23	0.30	0.66
NEE	7 th March	5.02	5.16	-0.14	0.68
NES	9 th March	5.30	5.51	-0.21	0.74
NWE	19 th February	4.52	4.00	0.52	0.74
NWS	24 th March	5.03	4.56	0.47	0.81
SEE	24 th February	5.42	5.38	0.04	0.55
SES	9 th March	5.72	5.18	0.54	0.55
SWE	17 th February	4.92	4.44	0.48	0.65
SWS	13 th March	4.87	5.17	-0.30	0.73
WA	19 th February	5.10	4.72	0.38	1.15
WM	27 th February	4.92	5.18	-0.26	0.73
YH	27 th February	5.32	4.90	0.42	0.78
UK	-	5.22	4.88	0.34	0.35

Mean yields for the baseline period (1961-1990) ranged from 3.66 (NI) to 4.57 (SES) tons ha⁻¹, with a UK average of 4.24 tons ha⁻¹ (Table 4-5). Six regions had mean yields higher than the UK mean yield. Only NI, NWE, SWE and WM had mean yields just under 4.0 tons ha⁻¹. The SEE and SES show the highest 90th percentiles (5.24 tons ha⁻¹) while NWE shows the lowest 10th percentile (2.88 tons ha⁻¹). The mean yields generally show a marginal increase from west to east and from south to north. Overall, the baseline yields are not widely dispersed from their respective mean values and the differences between regional yields are not substantial (Table 4-5). For all the regions, except SWS, the yields are positively skewed but the low skewness values indicate that few yield values exceed their respective mean yield values. There is low temporal variation in the baseline yields for all regions and the UK, suggesting yield stability over time (Figure 4-3). The baseline yields also tend to show an increasing trend over time.

Table 4-5: Descriptive statistics of observed yields for the baseline period (1961-1990).

Statistic	Mean	Max.	90th Perc.	Median	10th Perc.	Min.	Std. Error	Std. Dev.	Skewness
<i>EE</i>	4.34	5.69	5.14	4.20	3.68	3.45	0.11	0.60	0.54
<i>EM</i>	4.34	5.69	5.14	4.20	3.68	3.45	0.11	0.60	0.54
<i>NI</i>	3.66	4.80	4.53	3.51	3.20	2.91	0.09	0.51	0.75
<i>NEE</i>	4.04	5.39	4.84	3.90	3.38	3.15	0.11	0.60	0.54
<i>NES</i>	4.19	5.43	5.04	4.15	3.40	3.10	0.12	0.64	0.17
<i>NWE</i>	3.54	4.89	4.34	3.40	2.88	2.65	0.11	0.60	0.54
<i>NWS</i>	4.28	5.70	5.01	4.27	3.50	3.00	0.11	0.60	0.06
<i>SEE</i>	4.44	5.79	5.24	4.30	3.78	3.55	0.11	0.60	0.54
<i>SES</i>	4.57	5.72	5.24	4.62	4.00	3.60	0.10	0.56	0.18
<i>SWE</i>	3.94	5.29	4.74	3.80	3.28	3.05	0.11	0.60	0.54
<i>SWS</i>	4.03	4.99	4.86	4.14	3.22	2.70	0.11	0.62	-0.35
<i>WAL</i>	4.00	5.20	4.90	3.95	3.40	3.10	0.10	0.58	0.51
<i>WM</i>	3.94	5.29	4.74	3.80	3.28	3.05	0.11	0.60	0.54
<i>YH</i>	4.34	5.69	5.14	4.20	3.68	3.45	0.11	0.60	0.54
<i>UK</i>	4.24	5.59	5.04	4.10	3.58	3.35	0.11	0.60	0.54

Note: *Max.*, *Min.* are maximum and minimum respectively; *Perc.* is percentile; *Std.* is standard.

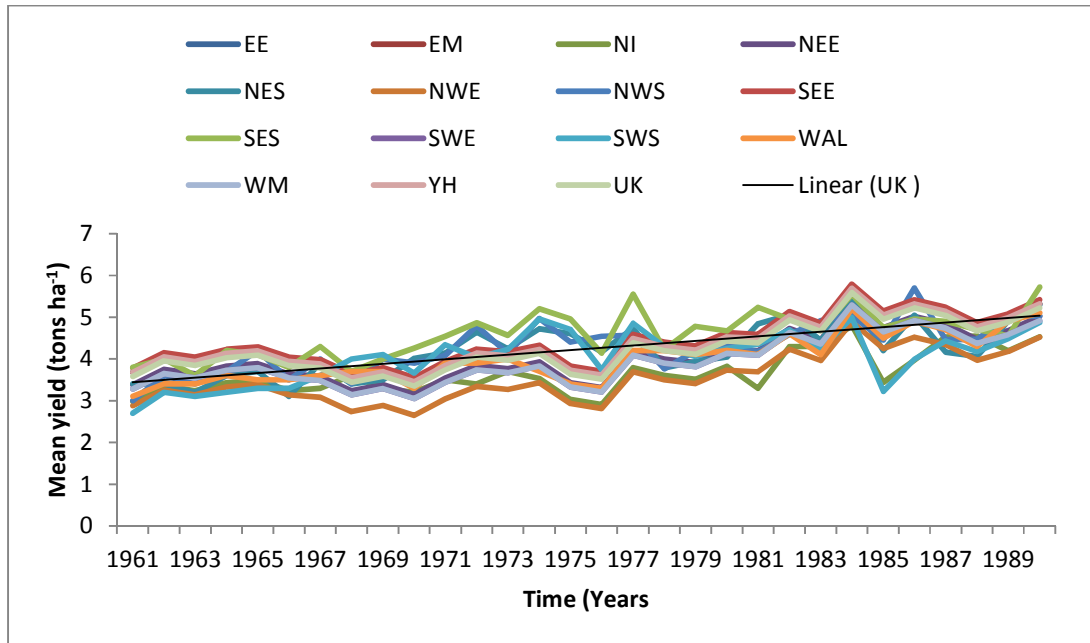


Figure 4-3: Temporal profile of observed yields for the baseline period (1961-1990). The trend-line is based on UK average.

4.3.2 Simulated Cumulative Seasonal Rainfall and Drainage

Under the low emission scenario (LES), simulated mean cumulative seasonal rainfall increased slightly from the 2030s to 2050s for EE, EM, and NEE but the difference was clearer between the 2050s and the other time slices (Figure 4-4A). Only NWE experienced a decrease in rainfall from the 2030s to 2050s. For the rest of the regions, there was no clear pattern but in the majority of cases, rainfall in the 2030s tended to be highest while rainfall in the 2040s was lowest. Overall, EE, EM, SEE, WM and YH had the lowest mean seasonal rainfall values across all time slices. The NWS had

extremely high seasonal rainfall values in the 2030s and 2040s compared to the other regions, probably due to an error from the GCMs or RCMs during the downscaling process in the UKCP09. For the UK, mean seasonal rainfall decreased from the 2030s to 2050s. Mean total rainfall ranged from approximately 229.7 mm year⁻¹ (EM) to 607.8 mm year⁻¹ (NWS) for the 2030s, 232.4 (EM) to 704.1 mm year⁻¹ (NWS) for the 2040s and 243.6 (EE) to 443.0 mm year⁻¹ (SWS) for the 2050s.

With the medium emission scenario (MES), there was a tendency towards decreasing rainfall from the 2030s to 2050s for some regions (EE, EM, NEE, NES, NI and SWS; Figure 4-4B). Generally, there was no substantial variation in mean seasonal rainfall across the time slices for the regions except that in few cases rainfall in the 2040s tended to be higher. Mean seasonal rainfall ranged from 240.1 (EE) to 429.4 mm year⁻¹ (SWS) for the 2030s, 243.7 (EE) to 429.7 mm year⁻¹ (SWS) for the 2040s and 234.3 (EE) to 416.3 mm year⁻¹ (SWS) for the 2050s.

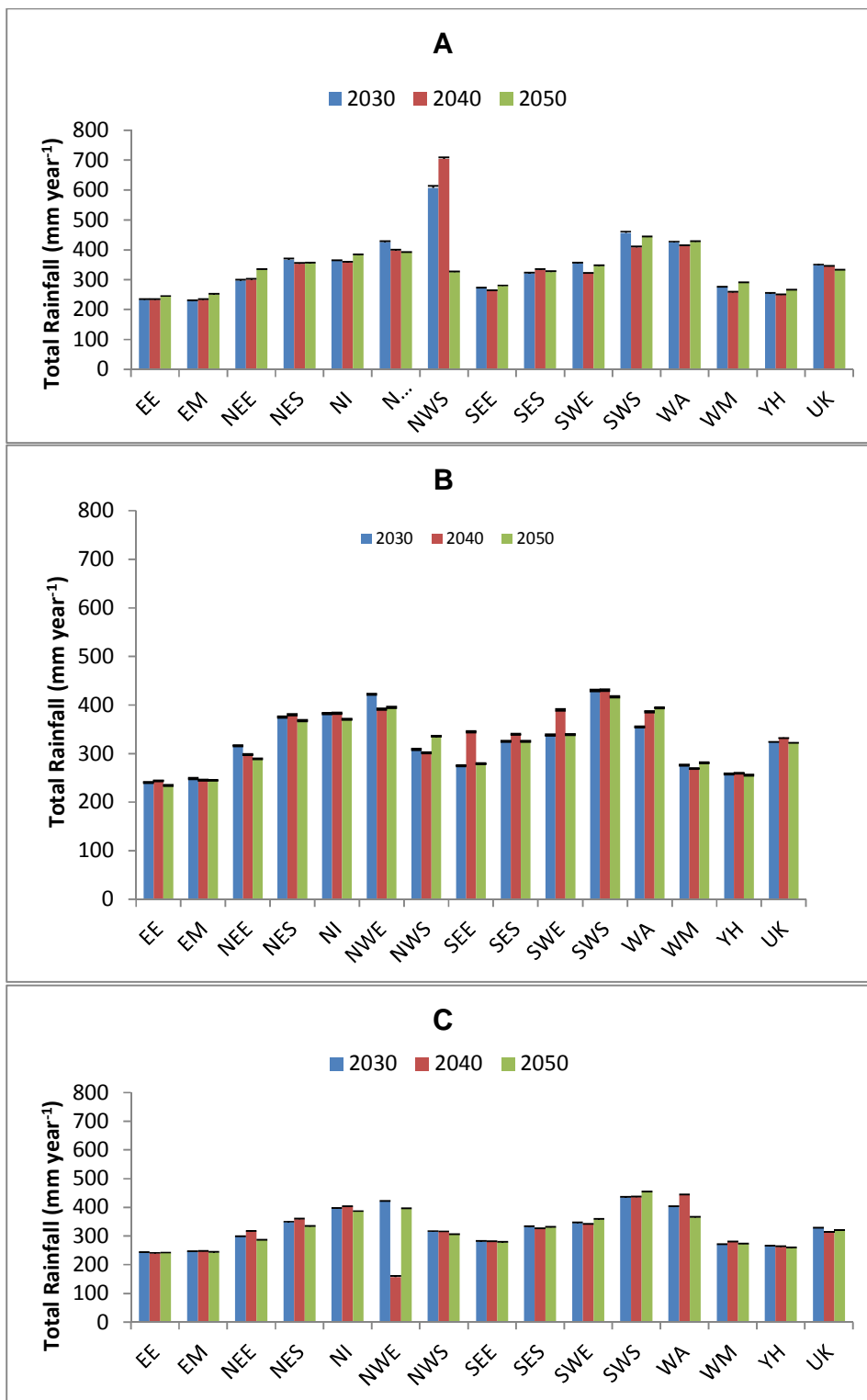


Figure 4-4: Simulated total seasonal rainfall for UK regions under (A) Low Emission Scenario, (B) Medium Emission Scenario and (C) High Emission Scenario. Error bars are standard errors.

For the high emission scenario (HES), there was no clear pattern across the time slices (Figure 4-4C). Except for NWE which had very low seasonal rainfall in 2040 (again, probably due to an error from the GCMs or RCMs during the downscaling process in the UKCP09), there was little variation in the seasonal rainfall across the time slices for the regions. Just as in the other emission scenarios, highest mean seasonal rainfall values occurred in Scottish regions, NI, NWE, SWE and WA. Mean seasonal rainfall ranged from 243.2 (EE) to 434.5 mm year⁻¹ (SWS) for 2030s, 156.8 (NWE) to 442.8 mm year⁻¹ (WA) for the 2040s and 241.4 (EE) to 453.1 mm year⁻¹ (SWS) in the 2050s.

Thus, apart from the extremely high values in the 2030s and 2040s for NWS (Figure 4-4A) and extremely low value for NWE in 2040 (Figure 4-4C), changes in mean seasonal rainfall between emission scenarios or time slices were not substantial. However, there were obviously substantial variations in regional seasonal rainfall, with higher values generally in the western half of the UK. For the LES, cumulative seasonal rainfall showed little temporal variation across the time slices, but variability increased slightly in the 2050s (Appendix 2A). This pattern of slightly increased variability across time was observed in all the time slices for the MES (Appendix 2B) and the HES (Appendix 2C). However, intra-seasonal variations in rainfall could be high.

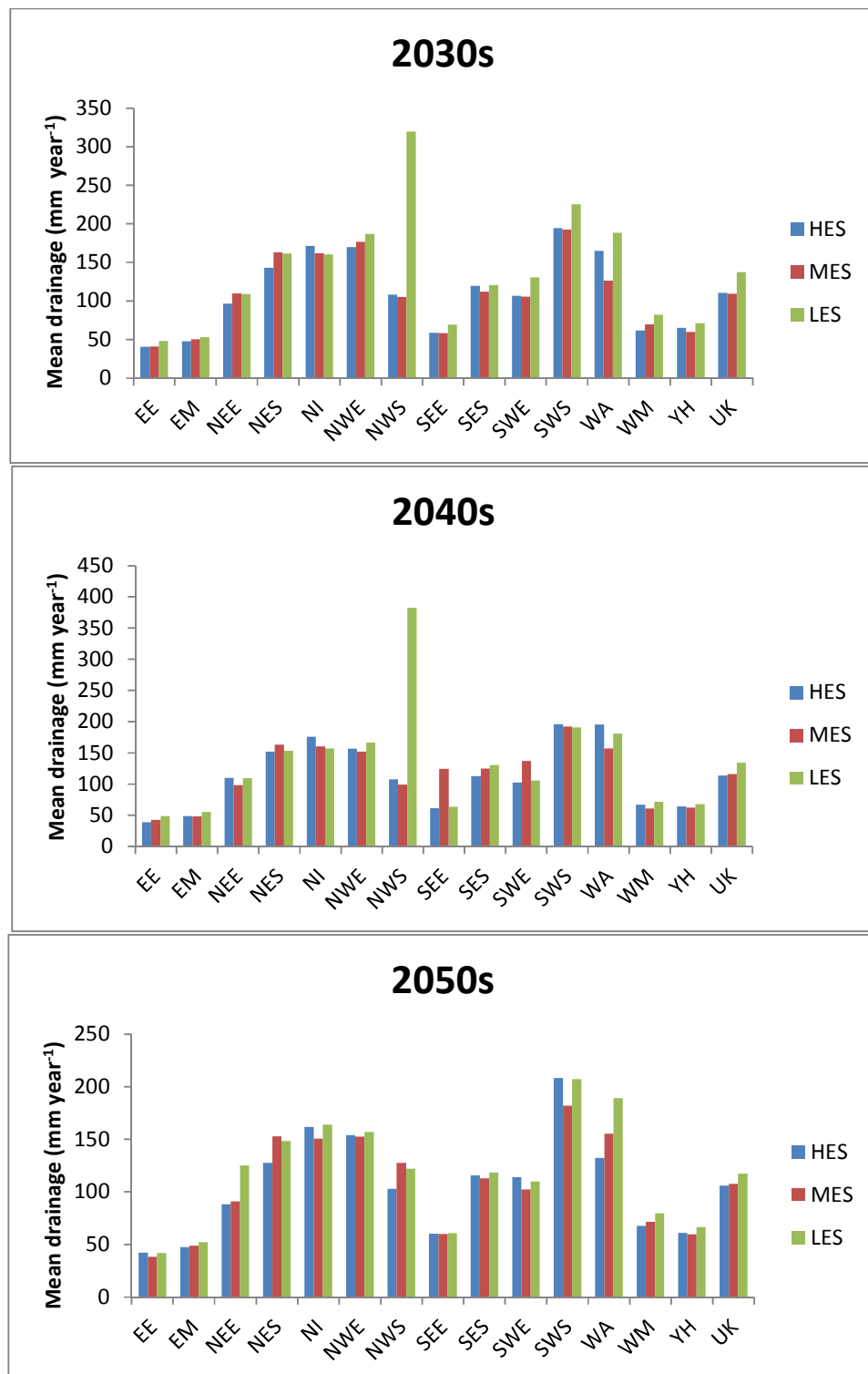


Figure 4-5: Simulated seasonal drainage losses for UK sub-regions in the 2030s, 2040s and the 2050s.

The pattern of seasonal water losses to drainage was similar to the seasonal rainfall across the regions, emission scenarios and time slices. Drainage losses were highest under the LES across all time slices with few exceptions (Figure 4-5). For the UK, however, drainage losses decreased slightly from the LES to the HES and from 2030s to 2050s. For the 2030s, seasonal drainage ranged from approximately 48 (EE) to 320 mm year⁻¹ (NWS) for the LES, 41 (EE) to 192 mm year⁻¹ (SWS) for the MES, and 41 (EE) to 194 mm year⁻¹ (SWS) for the HES respectively. In the 2040s, seasonal drainage ranges between approximately 49 (EE) and 383 mm year⁻¹ (NWS) for the LES, 42 (EE) to 192 mm year⁻¹ (SWS) for MES, and 39 (EE) to 196 mm year⁻¹ (SWS) for the HES. In the 2050s, drainage ranges from 42 (EE) to 207 mm year⁻¹ (SWS) for the LES, 38 (EE) to 182 mm year⁻¹ (SWS) for the MES and 42 (EE) to 208 mm year⁻¹ (SWS) for the HES. The regions with lowest drainage for all time slices and emission scenarios were EE, EM, SEE, WM and YH. The extremely high cumulative drainage for NWS in the 2030s and 2040s arises from the high seasonal rainfall observed under LES in those time slices (Figure 4-4A).

4.3.3 Simulated Barley Yields

In the 2030s, projected regional mean yield values for the LES ranged from 5.87 (EM) to 6.20 tons ha⁻¹ (SWE) and 6.04 tons ha⁻¹ for UK (Figure 4-6). Only EE, EM and YH had mean yields under 6.0 tons ha⁻¹. Projected median yields ranged between 5.88 to 6.16 tons ha⁻¹ (Table 4-6). The 90th and 10th percentile yield values ranged from 6.16 to 6.57 tons ha⁻¹ and 5.61 to 5.93 tons ha⁻¹ respectively. The 90th and 10th percentiles of yield for the UK were 6.45 and 5.71 tons ha⁻¹ respectively. Projected mean yields of nine regions

and the UK were positively skewed. Under the MES, projected mean yields ranged between 5.94 (NWE) and 6.96 tons ha⁻¹ (SEE), and 6.46 tons ha⁻¹ for the UK. Only EE, NWE and WA had mean yields just under 6.0 tons ha⁻¹. The projected median yields ranged from 6.34 to 6.96 tons ha⁻¹, while the 90th and 10th percentile of yields ranged from 7.15 to 7.59 tons ha⁻¹ and 3.01 to 6.40 tons ha⁻¹ respectively. For the UK, the 90th and 10th percentile were respectively 7.39 and 6.74 tons ha⁻¹. Under the HES, projected mean yields ranged from 5.36 (WA) to 7.10 tons ha⁻¹ (SEE), with a 6.53 tons ha⁻¹ for the UK. Only SEE had mean yield over 7.00 tons ha⁻¹ (Figure 4-6). The projected median yield values ranged from 5.94 to 6.99 tons ha⁻¹ (Table 4-6). The 90th and 10th percentile yield values ranged from 6.90 to 7.83 tons ha⁻¹ and 2.81 to 6.61 tons ha⁻¹. Unlike the LES, the yield values under the MES and HES for all regions (except for NWS under the HES) were negatively skewed. As indicated by the standard error and deviation values, there was little variability in yields within model variants and across the regions.

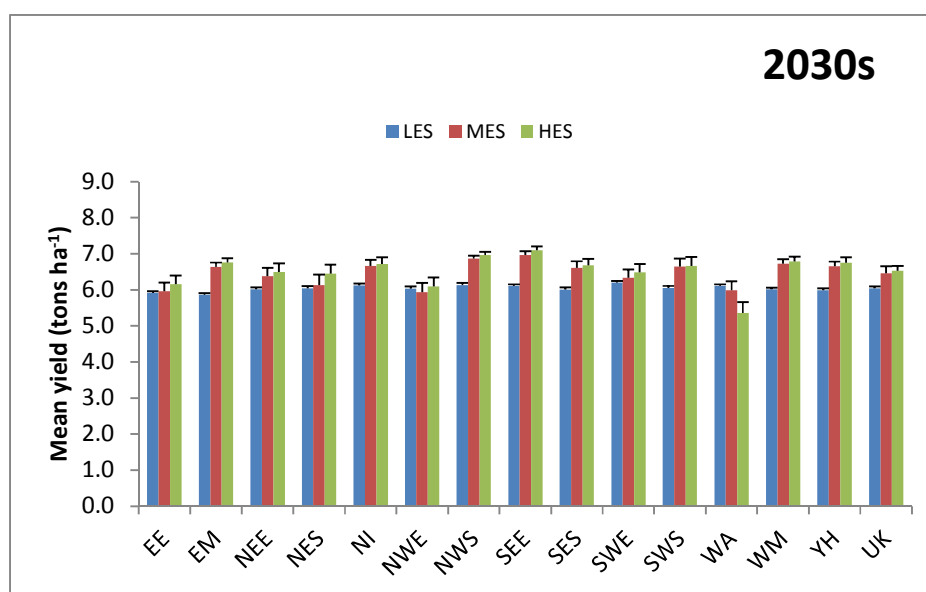


Figure 4-6: Simulated yields of UK regions in the 2030s under the LES, MES and HES. Error bars are standard errors.

Table 4-6: Descriptive statistics of simulated barley yields in the 2030s under the LES, MES and HES.

	EE	EM	NEE	NES	NI	NWE	NWS	SEE	SES	SWE	SWS	WA	WM	YH	UK
Statistic	LES														
Mean	5.92	5.87	6.01	6.04	6.12	6.03	6.13	6.11	6.00	6.20	6.05	6.11	6.01	5.99	6.04
Std. Error	0.04	0.04	0.06	0.06	0.06	0.06	0.06	0.05	0.07	0.04	0.07	0.04	0.04	0.05	0.05
Std. Dev.	0.21	0.23	0.31	0.33	0.32	0.32	0.32	0.25	0.36	0.23	0.37	0.24	0.23	0.26	0.27
Median	5.91	5.88	5.96	6.00	6.04	6.01	6.16	6.07	6.00	6.16	6.05	6.07	5.98	5.96	6.01
90th	6.16	6.16	6.49	6.54	6.57	6.48	6.54	6.45	6.52	6.49	6.57	6.50	6.32	6.35	6.45
10th	5.76	5.68	5.66	5.70	5.74	5.67	5.76	5.80	5.61	5.93	5.65	5.86	5.77	5.69	5.71
Skewness	-0.83	-1.15	0.09	-0.03	0.26	0.31	-0.12	0.23	0.06	0.23	0.12	0.51	-0.03	0.19	0.22
Minimum	5.25	5.08	5.44	5.37	5.60	5.58	5.43	5.74	5.30	5.80	5.41	5.68	5.49	5.50	5.60
Maximum	6.32	6.23	6.57	6.62	6.73	6.67	6.75	6.61	6.65	6.71	6.71	6.65	6.44	6.51	6.56
	MES														
Mean	5.96	6.64	6.38	6.13	6.66	5.94	6.88	6.96	6.61	6.33	6.65	5.99	6.73	6.65	6.46
Std. Error	0.24	0.12	0.24	0.29	0.17	0.26	0.07	0.10	0.18	0.23	0.23	0.25	0.13	0.13	0.19
Std. Dev	1.33	0.68	1.29	1.61	0.94	1.42	0.41	0.57	0.97	1.29	1.23	1.37	0.70	0.74	1.04
Median	6.34	6.75	6.74	6.75	6.90	6.55	6.88	6.96	6.88	6.76	6.92	6.50	6.81	6.64	6.74
90th	7.21	7.33	7.44	7.48	7.49	7.15	7.36	7.59	7.45	7.35	7.54	7.28	7.42	7.40	7.39
10th	4.30	5.88	4.73	3.01	5.37	4.01	6.40	6.40	4.89	4.79	6.32	4.02	5.97	5.98	5.15
Skewness	-1.38	-1.71	-1.63	-1.32	-1.55	-1.37	-0.35	-0.89	-1.41	-2.17	-2.78	-1.33	-1.44	-1.41	-1.48
Minimum	1.93	4.16	2.66	2.58	3.79	1.86	5.90	5.46	4.33	1.54	2.29	2.05	4.39	4.24	3.37
Maximum	7.46	7.52	7.69	7.59	7.71	7.59	7.60	7.78	7.70	7.61	7.77	7.45	7.57	7.60	7.62
	HES														
Mean	6.17	6.76	6.50	6.45	6.72	6.09	6.97	7.10	6.68	6.49	6.66	5.36	6.79	6.75	6.53
Std. Error	0.23	0.12	0.23	0.25	0.19	0.26	0.09	0.11	0.19	0.23	0.25	0.30	0.13	0.15	0.13
Std. Dev.	1.28	0.66	1.29	1.37	1.04	1.41	0.49	0.59	1.02	1.24	1.38	1.65	0.72	0.84	0.71
Median	6.50	6.78	6.70	6.74	6.89	6.59	6.98	6.99	6.82	6.79	6.91	5.94	6.84	6.75	6.58
90th	7.35	7.48	7.62	7.72	7.74	7.49	7.56	7.83	7.70	7.64	7.72	6.90	7.63	7.68	7.41
10th	4.36	6.06	4.93	3.78	5.22	4.29	6.40	6.61	5.03	5.14	6.14	2.81	6.08	5.89	5.79
Skewness	-1.41	-1.11	-1.51	-1.28	-1.38	-1.35	0.01	-0.24	-1.19	-2.11	-2.52	-0.87	-1.41	-1.11	-0.77
Minimum	2.19	4.56	2.72	3.44	3.66	2.00	6.08	5.80	4.25	1.84	1.93	1.55	4.28	4.15	4.55
Maximum	7.68	7.76	7.91	7.94	7.96	7.79	7.93	8.07	7.92	7.96	8.01	7.62	7.76	7.91	7.56

Key: 90th and 10th are 90th and 10th percentiles respectively.

In the 2040s, projected mean yield values under the LES for all regions ranged from 6.08 (EM) to 6.41 tons ha⁻¹ (SWE), with 6.24 tons ha⁻¹ for the UK (Figure 4-7). The projected median yield values ranged from 6.08 to 6.34 tons ha⁻¹ (Table 4-7). The 90th and 10th percentile yield values ranged from 6.28 to 6.74 tons ha⁻¹ and 5.77 to 6.17 tons ha⁻¹ respectively. The yields for EE, EM, NES, NWS and WM were negatively skewed while

the rest were positively skewed. Under the MES, projected mean yields ranged from 5.38 (WA) to 7.21 tons ha⁻¹ (NWS) and 6.70 tons ha⁻¹ for the UK. Five regions (EM, NI, NWS, WM and YH) had mean yields just over 7.0 tons ha⁻¹. The projected median, 90th and 10th percentile yield values ranged from 5.69 to 7.24 tons ha⁻¹, 7.53 to 7.88 tons ha⁻¹, and 2.90 to 6.72 tons ha⁻¹ respectively. Under the HES, projected mean yields for the regions ranged from 5.89 (WA) to 7.59 tons ha⁻¹ (SEE), with a UK average yield of 7.14 tons ha⁻¹ (Figure 4-7). Only EE, NWE, and WA had mean yields lower than 7 tons ha⁻¹. Projected median yields ranged from 6.46 to 7.57 tons ha⁻¹, while the 90th and 10th percentile yields ranged from 7.45 to 8.34 tons ha⁻¹ and 3.48 to 7.09 tons ha⁻¹ respectively (Table 4-7). The 90th and 10th percentiles for the UK were 7.88 and 6.44 tons ha⁻¹ respectively. The yield values for all regions under both the MES and HES were negatively skewed.

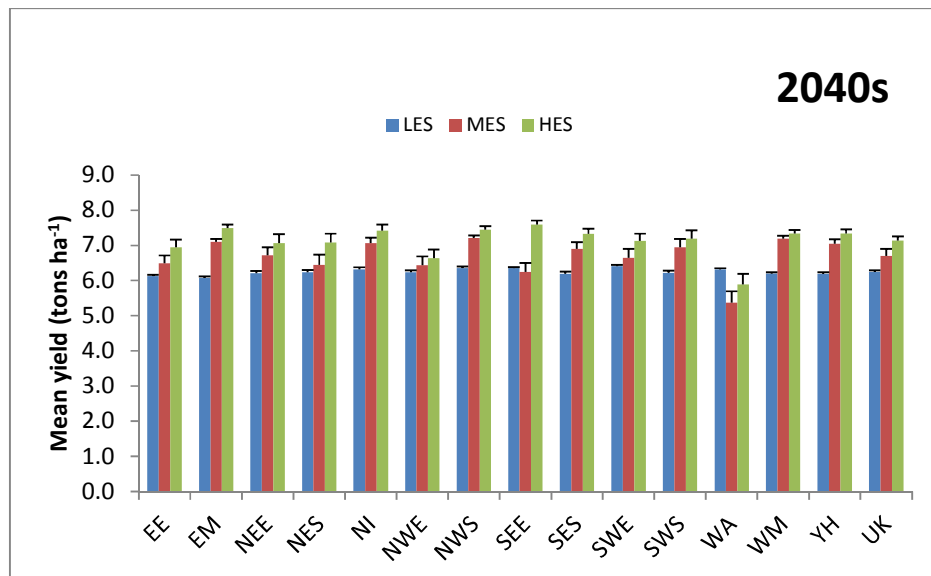


Figure 4-7: Simulated yields of UK regions in the 2040s under the LES, MES and HES. Error bars are standard errors.

Table 4-7: Descriptive statistics of simulated yields in the 2040s under the LES, MES and HES.

	EE	EM	NEE	NES	NI	NWE	NWS	SEE	SES	SWE	SWS	WA	WM	YH	UK
Statistic	LES														
Mean	6.12	6.08	6.21	6.24	6.32	6.24	6.35	6.35	6.19	6.41	6.21	6.31	6.20	6.19	6.24
Std. Error	0.04	0.04	0.06	0.06	0.06	0.05	0.06	0.04	0.07	0.04	0.06	0.04	0.04	0.04	0.04
Std. Dev.	0.20	0.21	0.31	0.31	0.31	0.29	0.31	0.21	0.36	0.21	0.35	0.22	0.19	0.25	0.25
Median	6.11	6.08	6.21	6.23	6.30	6.23	6.34	6.33	6.13	6.38	6.19	6.28	6.23	6.18	6.21
90th	6.35	6.28	6.66	6.70	6.74	6.61	6.74	6.60	6.70	6.65	6.70	6.60	6.44	6.51	6.58
10th	5.91	5.89	5.84	5.86	5.94	5.87	5.97	6.09	5.77	6.17	5.80	6.08	5.96	5.88	5.92
Skewness	-1.12	-1.25	0.09	-0.09	0.18	0.17	-0.17	0.10	0.04	0.17	0.16	0.02	-0.31	0.03	0.13
Minimum	5.45	5.34	5.67	5.64	5.83	5.83	5.69	5.97	5.54	6.04	5.64	5.82	5.73	5.74	5.83
Maximum	6.43	6.45	6.75	6.78	6.87	6.76	6.91	6.74	6.80	6.84	6.82	6.72	6.52	6.64	6.69
	MES														
Mean	6.49	7.10	6.72	6.45	7.07	6.44	7.21	6.24	6.90	6.65	6.95	5.38	7.19	7.05	6.70
Std. Error	0.23	0.09	0.23	0.29	0.15	0.25	0.07	0.25	0.19	0.25	0.24	0.32	0.09	0.12	0.20
Std. Dev.	1.25	0.47	1.24	1.60	0.81	1.36	0.38	1.38	1.03	1.38	1.30	1.73	0.48	0.65	1.08
Median	6.89	7.13	7.12	7.09	7.24	7.08	7.24	6.76	7.23	7.15	7.22	5.69	7.17	7.09	7.01
90th	7.55	7.69	7.80	7.68	7.79	7.53	7.75	7.64	7.76	7.65	7.88	7.18	7.73	7.81	7.67
10th	4.93	6.48	5.34	3.46	6.02	4.23	6.72	4.07	5.07	5.09	6.59	2.90	6.65	6.02	5.25
Skewness	-1.73	-0.48	-1.62	-1.31	-1.46	-1.66	-0.19	-0.91	-1.34	-2.22	-2.72	-0.86	-0.72	-0.75	-1.28
Minimum	2.12	5.90	3.14	2.95	4.52	2.24	6.48	2.76	4.57	1.47	2.42	1.49	5.92	5.45	3.67
Maximum	7.82	7.86	7.97	7.90	8.02	7.76	7.82	8.02	8.00	7.97	8.03	7.77	7.85	7.93	7.91
	HES														
Mean	6.94	7.49	7.07	7.09	7.42	6.64	7.45	7.59	7.33	7.12	7.19	5.89	7.33	7.34	7.14
Std. Error	0.23	0.09	0.24	0.24	0.17	0.25	0.09	0.11	0.15	0.21	0.24	0.30	0.11	0.12	0.12
Std. Dev.	1.24	0.50	1.32	1.33	0.91	1.36	0.51	0.62	0.80	1.14	1.30	1.64	0.60	0.68	0.64
Median	7.25	7.57	7.35	7.45	7.54	7.06	7.48	7.44	7.31	7.37	7.36	6.47	7.21	7.29	7.13
90th	7.99	8.10	8.17	8.23	8.25	7.88	8.11	8.34	8.20	8.02	8.26	7.45	8.09	8.18	7.88
10th	5.39	6.89	5.70	4.56	6.25	4.50	6.81	7.09	6.43	5.76	6.65	3.48	6.74	6.49	6.44
Skewness	-1.88	-0.44	-1.54	-1.25	-1.31	-1.53	-0.04	-0.32	-0.86	-2.13	-2.46	-1.03	-0.18	-0.21	-0.70
Minimum	2.41	6.25	3.31	4.23	4.68	2.37	6.59	6.13	5.43	2.80	2.66	1.94	5.83	5.95	5.30
Maximum	8.30	8.29	8.43	8.44	8.47	8.12	8.32	8.58	8.44	8.51	8.53	8.16	8.22	8.37	8.11

In the 2050s, projected yields increase over previous time slices for all emission scenarios. Under the LES, mean yields for the regions ranged from 6.03 (EE) to 6.63 tons ha⁻¹ (SEE), with 6.44 tons ha⁻¹ for UK (Figure 4-8, Table 4-8). Projected median yields ranged from 6.24 to 6.66 tons ha⁻¹ (Table 4-8). The 90th and 10th percentile yield values ranged from 6.62 to 6.86 tons ha⁻¹ and 4.47 and 6.44 tons ha⁻¹, respectively. For the UK,

the 90th and 10th percentiles were 6.75 and 6.10 tons ha⁻¹ respectively. Under the MES, projected yields ranged from 6.44 (WA) to 7.70 tons ha⁻¹ (SEE), with 7.24 tons ha⁻¹ for the UK. Only EE, NES, NWE and WA registered mean yields slightly lower than 7 tons ha⁻¹. Projected median yields ranged from 7.19 to 7.71 tons ha⁻¹. The 90th and 10th percentile yields ranged from 7.68 to 8.19 tons ha⁻¹ and 4.05 to 7.28 tons ha⁻¹ respectively. Few regions (EE, EM, NWS, and WA) had 90th percentile yield values lower than 8 tons ha⁻¹. Under the HES, the projected mean yields ranged from 7.49 (EE) to 8.18 tons ha⁻¹ (SEE), and 7.77 tons ha⁻¹ for the UK (Figure 4-8). Except for SEE, all regions had mean yield values lower than 8 tons ha⁻¹. Projected median yields ranged from 7.75 to 8.19 tons ha⁻¹ (Table 4-8). The 90th percentile of the yield values ranged from 8.24 to 8.60 tons ha⁻¹, while the 10th percentile ranged from 5.55 to 7.84 tons ha⁻¹. For the UK, the 90th and 10th percentiles were 8.27 and 7.33 tons ha⁻¹, respectively. For all regions and the UK, the yield values were negatively skewed under all emission scenarios.

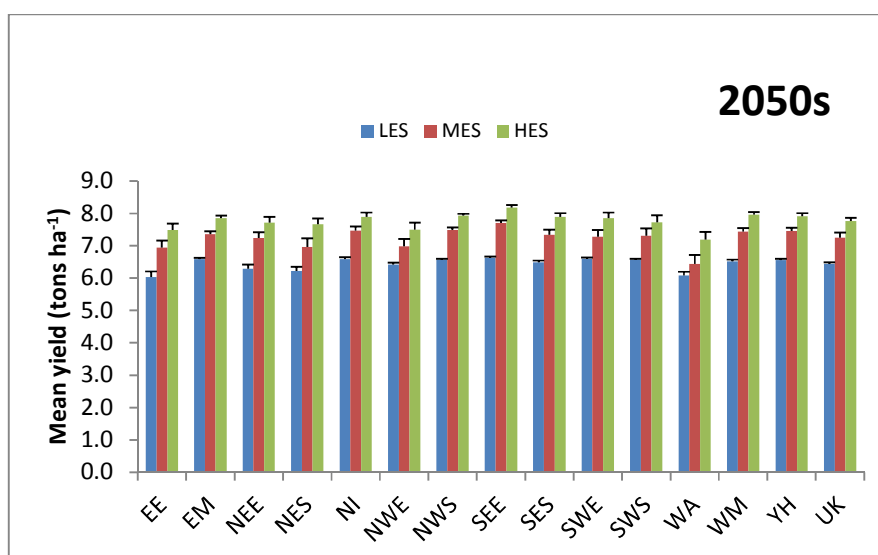


Figure 4-8: Simulated yields of UK regions in the 2050s.

Table 4-8: Descriptive statistics of simulated yields in the 2050s under LES, MES and HES.

	EE	EM	NEE	NES	NI	NWE	NWS	SEE	SES	SWE	SWS	WA	WM	YH	UK
Statistic	LES														
Mean	6.03	6.59	6.29	6.23	6.59	6.42	6.57	6.63	6.48	6.60	6.56	6.08	6.52	6.55	6.44
Std. Error	0.18	0.04	0.13	0.12	0.06	0.05	0.04	0.04	0.06	0.04	0.04	0.11	0.06	0.04	0.05
St .Dev.	0.97	0.21	0.69	0.67	0.31	0.30	0.20	0.20	0.34	0.22	0.22	0.60	0.32	0.22	0.26
Median	6.34	6.58	6.50	6.44	6.66	6.43	6.59	6.64	6.54	6.59	6.58	6.24	6.57	6.55	6.46
90th	6.62	6.81	6.71	6.62	6.81	6.77	6.80	6.86	6.76	6.86	6.82	6.73	6.82	6.82	6.75
10th	4.47	6.44	6.08	5.96	6.38	6.21	6.30	6.40	6.16	6.43	6.27	5.38	6.10	6.31	6.10
Skewness	-2.13	-1.43	-3.75	-2.95	-3.31	-1.51	-0.38	-1.14	-2.55	-1.43	-0.54	-0.94	-2.17	-1.35	-0.77
Minimum	2.84	5.89	3.12	3.61	5.21	5.37	6.07	5.99	5.11	5.88	6.03	4.57	5.28	5.79	5.81
Maximum	6.82	6.86	6.80	6.76	6.90	6.82	6.89	6.89	6.84	6.88	6.90	6.78	6.86	6.85	6.82
	MES														
Mean	6.95	7.36	7.23	6.97	7.47	6.98	7.49	7.70	7.34	7.27	7.32	6.44	7.44	7.45	7.24
Std. Error	0.21	0.09	0.19	0.26	0.13	0.23	0.08	0.08	0.15	0.21	0.22	0.28	0.11	0.10	0.17
Std. Dev.	1.15	0.50	1.02	1.41	0.72	1.24	0.41	0.44	0.83	1.14	1.18	1.51	0.60	0.57	0.91
Median	7.19	7.45	7.50	7.51	7.64	7.45	7.50	7.71	7.59	7.59	7.60	7.11	7.52	7.52	7.49
90th	7.80	7.92	8.00	8.07	8.12	8.01	7.97	8.19	8.10	8.08	8.13	7.68	8.03	8.00	8.01
10th	5.61	6.92	6.26	4.05	6.68	5.69	6.98	7.28	6.12	5.93	7.08	4.30	6.93	6.95	6.20
Skewness	-2.27	-1.98	-2.09	-1.48	-1.90	-1.99	-0.88	-0.82	-1.50	-2.76	-2.98	-1.33	-1.98	-1.73	-1.83
Maximum	8.11	8.11	8.20	8.19	8.25	8.20	8.12	8.32	8.26	8.32	8.22	8.04	8.11	8.11	8.18
Minimum	2.57	5.40	3.87	3.85	4.98	2.66	6.22	6.50	5.23	2.57	2.94	2.15	5.15	5.42	4.25
	HES														
Mean	7.49	7.85	7.72	7.67	7.89	7.50	7.93	8.18	7.89	7.85	7.72	7.19	7.96	7.91	7.77
Std. Error	0.20	0.08	0.17	0.17	0.13	0.22	0.06	0.07	0.12	0.17	0.22	0.24	0.09	0.10	0.09
Std. Dev.	1.11	0.43	0.94	0.95	0.74	1.19	0.33	0.39	0.63	0.92	1.20	1.31	0.47	0.53	0.49
Median	7.79	7.92	7.99	7.96	8.07	7.93	7.94	8.19	8.04	8.11	7.99	7.75	8.01	8.00	7.87
90th	8.25	8.35	8.41	8.49	8.53	8.38	8.37	8.60	8.49	8.51	8.57	8.24	8.38	8.44	8.27
10th	6.38	7.40	7.02	6.03	7.01	6.50	7.44	7.84	7.06	7.09	7.42	5.55	7.52	7.48	7.33
Skewness	-2.60	-1.61	-2.42	-1.51	-2.00	-2.47	-0.38	-1.22	-1.34	-3.06	-2.91	-1.69	-2.15	-1.96	-1.53
Maximum	8.53	8.50	8.54	8.62	8.68	8.59	8.43	8.73	8.67	8.71	8.70	8.48	8.51	8.47	8.37
Minimum	3.02	6.30	4.43	5.33	5.24	2.92	7.26	6.95	6.16	3.88	3.32	3.08	6.10	5.93	6.09

4.3.4 Projected Changes in Yields

Differences in projected barley yields, relative to the yields of the baseline period (1961-1990), increased from the 2030s to the 2050s for all emission scenarios and regions except NWE in the 2030s and WA in the 2030s and 2040s (Figure 4-9). The pattern and magnitude of the differences represent the trend in yields in the future time slices and

emission scenarios. Thus, yield increased for all regions from the 2030s to 2050s and across the emission scenarios with very few exceptions. In the 2030s, yield differences relative to the baseline ranged from 1.43 (SES) to 2.49 tons ha⁻¹ (NWE) under the LES, 1.62 (EE) to 2.79 tons ha⁻¹ (WM) under the MES, and 1.36 (WA) to 2.86 tons ha⁻¹ (WM) under the HES. For WA, however, the difference between the projected and baseline yields decreased from the LES to the HES. Only EE and WA had yield increases lower than 2 tons ha⁻¹ for the MES and HES. For the UK, the differences between the projected yields in the 2030s and the baseline yields were 1.80, 2.22 and 2.29 tons ha⁻¹ for the LES, MES and HES respectively.

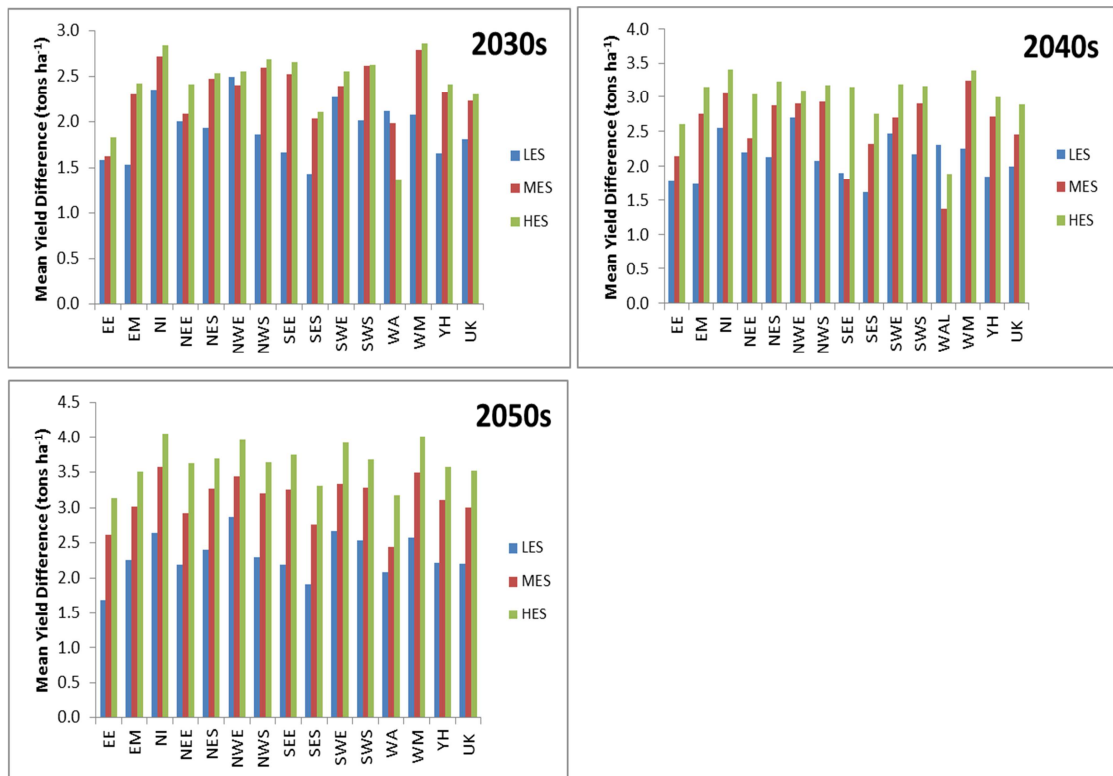


Figure 4-9: Increase in projected yields (tons ha⁻¹) over baseline yields.

In the 2040s, differences between projected and baseline yields ranged from 1.62 (SES) to 2.70 tons ha⁻¹ (NWE) for the LES, 1.37 (WA) to 3.25 tons ha⁻¹ (WM) for the MES, and 1.89 (WA) to 3.41 tons ha⁻¹ (NI) for the HES, respectively. Only NI had a yield increase over 3 tons ha⁻¹ while SEE and WA had yield increases lower than 2 tons ha⁻¹ under the MES. For the HES, only EE, SES and WA had yield increases under 3 tons ha⁻¹. The average increases in yield for the UK were 2.00, 2.46 and 2.90 tons ha⁻¹ respectively for the LES, MES and HES. By the 2050s, projected yield increases over the baseline ranged from 1.69 (EE) to 2.88 tons ha⁻¹ (NWE) for the LES, 2.43 (WA) to 3.57 tons ha⁻¹ (NI) for the MES, and 3.15 (EE) to 4.05 tons ha⁻¹ (NI) for the HES, respectively. The corresponding values for the UK were 2.20, 3.00 and 3.53 tons ha⁻¹ for the LES, MES and HES, respectively. Only EE and SES had yield increases lower than 2 tons ha⁻¹ for the LES while only NI and WM had yield increases over 4 tons ha⁻¹ for the HES.

For all emission scenarios and time slices (except for WA in the 2030s and 2040s), projected absolute increases in yields over the baseline were generally higher in the western half than in the eastern half of the UK, but marginally from south to north. However, for each emission scenario, changes in yields between time slices were not substantial under the LES, but were greater under the MES and HES. The difference between the MES and HES was not substantial and less obvious in the 2030s but became greater and clearer from the 2040s to 2050s.

Temporal variations in yield for each time slice and emission scenario give impressions of uncertainties associated with climate change effects on yield. Compared to the baseline which showed yield stability, only the temporal profiles of the LES showed high yield stability in the 2030s and 2040s (Appendix 3A). In the 2050s, however, the

consistency of higher yields was disrupted by dips in yield, with some dips being deep (e.g. EE, NEE and NES). Under the MES, yield dips became deeper, wider or more frequent and affected more regions in all the time slices (Appendix 3B). Although the pattern of yield dips were similar for all the time slices, the depth and width were greater in the 2040s compared to the other time slices. For the temporal profiles of yields under the HES, the pattern of yield dips within the time slices were similar to that observed for the MES, but the dips under the HES were comparatively greater in their depth and width (Appendix 3C). The depth of the yield dips was lowest in the 2050s for the HES. In all, the projected yields showed an increasing trend for all time slices and emissions scenarios (Appendix 3A – 2C). Regions that showed deep and frequent yield dips for all time slices were EE, NEE, NES and WA while EM, SEE, WM, and YH exhibited consistency or stability in yield (except that SEE became variable in the 2050s under the HES).

4.3.5 Projected Virtual Water Content of UK Barley Grains

The virtual water content (VWC) of future UK barley grains (average of the 14 regions) ranged from 390 m³ ton⁻¹ (HES) to 460 m³ ton⁻¹ (LES) in 2050 (Figure 4-10). The VWC decreased from the LES to the HES and from 2030 to 2050 (due to improvement in crop water productivity), except for the LES where the VWC for 2030 is greater than that of 2040.

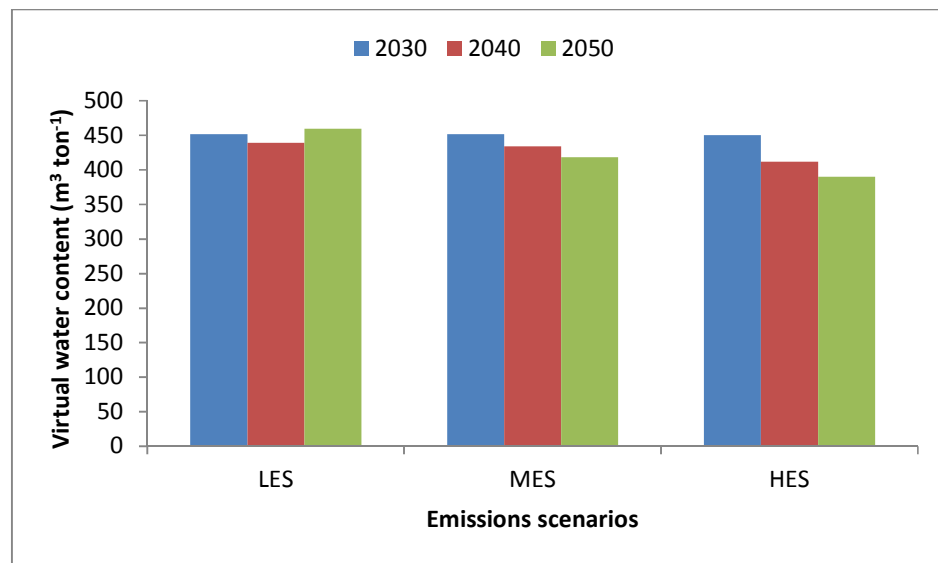


Figure 4-10: Projected virtual water content of UK barley grains

4.3.6 Yield Relationships with Atmospheric CO₂ Concentrations

Poor relationships were found between projected yields and cumulative seasonal rainfall for all time slices and emission scenarios. However, in most cases, positive and negative relationships were observed for the eastern and western regions, respectively. Projected yields showed positive linear relationships with increasing atmospheric CO₂ concentration ($[\text{CO}_2]_{\text{atm}}$) for all time slices and emission scenarios for most regions (Table 4-9). Projected yields in three regions (EM, WM and YH) showed a linear relationship with $[\text{CO}_2]_{\text{atm}}$ for all emission scenarios and time slices. The projected yields in EE and WA showed a relationship with $[\text{CO}_2]_{\text{atm}}$ only under the LES, while projected yields of NWE showed no relationship at all with $[\text{CO}_2]_{\text{atm}}$.

Table 4-9: Relationships between simulated yields and atmospheric CO₂ concentrations.
 NB: only relationships with R² value of 0.3 or above (p < 0.05) are reported.

	Regression Equation Parameters			R ²		
	2030	2040	2050	2030	2040	2050
EE	0.007x + 2.7656 ^a	0.0054x+3.6172 ^a	-	0.552 ^a	0.560 ^a	
EM	0.0073x+2.5966 ^a 0.0094x+2.3559 ^b 0.0091x+2.4642 ^c	0.0065x+3.0043 ^a 0.0084x+2.9456 ^b 0.0072x+3.5632 ^c	0.0074x+2.9537 ^a 0.0057x+4.2782 ^b 0.0055x+4.6102 ^c	0.487 ^a 0.542 ^b 0.586 ^c	0.434 ^a 0.726 ^b 0.584 ^c	0.716 ^a 0.350 ^b 0.417 ^c
NEE	0.0135x+0.4505 ^b	0.0109x+1.6565 ^b	0.0084x+2.2665 ^a 0.0088x+2.7064 ^b	0.346 ^b	0.398 ^b	0.399 ^a 0.383 ^b
NES	0.0119x+1.2499 ^b	0.0104x+1.9 ^b	0.0061x+3.3748 ^a 0.0084x+3.0375 ^b	0.456 ^b	0.498 ^b	0.373 ^a 0.536 ^b
NI	0.0113x+1.6059 ^b 0.0113x+1.5965 ^c	0.0088x+2.8598 ^b 0.0078x+3.3263 ^c	0.0066x+3.3767 ^a 0.0063x+4.2388 ^b	0.392 ^b 0.474 ^c	0.478 ^b 0.395 ^c	0.577 ^a 0.469 ^b
NWE	-	-	-	-	-	-
NWS	0.096x+2.35007 ^b 0.0094x+2.4317 ^c	0.0085x+2.8652 ^b 0.009x+2.4824 ^c	0.0062x+3.4863 ^a 0.0064x+4.0147 ^b	0.596 ^b 0.713 ^c	0.621 ^b 0.710 ^c	0.411 ^a 0.433 ^b
SEE	0.0082x+2.4591 ^a 0.0097x+2.5139 ^b 0.0097x+2.5289 ^c	0.007x+3.038 ^a 0.0083x+3.239 ^c	0.0073x+3.0614 ^a 0.0069x+4.0405 ^b	0.491 ^a 0.560 ^b 0.777 ^c	0.483 ^a 0.817 ^c	0.805 ^a 0.633 ^b
SES	- 0.0076x+3.4379 ^b	- 0.0081x+3.2625 ^b 0.0065x+3.9997 ^c	0.0067x+3.1861 ^a 0.0054x+4.6848 ^b	- 0.477 ^b	- 0.613 ^b 0.431 ^c	0.341 ^a 0.354 ^b
SWE	0.0081x+2.5758 ^a -	0.0072x+3.0316 ^a - 0.0084x+2.8955 ^c	0.0074x+2.9536 ^a 0.0057x+4.5698 ^b	0.572 ^a -	0.507 ^a - 0.432 ^c	0.589 ^a 0.350 ^b
SWS	- 0.0094x+2.5674 ^b 0.0099x+2.2612 ^c	- 0.0087x+2.9099 ^b 0.0083x+3.0875 ^c	0.0066x+3.3124 ^a 0.0066x+4.0012 ^b 0.0056x+4.7156 ^c	- 0.612 ^b 0.736 ^c	- 0.609 ^b 0.760 ^c	0.487 ^a 0.524 ^b 0.355 ^c
WA	0.0067x+3.0863 ^a	-	-	0.390 ^a	-	-
WM	0.0073x+2.7521 ^a 0.0095x+2.4432 ^b 0.0085x+2.84 ^c	0.006x+3.3809 ^a 0.0081x+3.161 ^b 0.0077x+3.2612 ^c	0.0079x+2.6445 ^a 0.0071x+3.7067 ^b 0.0054x+4.7711 ^c	0.471 ^a 0.518 ^b 0.583 ^c	0.415 ^a 0.678 ^b 0.606 ^c	0.398 ^a 0.543 ^b 0.392 ^c
YH	0.0069x+2.9015 ^a 0.0096x+2.3284 ^b 0.0096x+2.3611 ^c	0.0065x+3.1317 ^a 0.0086x+2.8559 ^b 0.0085x+2.9482 ^c	0.0078x+2.707 ^a 0.0074x+3.5562 ^b 0.0056x+4.6312 ^c	0.352 ^a 0.495 ^b 0.608 ^c	0.312 ^a 0.494 ^b 0.752 ^c	0.703 ^a 0.665 ^b 0.407 ^c
UK	0.0067x+3.0251 ^a 0.008x+2.8622 ^b 0.0082x+2.74 ^c	0.0065x+3.1937 ^a 0.0067x+3.4941 ^b 0.007x+3.4378 ^c	0.0075x+2.7572 ^a 0.0055x+4.3859 ^b 0.005x+4.9272 ^c	0.323 ^a 0.349 ^b 0.496 ^c	0.303 ^a 0.356 ^b 0.532 ^c	0.465 ^a 0.316 ^b 0.423 ^c

Key: a, b, and c represent low, medium and high emission scenarios respectively.

Under the LES, variation in projected yield accounted for by increasing $[\text{CO}_2]_{\text{atm}}$ for all the time slices ranged from ca. 31% (YH, 2040s) to 81% (SEE, 2050s). In most cases, $[\text{CO}_2]_{\text{atm}}$ accounted for yield variations in the range of over 30% to over 50%. Under the MES, $[\text{CO}_2]_{\text{atm}}$ accounted for ca. 35% to 73% of the yield variations. For the HES, $[\text{CO}_2]_{\text{atm}}$ explained 36% (SWS, 2050s) to 82% (SEE, 2040s) of the variation in yield. For the UK, $[\text{CO}_2]_{\text{atm}}$ explained ca. 30% to 53% of the yield variations for all emission scenarios and time slices, with highest values occurring under the HES. In all, positive relationships between projected yield and increasing $[\text{CO}_2]_{\text{atm}}$ were observed for one or more time slices in 12, 11 and 8 regions under the LES, MES and HES, respectively.

4.4 Discussion

4.4.1 Sowing Dates and Model Uncertainties in Baseline Yields

In simulating the effect of climate change on crop yields, uncertainties in the projected yields can arise from three main sources (Yao *et al.*, 2011; Niu *et al.*, 2009; Murphy *et al.*, 2004; Corfee-Morlot & Höhne, 2003): (i) the projected climate data due to uncertainties in the emission scenarios, gaps or limitations in knowledge of the climate system, and uncertainty in the structure and parameters of the climate model; (ii) the crop growth simulation model used due to uncertainty in the structure and parameterization of the simulation model, calibration and validation and crop response to climate change; and (iii) soil and crop input data such as soil fertility, influence of biotic stresses, crop genotype and sowing date. Tracking and quantifying the aggregate effect of these

uncertainties on simulated yields are difficult and require complex mathematical procedures (Yao *et al.*, 2011). It is important, however, that model users are aware of the potential effect of these uncertainties on their predictions and, where possible, take measures to minimize it (Yao *et al.*, 2011; Niu *et al.*, 2009). The UKCP09 probabilistic projections are meant to minimize uncertainties (Murphy *et al.*, 2009; 2008).

Sowing date is a sensitive parameter as it affects crop phenology and therefore biomass production, abiotic stresses and yields (Rötter *et al.* 2012; 2011; Biernath *et al.*, 2011; Guereña *et al.*, 2001). Sowing dates are highly variable over time and space (Rötter *et al.* 2012; 2011; Biernath *et al.*, 2011; Holden *et al.*, 2003). Therefore, use of actual sowing date is crucially important for minimizing uncertainties in simulated yields under climate change. However, it is difficult to accurately predict sowing dates under future climates. Hence, climate change studies rely on current sowing dates and adjustments are explored as adaptation options for future climates (Matthews *et al.* 2013; Rötter *et al.*, 2011; Wilby *et al.* 2010; Holden *et al.* 2003). Indicative sowing dates, therefore, become useful when data are lacking.

In this thesis, the indicative sowing dates used were within the HGCA recommended sowing window (Table 4-4). For the 1990 baseline, the simulated yields were mostly lower than the actual yields (Table 4-4). This could be due to the reduction in the Hlo in the simulations to compensate for the current high yields resulting from genetic improvement. However, for the baseline period 1980-1989, simulated yields were slightly higher than the observed yields in most cases. Moreover, the actual regional yields represent averages of yields of several genotypes, sites and management practices. Even though the average evens out spatio-temporal and genetic variations in regional yields, the

actual yield can still differ greatly from the simulated yield which is obtained at a plot-scale. Notwithstanding, the baseline calibration and validation using indicative sowing dates showed acceptable error margins for the simulated yields (Table 4-4).

Rötter *et al.* (2012) compared the performance of nine crop models for predicting the yields of spring barley grown over 44 crop seasons at 7 sites in Northern and Central Europe, using average sowing dates derived from experimental reports. They reported that the best three performing models (HERMES, MONICA and WOFOST) gave lowest RMSE values of 1.124, 1.128 and 1.325 tons ha⁻¹ respectively, which are greater than the RMSE values reported in the current chapter (Table 4-4). Richter & Semenov (2005) used the model Sirius to assess the effect of climate change on wheat yield in England and Wales. They reported overall RMSE of 1.14 tons ha⁻¹. Mainuddin *et al.* (2011) also used AquaCrop to simulate climate change effects on rice yields in the Lower Mekong Basin using a calibration approach for sowing dates similar to the approach in the current study. They reported RMSE values for rain-fed rice ranging from 0.04 to 0.45 tons ha⁻¹ (for a yield range of 0-7.14 tons ha⁻¹), which are lower than but not substantially different from the RMSE values obtained in the current study. It is not always guaranteed that use of actual sowing dates for calibration always gives accurate predictions as uncertainties in other input data can equally generate uncertainties in simulated yields (Guereña *et al.*, 2001). Model structure also contributes to uncertainties in simulated yields and this is probably the source of uncertainty most difficult to quantify (Rötter *et al.* 2012). Hence, it is concluded that the model setup and the indicative sowing dates gave acceptable prediction of yields in the baseline period.

4.4.2 Changes in Yields under Climate Change

The baseline yields show an increasing trend (Figure 4-3) with 90th percentile of yields around 5 tons ha⁻¹ (Table 4-5) which could be attributed to genetic improvement and increasing potential evapotranspiration resulting in higher biomass accumulation. Current mean yields (2000 – 2010) range from 4.60 to 5.50 tons ha⁻¹, but mean yields as low as 3 tons ha⁻¹ can still be observed occasionally in certain years. Yields as high as 6 – 10 tons ha⁻¹ have been recorded from experiments with genotype Westminster in SES from 2009 to 2011 (see Chapter 3, Table 3-6; also McKenzie *et al.*, 2009), indicating that the simulated future yields are possible. The longitudinal and latitudinal variations in baseline yields could be attributed to the observed pattern of relative wet and dry conditions from west to east and south to north in the UK.

Generally, there was no limitation to the establishment and grain yield of simulated barley growth under the baseline or future climates for all emission scenarios and time slices. Seasonal rainfall will not likely vary substantially in the UK across emission scenarios and time slices and the geographical distribution is likely to remain unchanged with wetter conditions to the west. While seasonal rainfall can be said to be reasonably stable, slight variations are observable for all time slices under the MES and HES and in the 2050s for the LES (Figure 4-4). Summer rainfall is projected to decrease over Europe (Semenov & Shewry 2011; Bates *et al.*, 2008; Christensen *et al.*, 2007) and the UK (Murphy *et al.*, 2009), which has the potential to decrease cereal yields. However, based on the mean grain yields for the emission scenarios and time slices in this study, seasonal rainfall is predicted to be sufficient to maintain the viability of barley production under the future climates. Drainage losses (and for that matter contribution to groundwater recharge)

followed a pattern similar to rainfall. However, for the UK, there is a slight decrease in drainage from the LES to the HES and from the 2030s to the 2050s. This requires further investigation in studies on groundwater recharge and water pollution from arable land uses under future climates.

There are very few simulation studies for barley crops under current conditions in northern temperate environments and fewer under future climates (Rötter *et al.* 2012; 2011) The simulations in the current study predict that grain yields of barley will increase over baseline yields from the 2030s to the 2050s for all emission scenarios in all UK regions (Figure 4-9). The magnitude of increase in yield relative to the baseline is predicted to be greater under the HES, followed by the MES. Thus, yields are predicted to increase markedly under the HES from the 2030s to the 2050s. For example, under the HES, 90th percentiles of yields in the 2050s are projected to exceed 8 tons ha⁻¹ (Table 4-8), with greatest absolute increases in yield occurring in SEE. However, geographically, the greatest projected increases in yield relative to the baseline are predicted to occur in the western regions (except WA in some cases) even though the east-west yield gradient observed in the baseline period will remain unchanged. Moreover, the low skew values indicate high certainty in yields (Richter & Semenov, 2005). Little variability in regional yields might be due to the use of same phenology and crop parameters (apart from sowing dates) in the context of sufficient rainfall. However, little variability in yield across emission scenarios might be due to insubstantial differences in rainfall and atmospheric CO₂ concentrations up to the 2050s. These variables, including temperature, become substantially different for different emission scenarios after the 2050s (Wilby *et al.* 2010; Murphy *et al.*, 2009). Hence, unless there is a substantial reduction in rainfall, or increase

in temperature, for a given region, the difference in yields between emission scenarios for a given time slice will likely be insubstantial in this study.

The projected increases in barley yields are consistent with the results of previous studies. Holden *et al.* (2003) predicted barley grain yields would increase substantially across Ireland, under elevated $[\text{CO}_2]_{\text{atm}}$, exceeding 8 tons ha^{-1} in 2055 and be even greater in 2075. They also predicted that absolute increase in yield relative to baseline yields was higher in the western half of Ireland though the current spatial distribution of yield potential will remain the same. Rivington *et al.* (not dated, http://www.adaptationscotland.org.uk/Upload/Documents/MLURI_webversion.pdf) used climate data generated with the UKCP09 weather generator and the CropSyst model to simulate barley yields in Scotland. They predicted that the mode of Scottish barley yields would be over 7 tons ha^{-1} in the 2040s under the HES, with maximum yields approaching 10 tons ha^{-1} . Richter & Semenov (2005) suggested that, despite projected decrease in summer rains, wheat yields in England and Wales are likely to increase by up to 2 tons ha^{-1} in the 2050s over baseline yields due to elevated $[\text{CO}_2]_{\text{atm}}$, with greatest increase in East Anglia and the south-east. Studies in other temperate European environments have also predicted increases in barley biomass and grain yields under elevated CO_2 concentrations (Clausen *et al.*, 2011; Manderscheid *et al.*, 2009; Sæbø & Mortensen, 1996). Even in China, average yields of rain-fed wheat are projected to increase, under the A2 emissions scenario, by approximately 10 to 20% (from the 2020s to 2080s) over baseline yields under elevated $[\text{CO}_2]_{\text{atm}}$ (Erda *et al.*, 2005). Without CO_2 fertilization, yields decrease from 10 to 36% (Erda *et al.*, 2005). The projected ranges of increase and decrease in

yields under the B2 emissions scenario were 4 – 13% and 10 – 13% respectively from the 2020s to 2080s (Erda *et al.*, 2005).

The observed variations in yields between the time slices for the regions in the current study can be attributed to elevated atmospheric CO₂ combining with the small increase in temperature and changes in rainfall to proportionately increase biomass and grain yield of barley so that grain:biomass ratio remains unchanged (Holden *et al.*, 2003). This favourable effect of climate change might also explain the observed greater absolute increase in yield over baseline yields in the western regions where wet conditions around anthesis might be suppressing yields (Robredo *et al.*, 2011). Generally, it is believed that when water is not limiting, elevated atmospheric CO₂ and moderate warming might benefit C₃ crops in northern temperate environments substantially (Rötter *et al.*, 2011; DaMatta *et al.*, 2010; Richter & Semenov, 2005; Fuhrer, 2003). In such environments, projected changes in temperature, together with elevated [CO₂]_{atm}, increase radiation use efficiency, water use efficiency and photosynthesis assuming there is no severe water stress and nitrogen is not limiting (Robredo *et al.* 2011; 2007; Manderscheid *et al.*, 2009). The positive effect of elevated [CO₂]_{atm} on barley grain yield has been found to result mostly from higher biomass production and grain number (Clausen *et al.*, 2011; Manderscheid *et al.*, 2009, Fangmeier *et al.*, 2000; Sæbø & Mortensen, 1996) and, to a lesser extent, from increased grain weight due to varied effects of CO₂-temperature-water interactions on the duration and effectiveness of grain filling and canopy senescence (Fangmeier *et al.*, 2000).

In the current study, positive relationships were found between projected yields and [CO₂]_{atm} but poor relationships were found between projected yields and seasonal

rainfall and temperature. The $[\text{CO}_2]_{\text{atm}}$ explained between 30 and 82% of the variations in projected yields for all emission scenarios and time slices and 30% to 53% of the variations in projected UK yields. This suggests that elevated $[\text{CO}_2]_{\text{atm}}$ will benefit barley yields and barley production in the UK substantially, all other things being equal. The observed increase in projected yields over the baseline yields across the emissions scenarios and time slices suggests that current climatic conditions limit yield potential. This is in agreement with some previous studies. According to Richter & Semenov (2005), $[\text{CO}_2]_{\text{atm}}$ accounts for yield increases in wheat and the compensating effect of rising CO_2 will be stronger than the effect of drought on wheat yields in England and Wales in the future. On the contrary, they found that the effect of $[\text{CO}_2]_{\text{atm}}$ on wheat yields was highest in the 2020s but decreases subsequently up to the 2050s. Rötter *et al.* (2011) observed that warmer temperatures only decreased the length of the season but did not affect yield variability, whereas low temperatures rather increased both yield and yield variability of barley in Finland. They also reported that elevated $[\text{CO}_2]_{\text{atm}}$ increases yield even under elevated temperatures when the duration of water stress was short. Barley is well-known for its ability to recover from short-term water stress (González 2011; González *et al.*, 1999; Shone & Flood, 1983). Studies show that elevated $[\text{CO}_2]_{\text{atm}}$ in the future will likely increase drought tolerance and yield in barley through adjustments in stomatal conductance, osmotic potential and improved nitrogen metabolism (Burkart *et al.* 2011; Robredo *et al.* 2011; 2007). Holden *et al.* (2003), however, reported that the predicted increase in barley yields in the 2050s in Ireland was probably attributable to rainfall but $[\text{CO}_2]_{\text{atm}}$ accounted for predicted yield increases in the 2070s. This is probably largely due to the differences in the $[\text{CO}_2]_{\text{atm}}$ used in the study by Holden *et al.* (2003) and

the current study. Holden *et al.* (2003) used $[\text{CO}_2]_{\text{atm}}$ of 581 ppm and 647 ppm respectively for the 2050s and 2070s, which are both within the range of the $[\text{CO}_2]_{\text{atm}}$ under the HES in the 2050s in the current study. The favourable combination of climatic factors also has implications for the incidence and prevalence of diseases and pests which were not considered in the current study.

Soil hydraulic properties will also play a key role in mitigating or amplifying water stress and therefore unlocking the full benefit of elevated $[\text{CO}_2]_{\text{atm}}$ for barley yields in the future (Calanca *et al.* 2006). Few studies have incorporated the effect of soil dryness on yield of cereals under climate change (Richter & Semenov, 2005). In current study, the soil data generally show little differences in the rooting depth and available soil water (ASW) content for the regions (Table 4-2). It would generally be expected that the relatively drier conditions and shallow soils in Southern England would result in dramatic reductions in barley yield. However, the observed high yields in SEE even under the HES might partly be due to the high ASW content due to the presence of clay in these soils. This is consistent with the findings of Richter & Semenov (2005) who reported highest yield increases in wheat in the Southeast of England regardless of reductions in rainfall and warmer temperatures under future climates. They reported that the effect of water stress on yield was substantial only when ASW content remained very low for a long time. Considering the ASW content and stability of seasonal rainfall for the regions in the current study, it is likely that the soil water content in the root zone was normally sufficient to satisfy the crop water requirements. However, given the coarse scale of the soil data in the current study, it is recommended that future studies employ soil data with a greater spatial resolution to explore the effects of the interactions between climatic factors

and soil hydraulic properties on cereal yields under future climates. This is important as excessive soil water content could affect, for example, soil workability and thereby influence management decisions and practices.

4.4.3 Stresses and Risks to Yields

The potential gain from elevated $[\text{CO}_2]_{\text{atm}}$ can be offset by other parallel climate change effects such as heat stress and stresses due to soil water deficit or waterlogging (Rötter *et al.* 2011; Easterling *et al.*, 2007; Ainsworth & Rogers, 2007; Fuhrer 2003). The temporal profiles of barley yields show some yield dips within time slices for all emission scenarios. Yields under 2 tons ha^{-1} were observed for WA in the 2040s and 2050s under the HES. Stresses related to temperature and water observed in the simulations could account for a substantial amount of the observed yield dips. AquaCrop distinguishes between the effects of temperature and water stresses on biomass and yield (Raes *et al.*, 2009). Thresholds for the effects of water and temperature stresses on biomass production are executed mainly through alterations in three canopy properties: expansion, stomatal closure and early senescence. Water and temperature stresses affect yield directly through pollination failure and reductions in HI_0 . Thus, there are situations where biomass production could be affected (e.g. when maximum canopy cover is not reached) independent of yield formation and in such situations, biomass production should be substantially limited in order to reduce yield.

Water stresses resulting in stomatal closure (as high as 72% stomatal closure was observed in a model variant under the HES, see Figure 4-11a) and early canopy

senescence were observed, resulting in reductions in biomass production. Stomatal closure can potentially elevate leaf and canopy temperature and thereby reduce photosynthesis (Hanjra & Qureshi, 2010; Kimball & Bernacchi, 2006). There were occasions when water stresses coincided with either anthesis or post-anthesis (illustrated with Figure 4-11b), resulting in substantial reductions in both biomass production and harvest index. Interestingly, there were also occasions when the soil water content was in excess of field capacity around anthesis. There were occasions when soil water content exceeded the anaerobiosis point, which results in transpiration suppression and consequent reductions in biomass production and yield. Though this was commonly observed, it was predominant in WA, SWS and NI where the initial canopy development was negatively affected and maximum canopy cover was not reached. This suggests that stresses arising from both soil water deficits and surpluses could have adverse effects on future barley production in the UK. Therefore, the potential effect of saturated soil conditions on the production of barley and cereals in general under future climates should be given due research attention to identify agronomic strategies that can be used to mitigate this effect.

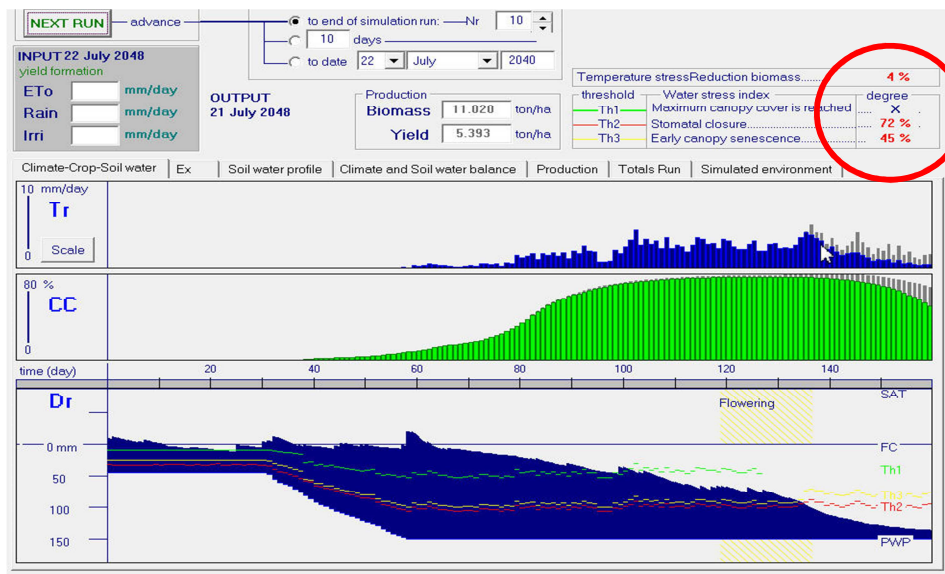


Figure 4-11a: A screenshot of AquaCrop output graphic of a climatic variant illustrating high effect of water stress on stomatal closure and early canopy senescence (marked with red circle at upper right-hand corner) under the HES in the 2040s.

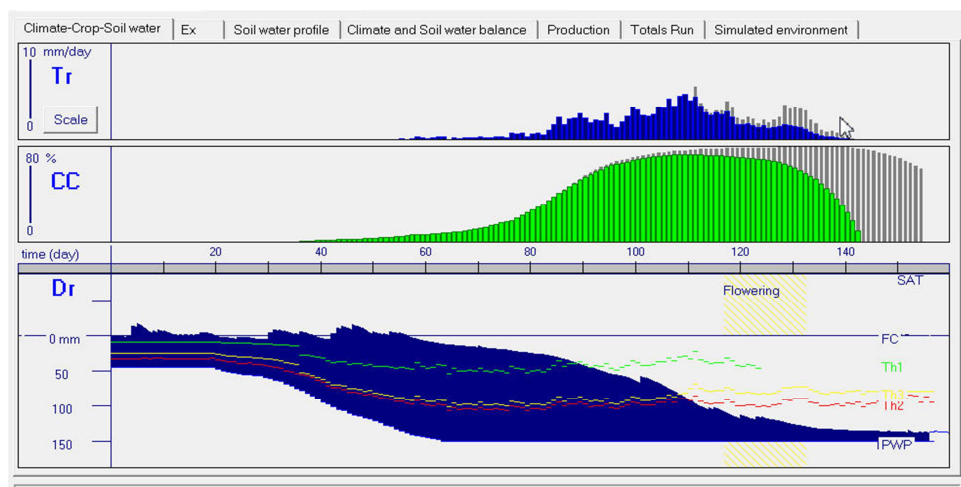


Figure 4-11b: A screenshot of AquaCrop output graphic of a climatic variant illustrating occurrence of water stress before, during and after flowering under the HES in the 2050s. The lower box *Dr* shows soil water depletion, with the blue line indicating field capacity. The green, yellow and red squiggly lines represent the 3 water stress thresholds for canopy expansion, stomatal closure and early canopy senescence. The middle box *CC* shows water stress effect on canopy cover development. The grey bars show reductions or deviation from the potential canopy cover trajectory. The upper box *Tr* shows the pattern of transpiration, with the grey bars representing reductions in transpiration

Reductions in biomass production due to temperature stress ranged from 2% to 53% across emission scenarios and time slices, with highest reductions occurring under the HES in EE. In most cases, maximum canopy cover was not reached. This suggests that even though barley can be popular for its drought tolerance, heat stress can potentially increase photorespiration, limit CO₂ assimilation and reduce biomass production (Easterling *et al.*, 2007; Fuhrer, 2003) in some UK regions under future climates, especially under the HES. Heat-stress can shorten crop phenology and reduce radiation capture, upset net carbon balance, reduce seed set and pollen viability, cause grain sterility and yield losses (DaMatta *et al.*, 2010; Porter & Semenov, 2005; Fuhrer, 2003). It has been suggested that heat stress, due to climate change, poses a serious threat to wheat yields in England and Wales (Richter & Semenov 2005) and in Europe (Semenov & Shewry, 2011) or barley production in Finland (Rötter *et al.* 2011) and Denmark (Clausen *et al.*, 2011). The risk is that the years in the time slices do not represent actual future years, meaning the observed stresses can occur in any crop season in the future. These findings highlight the need for adapting crops to such future climatic conditions.

However, in all, early maturity due to faster accumulation of total thermal time allowed the crop to escape heat or water deficit stresses, which normally occurred around mid-summer. Total thermal time required for maturity was accumulated faster, resulting in the season being shortened by between 3 and 15 days. On average, harvest dates for most southern regions were in late June but overall harvest dates largely occurred in July, with very few occurring in late July to early August. The projected reductions in summer precipitation and warmer temperatures are centered on June-July-August (Wilby *et al.* 2010; Jenkins *et al.*, 2009; Murphy *et al.*, 2009). Thus, the crop would probably escape the

effects of summer water deficits or heat stress, as it will have attained physiological maturity at this time, confirming the usefulness of early sowing (Wilby *et al.* 2010; Barnabàs *et al.*, 2008; Richter & Semenov 2005). Thus, in most of such cases, the stresses would only be effective in accelerating normal canopy decline. It was, however, not always clear what stresses caused reductions in biomass production or yields. Such cases might be attributable to model structural errors (Rötter *et al.* 2012; Brouwer & van Ittersum, 2010; Todorovic *et al.*, 2009; Richter & Semenov, 2005; Guereña *et al.*, 2001).

Therefore, within the limits of the current study, it can be concluded that projected seasonal rainfall would likely be sufficient to keep barley production viable from the 2030s to the 2050s. However, water and heat stresses are likely to pose risks to biomass production and yield in some years in the future. In the current study, extreme events and their intensities, or the probability of exceeding a certain threshold of climate change signal (e.g. temperature increase exceeding 4 °C) were not assessed. These are important for quantifying and better understanding risks and planning adaptation (Fuhrer *et al.* 2006). The findings in this study show that such an exercise is necessary for understanding the bigger picture of climate change effects on barley yields in the UK. Heat stress in particular is obviously a problem that warrants further investigations.

4.5 Conclusions

1. Projected barley yields increased over the baseline yields in all UK regions for all the time slices and emission scenarios, with greatest increases

occurring in the 2050s. The increase in yields for the emission scenarios followed the order: HES > MES > LES.

2. Projected absolute increases in yields over the baseline yields were greater in the west than in the eastern half of the UK.
3. Elevated $[\text{CO}_2]_{\text{atm}}$ would likely benefit UK barley production substantially. The $[\text{CO}_2]_{\text{atm}}$ explained between 30 and over 80% of variations in projected yields for all UK regions, emission scenarios and time slices, but explained 30-50% of variation in projected yields for the UK.
4. Barley will remain a viable rain-fed crop in the UK under the projected climate change. However, potential yield dips in some years within all the time slices and emissions scenarios (except under the LES in the 2030s and 2040s) due to water and heat stresses pose risks to high and stable yields.

CHAPTER 5**FUTURE BARLEY PRODUCTION, VIRTUAL WATER FLOWS AND FOOD SECURITY IMPLICATIONS****5.1 Introduction**

By 2050, per capita meat consumption will be about 49 kg for the world and 91 kg in the advanced countries (Alexandratos & Bruinsma, 2012) due to a projected increase in income, population and dietary shifts (Thornton, 2010; de Fraiture *et al.*, 2007). To meet projected demand (even if total demand grows more slowly), global meat production must increase from 258 million tons (2005/07 average) to 455 million tons in 2050 (Alexandratos & Bruinsma, 2012). The production of meat and animal products is highly dependent on the availability of, and access to, animal feed. Hence, the large increase in projected meat demand has implications for use of cereal grains as animal feed in the future.

Currently, about 35% of total grain produced in the world is used for animal feed (the bulk of it being coarse grains), 46% is directly consumed as food and 19% is used for industrial purposes mainly brewing and distilling (Alexandratos & Bruinsma, 2012; Foresight, 2011). It has been projected that world cereal production will have to increase from the current 2.1 billion (2005/07 average) to 3 billion tons by 2050 (Alexandratos & Bruinsma, 2012) partly due to the substantial increase in demand for animal feed (de Fraiture *et al.*, 2007) which is projected to reach 1.1 billion tons, as well as for biofuel (Alexandratos & Bruinsma, 2012). About 52% and 54% of grains produced in the UK and the EU respectively are used as animal feed (Bruinsma, 2012; Foresight, 2011). Total

cereal and meat demand in Europe and Central Asia are projected to be 600 million and 71 million tons respectively by 2050, with feed use of cereal grains at 35 million tons (Bruinsma, 2012). However, the demand for grain (mostly wheat and maize) for biofuel production could drive up the prices of grains that can be used for animal feed. It has been projected that biofuel demand will likely reduce the proportion of grains allocated to animal feed (Alexandratos & Bruinsma, 2012).

Barley is an important source of animal feed grain and it is the dominant component of coarse grains used as animal feed (Newton *et al.*, 2011). Industrially advancing countries will account for about 56% of global use of coarse grains as animal feed by 2050 and are therefore expected to increase their import of coarse grains substantially (Alexandratos & Bruinsma, 2012). Kruse (2011) indicated that, between 2000 and 2050, world aggregate barley production will have to increase by 54% to meet projected demand for food, feed and industrial purposes.

In the UK, the main end uses of barley grain are animal feed (over 60%) and industrial purposes mainly brewing and distilling (a little over 30%), while the remaining grain goes into stocks, seed, food and waste (Defra, 2011). The current UK food balance sheet (FBS) shows that nearly half the total grain supply for domestic uses (mainly wheat, barley and oat) is used as animal feed. Even though the UK is currently self-sufficient in barley production, it has high trade deficits in meat and aggregate animal feed (Defra, 2011). According to Defra (2011), the three major farm inputs that have shown the greatest increases in cost recently for the UK are fuel, fertilizer and feed. The cost of animal feed has emerged as the largest item of expenditure on the agricultural production and income account (Defra, 2011). Figure 5-1 suggests that total expenditure on animal

feed has been rising sharply from 1973 to 1984, leveling off due to policy intervention (milk production quota) in 1984 and declining after 1996 mainly due to a slump in commodity prices caused by exchange rates and world prices (Defra, 2011).

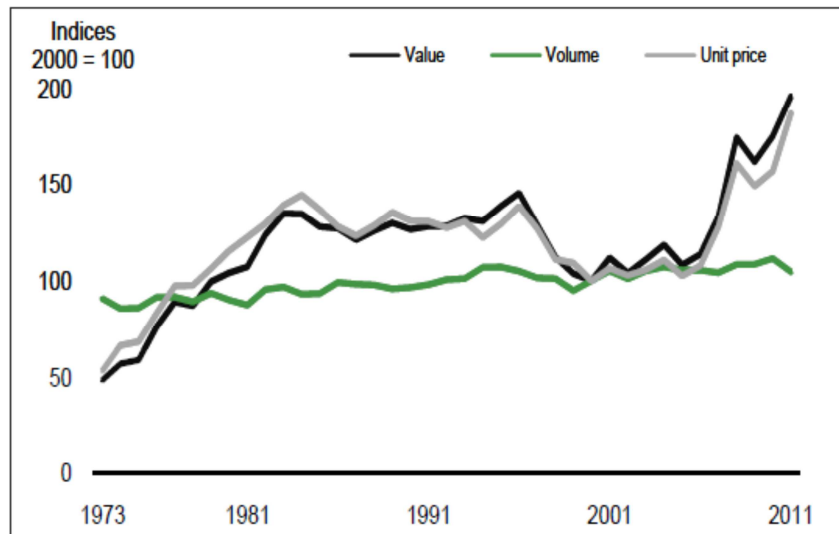


Figure 5-1: Animal feed expenditure indices. Figure taken from Defra (2011).

From 2005 to 2011, the cost of animal feed in the UK has increased by 80% due to rise in cereal prices (Defra, 2011). For example, the total volume of all purchased feed decreased by 5.1% from 2010 to 2011 but the total expenditure on all animal feed increased by 12% to £4.4 billion due to increased prices of mainly cereals (Defra, 2011). Prices of agriculture commodities in the UK (and, for that matter, incentives to UK farmers) are currently largely dependent on three main factors: world market prices, levels of EU tariffs on import of agricultural commodities and the currency exchange rate (Foresight, 2011). Clearly, increased feed barley production in the future is necessary for economic and food security reasons as it can contribute to reducing the cost of animal feed and thereby enhance food security in the UK. It is also likely, however, that demand for malt barley will remain strong and competitive.

However, total UK feed barley production and supply in the future will be determined, both directly and indirectly, by changes in land use, climate, meat demand, malt barley demand, biofuel production and demand, technology, commodity prices and availability of substitutes at both national and global scales (Huang *et al.*, 2010). Particularly, policies regarding climate change mitigation or adaptation and land use will affect future production and trade flows of any crop (Thomson *et al.*, 2013; Foresight, 2011; Huang *et al.*, 2010; IPCC, 2007) including feed barley. The extent of agricultural land use in the UK is known to correspond well with the proportion of the UK's raw food needs sourced from UK farms (Foresight, 2011). Potential land use change, however, has not been considered in most climate change and aggregate crop production studies. Market forces and economic incentives will also influence farmers' decisions on what crop to produce, technologies to adopt and ultimately the quantity produced (Huang *et al.*, 2010). In the virtual water literature, no study has yet assessed the consequences of the combined effect of climate change, land use change, and projected demand of a given crop for future virtual water flows and food security at any spatio-temporal scale.

In this thesis, food security is defined as “*the risk of adequate food not being available*” (Chakraborty & Newton, 2011; Newton *et al.*, 2011); ‘food’ here refers to feed barley and meat. The question therefore remains whether there will be a sufficient feed barley supply domestically to meet future requirements without adversely affecting allocation to malting and other uses. This question has received little research attention and particularly, barley is subsumed under aggregate feed or cereal demand when such studies are conducted. The objective of this chapter is therefore to assess the feedback relationship between future feed barley supply on one hand and demand for meat on the

other, the possible effects of this relationship on trade flows of feed barley and meat, and the implications for UK food security. The central question is: will future UK barley production be sufficient to serve its domestic demand and food security needs?

5.2 Materials and Methods

The methodological approach adopted is shown in Figure 5-2.

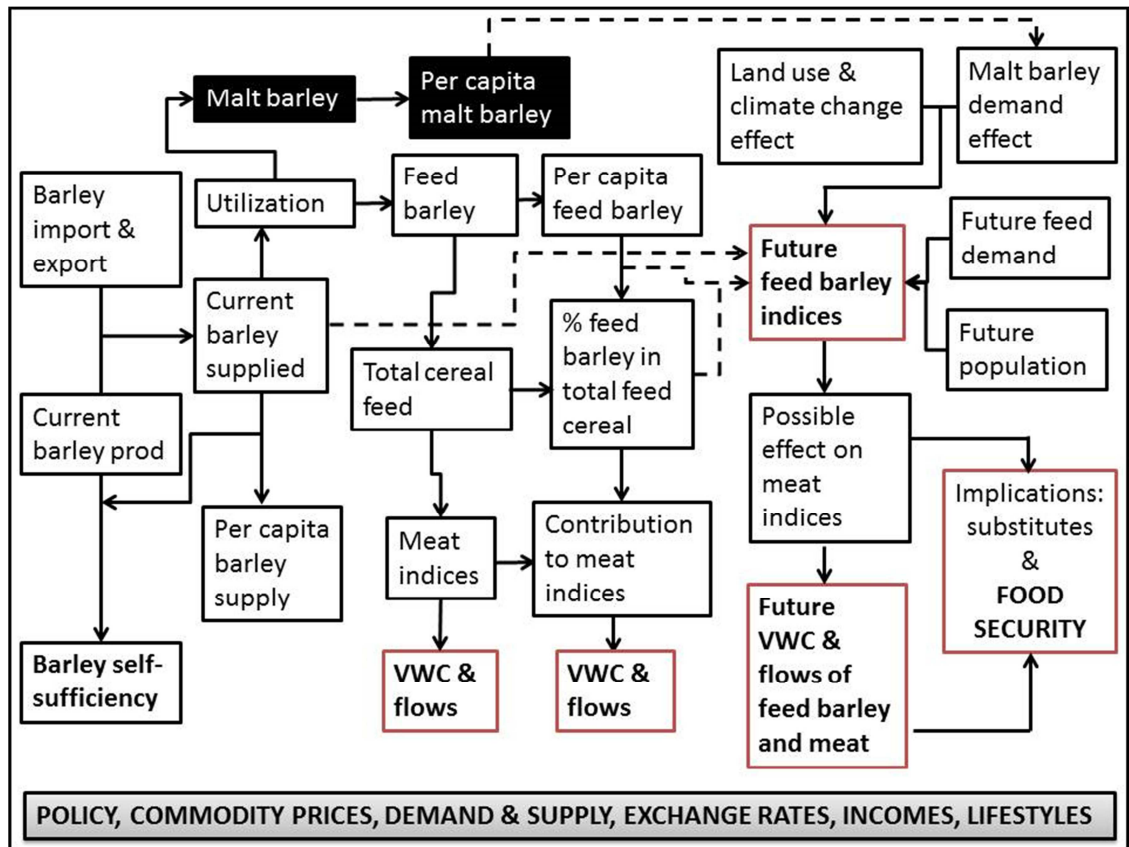


Figure 5-2: A schematic diagram of the methodology.

Current indices related to barley and meat production and consumption were used to compute future indices to assess the potential gap for trade and food security. It is acknowledged, however, that the future situation will be shaped by policies, commodity

prices, demand and supply, exchange rates, incomes and lifestyles (Figure 5-2) at both national and global levels.

5.2.1 The Current Situation

The calculations of current barley and meat indices were based on the food balance sheet (FBS) published by the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2001). Key sources of data for analysis of patterns of food supply and consumption are the FBS, household budget surveys and individual dietary surveys (Kearney, 2010). However, at the national or international scales, the FBS is widely used as it is readily and cheaply accessible and eases international comparisons (Kearney, 2010). A FBS gives an overview of the supply and uses of food items in a given country during a given reference period (a 3-year average) (FAO, 2001). For a given reference period and any food item, total *supply* is the total quantity of domestic production plus imports and adjusted to changes in stocks that might have occurred since the beginning of the reference period. On the utilization side, the total supply of the food item is decomposed into quantities exported, utilized for animal feed and seed, processed for food and non-food uses, losses during transportation and the proportion available for human consumption (FAO, 2001). The proportion of supply available for human consumption is divided by the population of the given country to obtain the per cap supply of the given food item. Per cap kcal supply is computed by applying appropriate food composition factors for supplies of all primary and processed products available for human consumption (FAO, 2001).

The FBS is useful for estimating overall shortages or surpluses of food, projecting future food requirements and providing a basis for policy analysis on food production and trade to ensure food security in a country (Kearney, 2010; FAO, 2001). The latest FBS is 2009 (FAOSTAT, 2009). Barley and meat indices retrieved from the current UK FBS (Table 5-1a, 5-1b) were used as the baseline. The percentage domestic use and feed use of barley, as well as proportionate feed barley in total feed grain, were considered representative for the calculation of future feed barley supply from total production. That is, it was assumed that these ratios (Table 5-1a, item numbers 5, 7 and 13) would remain unchanged.

Table 5-1a: Metrics on barley production and use derived from the UK FBS for the baseline period.

Item Number	Description	Value
(1)	Total domestic production	5,964 thousand tons
(2)	Total export	633 thousand tons
(3)	Total import	115 thousand tons
(4)	Total supplied for domestic use	4,953 thousand tons
(5)	% domestic use	(5) = [(4) / (1)] x 100 = 83.0 %
(6)	Total supplied for animal feed	3,037 thousand tons
(7)	% feed use	(7) = [(6) / (4)] x 100 = 61.3 %
(8)	Total supplied for brewing and distilling (considered collectively as 'malt use')	1,713 thousand tons
(9)	% malt use	(9) = [(8) / (4)] x 100 = 34.6 %
(10)	Self sufficiency	(10) = [(1) / (4)] x 100 = 120.4 %
(11)	Per cap barley use	(11) = [(4) / total population*] = 80 kg year ⁻¹
(12)	Per cap feed barley	(12) = [(6) / total population] = 49 kg year ⁻¹
(13)	Proportion of feed barley in total feed grain*	38.5 %
(14)	Per cap feed grain	153.5 kg year ⁻¹

* Total feed grain (sum of all cereal grain used as animal feed) was represented by wheat and barley used as animal feed since they contributed 96% of all feed use of grains, with oats contributing only 2%. Hence, total feed grain comprised 61.5% wheat and 38.5% barley. These values were adjusted to make them consistent with the data in Defra (2011). Total UK population on the FBS was 61,887,000 people. Data taken from FAOSTAT (2009).

Table 5-1b: Metrics on meat production and use derived from the UK FBS for the baseline period. Data taken from FAOSTAT (2009).

Item Number	Description	Value
(1)	Total domestic production	3.5 million tons
(2)	Total export	695 thousand tons
(3)	Total import	2.4 million tons
(4)	Per cap consumption	84.2 kg year ⁻¹
(5)	kcal cap ⁻¹ day ⁻¹ supplied	457

Indices of meat production and supply for consumption were retrieved from the current UK FBS (Table 5-1b). Total meat consumption was based on bovine, mutton and goat, poultry and pig meat. The consumption of other meats and animal products was not considered. To enable the assessment of the effect of future feed barley supply on domestic meat production or supply, the current total feed grain was equated to total meat production. Hence, feed barley equivalent meat (FBEM) supply, defined as the quantity of meat (tons) that can be produced or supplied per unit feed barley supply, was calculated as follows:

$$FBEM \text{ (tons)} = \frac{y}{x} \cdot z \quad \text{Equation 5-1}$$

Where y is the quantity of feed barley in total feed grain (tons); x is total feed grain (tons) and z is total domestic meat production (tons). To obtain a single value that can be used in future calculations, final $FBEM$ (ton meat ton barley⁻¹) was obtained by dividing the result of Equation 5-1 with the amount of feed barley supply. This enabled a direct relationship to be established between unit feed barley required for unit meat production in the future.

It is recognized that feed barley is used not only for meat production but also in the dairy sector, as well as for egg production. In this thesis, however, it is assumed that total

feed barley supply is used for meat production, the proportional demand for different types of meat will remain unchanged in the future and the proportional demand for meat and dairy produce will also remain unchanged in the future.

5.2.2 The Future Situation

5.2.2.1 Future Barley Production

Land use change will affect the quantity of barley produced in the future substantially. Predictions of future agricultural land uses are characterized by great uncertainty (Rounsevell & Reay, 2009; Rounsevell *et al.*, 2006). Nevertheless, such predictions are useful in providing general conclusions about trajectories of future land use change (Rounsevell & Reay, 2009). There are few studies on agricultural land use futures in the UK, but key findings of most studies reviewed by Angus *et al.* (2009) and Rounsevell & Reay (2009) show: (a) a decrease in area of cropland and increase in area of land for bioenergy crops and forest, (b) expansion of urban areas with changes in the spatial structure of urban growth and infrastructural networks for land-based transport, and (c) a loss of land in coastal areas.

The projected areas of UK croplands in 2030, 2040 and 2050 were taken from Thomson *et al.* (2013). This is a recent report for the Department of Energy and Climate Change (DECC) on the effects of changes in land use and land cover on greenhouse gas emissions and removals in the UK. The land use, land-use change, forestry (LULUCF) sector is divided into six land use categories: forest land, cropland, grassland, wetlands, settlements and other land. Changes in these categories are structured to be internally

consistent and incorporate UK land use policies and aspirations such as targets on food production, reductions in greenhouse gas emissions or achieving a certain percentage of forest cover by 2050 (Thomson *et al.*, 2013). Based on the land use policy priorities and aspirations, four scenarios of land use futures were developed: business-as-usual (BAU), Low, Mid and High scenarios. The BAU scenario represents a continuation of current afforestation rate to 2050 but other factors are similar to the Mid scenario. The Low scenario emphasizes the production of bio-energy crops and creation of woodland. The High scenario prioritizes increase in food production with little emphasis on bio-energy crops and forestry. The Mid scenario represents land use change midway between the High and Low scenarios (Thomson *et al.*, 2013). These projections are based mainly on likely policy goals and directions in the nexus of energy, food and climate change mitigation. Policies that will influence future land use changes are also likely to be oriented towards multi-functionality and ecosystem services (Winter, 2009). According to Foresight (2011), a positive environmental value of about £1.7bn is generated annually from UK agriculture as a result of landscape and habitats management and a negative environmental value of about £2.57bn is incurred annually mainly from greenhouse gas emissions (accounting for £2bn) and the remainder is associated with flooding, water pollution and soil degradation. This suggests that effort could be intensified to offset the net negative environmental value of agro-ecosystems in the future. Hence, in the context of policy, and in conformity to EU commitments, it is likely that overall future changes in agricultural land use will be influenced substantially by energy security and mitigation of climate change, as well as environmental goals such as water quality, biodiversity protection and enhancement of ecosystem services (Foresight, 2011; Angus *et al.*, 2009;

Winter, 2009). Projections of future changes in agricultural land use, however, will require a balance between policy-driven goals and market forces in relation to food production, as well as an evaluation of the impacts on desirable outcomes across sectors (Angus *et al.*, 2009). The disadvantage of the projections of Thomson *et al.* (2013) is that the influence of market forces and other non-policy factors were not explicitly considered. Changes in crop-specific land uses are likely to be driven largely by market forces such as commodity prices, input prices, demand and supply and overall profitability (Angus *et al.*, 2009; Winter, 2009) on one hand, and technological advancement on the other hand (Burgess & Morris, 2009).

Notwithstanding its limitations, the projected changes in cropland areas described by Thomson *et al.* (2013) were used in this thesis because of its currency and because it is difficult to obtain such information at the UK-level and at the relevant time scales. The projected changes in the area of croplands under the Mid scenario were used. This is because the High scenario is considered unlikely as it significantly increases the area of croplands and the UK's net emissions of greenhouse gases. Studies on possible future changes in land use that formed the basis of the Foresight (2011) report showed in most cases a reduction in croplands. The Low scenario was also not used because the scale of bio-fuel crop production was extremely high and probably unlikely.

The total areas of cropland and barley production for the period 2000 – 2012 were obtained from the UK key crops areas compiled by Defra from the June agricultural surveys (Defra, 2012). The average area of barley production over this period (1,026 million ha) was taken as the current area of land under barley cultivation and was expressed as a percentage of the average of the total area of croplands over the same

period. This proportion (16.36 %) was taken as the representative proportion of the projected area of croplands for future barley production. Hence, 16.36 % of the projected area of cropland, under the Mid scenario (Thomson *et al.*, 2013), was calculated for each of 2030, 2040 and 2050. The projected total areas of croplands under the Mid scenario were 5,777, 5,832 and 5,887 thousand ha respectively for 2030, 2040 and 2050.

However, to incorporate possible crop-specific land use changes, in response to market forces and other non-policy factors, a range of changes from $\pm 5\%$ to $\pm 20\%$, relative to the projected area of land for barley, were used. This range was based on the calculated range of annual changes in the area of land for barley production over the period 2000 – 2012 (Defra, 2012), which was -19.41% to 14.94% . In the analysis described in this thesis, the BAU was represented by the current (2000 – 2012) average area of land for barley production, which remains unchanged to 2050. To obtain future total barley production and to incorporate the effect of climate change, the future area of land for barley production was multiplied by each of the projected mean yields of barley under the low, medium and high emissions scenarios (LES, MES and HES, respectively, see chapter 4) in the 2030s, 2040s and 2050s.

It is acknowledged that, in the UK, winter barley is predominantly used for animal feed whereas spring barley is predominantly used for malting. The simulated future yields (see Chapter 4) used in the current chapter was based on spring barley. This is because spring barley production is more relevant for studying the effect of water deficit stress on yields under climate change compared to winter barley and it would have been time-consuming to simulate the effect of climate change on yields of both winter and spring barley. The use of projected spring barley yields will have implications for the projected

total barley production and therefore feed barley supply. Spring barley has a larger land area, total production but lower yields compared to winter barley (Figure 5-3).

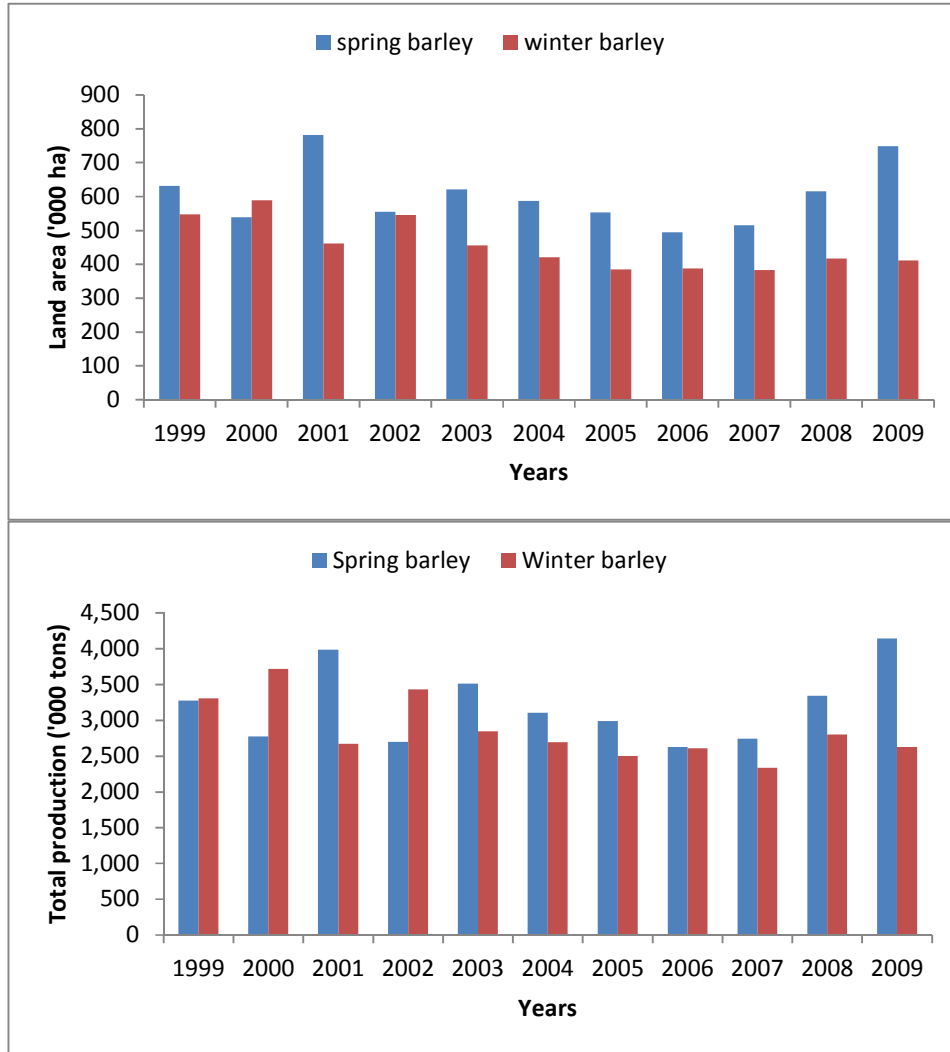


Figure 5-3: Total land area (top) and total production (bottom) of spring and winter barley in the UK. Data taken from Defra (2010).

Records show that UK total winter barley production for the period 1999 – 2009 was 2,868 thousand tons, with a total land area of 455 thousand ha and average yield of 6.3 tons ha⁻¹, contrasted with 604 thousand ha, 3,200 thousand tons and 5.3 tons ha⁻¹ for spring barley (Defra, 2010). However, the statistics used in this thesis are based on total

barley production and allocation to end-uses. Hence, the relevance of the distinction between the areas of spring and winter barley is diminished. The error in projected total production and allocation to feed barley can therefore arise only from differences between yields of spring and winter barley. Thus, about 50% of the projected production levels for each scenario might be underestimated by 1 ton ha⁻¹, assuming the ratio of spring and winter barley yields remain unchanged. Nonetheless, it can be argued that the effect of this yield difference on projected quantity of feed barley supply can be offset by the quantity allocated to malting in this thesis. Moreover, proportional allocation of land to winter or spring barley will depend on several factors.

5.2.2.2 Future Feed Barley and Meat Demand Indices

Projected population data for 2030, 2040 and 2050 were obtained from the UK National Population Projections (2010 – 2085) by the Office of National Statistics (<http://www.ons.gov.uk/ons/interactive/uk-national-population-projections---dvc3/index.html>). In carrying out these projections, four scenarios of population growth trajectories were used: high fertility, low fertility, constant fertility and balanced long-term migration. The projected population data for these four scenarios and the three time periods were obtained. It is acknowledged that population projections show great uncertainty.

Most studies that project world food demand to 2050 have used different and separate assumptions about changes in population, income, diets and policy to simulate supply, demand, trade and prices of food items (Foresight, 2011; Huang *et al.*, 2010).

Examples of such projections published recently include the Comprehensive Assessment of Water Management in Agriculture (2007) by the International Water Management Institute (IWMI), The Global Harvest Initiative report (Kruse, 2011), Tilman *et al.* (2011) and the updated FAO projections (Alexandratos & Bruinsma, 2012). Regardless of the uncertainties and variations in these projections, they provide insights on possible future trends in food demand and supply (Foresight, 2011). The FAO projections are widely cited and used in global scale studies. However, the FAO projections are a linear extrapolation of past changes over a comparable time period. Also, to my knowledge, future feed demand from grains is provided explicitly only in the Comprehensive Assessment of Water Management in Agriculture (2007), which incorporates a range of drivers such as population, incomes, prices of commodities and inputs. Hence, projections of meat and feed demand from the Comprehensive Assessment of Water Management in Agriculture (2007) were used in the current study. It is acknowledged that different types of animals have different grain feed requirements and conversion efficiencies. However, total grain feed requirement for total meat production is considered in this thesis.

From the Comprehensive Assessment of Water Management in Agriculture (2007) report, the projected per capita meat and grain feed demand for the OECD (Organization for Economic Co-operation and Development) countries was used to represent future UK meat and feed grain demand per capita. The values of meat and grain feed demand for 2025 (96 and 396 kg cap⁻¹ year⁻¹ respectively) were used to represent 2030 and the averages of the values for 2025 and 2050 were used to represent the values for 2040. Consequently, the per capita meat demand was 96, 96.5 and 97 kg per year respectively for 2030, 2040 and 2050. The corresponding feed grain demand per person per year was

396, 397 and 398 kg respectively for 2030, 2040 and 2050. From the per capita feed grain demand, the proportional contribution of feed barley (38.5%) was calculated to represent future UK feed barley demand per capita (152, 153 and 153 kg respectively for 2030, 2040 and 2050). Subsequently, *FBEM* was calculated, using equation 5-1. Total feed barley and meat demand was obtained as the product of projected population and either per capita feed barley demand or meat demand. The possible supply of barley for domestic uses was calculated as a proportion (83%) of future UK barley production under each land use scenario, time slice and climate change emissions scenario. Then, possible feed and malt barley supply was calculated as proportions of barley supply for domestic uses for each land use scenario, time slice and emissions scenario. Subsequently, the projected future feed barley demand was compared with the possible feed barley supply under the constant population growth scenario; the difference indicated trade (import or export) potential. Similarly, the trade potential for feed barley equivalent meat was calculated.

5.2.2.3 Virtual Water Flows

The virtual water content (VWC, $\text{m}^3 \text{ton}^{-1}$) of future UK barley grains for all time slices and emissions scenarios were obtained from the climate change simulations reported in Chapter 4 (see Figure 4-10). Total virtual water (TVW, m^3) associated with total barley production and feed barley supply was, therefore, obtained as:

$$TVW = VWC \cdot T \quad \text{Equation 5-2}$$

Where T is the total tonnage of food item considered (barley in this case).

It was assumed that deficits in feed barley supply or feed barley equivalent meat supply would be imported. Hence, virtual water flows to the UK associated with imports of feed barley and feed barley equivalent meat to balance deficits were also calculated. However, the VWC of barley and meat imported were obtained differently. The quantities of UK barley and meat imports for the baseline period (2007-2009) were retrieved from the FAOSTAT trade database (FAOSTAT, 2010). The top 8 countries (out of 21) that accounted for approximately 95% of total UK barley imports (345,712 tons) were Ireland (44%), France (16.4%), Germany (12.6%), Ukraine (6.8%), Spain (5.1%), Denmark (3.8%), Sweden (3.6%) and Italy (2.6%). Each of the remaining countries accounted for less than 2% of the total barley import and they were therefore aggregated as import from the rest of the world. It was assumed that these countries would remain the main sources of barley import to the UK in the future. The VWC of barley for each country (country average) was retrieved from the WaterStat Database of the Water Footprint Network (www.waterfootprint.org) (Mekonnen & Hoekstra, 2010a). Total virtual water inflow due to feed barley import was calculated using equation 5-2.

Ten countries accounted for 92% of total meat import by the UK. These were Ireland (20.4%), Netherlands (20.9%), Denmark (14.7%), Germany (8.2%), New Zealand (8.2%), Belgium (6.1%), France (6.1%), Spain (2.7%), Poland (2.6%) and Brazil (2.1%). The remaining 39 countries contributed either a little over or below 1% and were therefore represented as the rest of the world. Again, it was assumed that these countries would remain the main sources of future imports of meat to the UK. The VWC of meat for each country was retrieved from the WaterStat Database of the Water Footprint Network (Mekonnen & Hoekstra, 2010b). For each country, the weighted averages of the water

footprints of fresh or chilled carcasses of bovine, lamb and goat, pork and poultry were retrieved from the database and averaged to represent the VWC of total meat. The weighted average of water footprint of products in this database comprises a mix of production systems: grazing, mixed, and industrial. The average of the VWC of all meat types was calculated for each country. Subsequently, the average (including the world average) of the VWC of total meat for all countries was used to calculate the virtual water inflows associated with import of feed barley equivalent meat, using equation 5-2. This was done separately for blue and green water. Green and blue VWC of meat, in this database, was obtained following the conventional water footprint methodology (Mekonnen & Hoekstra, 2010b). Because projected warmer temperatures can cause heat stress, which can adversely affects productivity in farm animals, and raises the need for additional water supply to cool the animals (Flamenbaum & Galon, 2010; Lee, 1993), the blue VWC was adjusted upward by 2.5%. In all, it was assumed that future VWC would not differ substantially from current VWC as productivity gains of feed crops from climate change in northern temperate countries might offset increases elsewhere.

5.2.2.4 Implications for Food Security

The implications for food security were explored qualitatively using systems dynamics analysis approach. The main tool employed here was a simplified causal loop diagram (CLD) analysis (Olsson & Sjöstedt, 2005) to conceptualize food security risks induced by possible feed barley deficits (see Figure 5-4). System dynamics deals with feedback and delays that affect system behaviour over time (Armah *et al.*, 2010; Olsson &

Sjöstedt, 2005). As a tool, systems dynamics analysis helps address a problem by providing insight into the structure of a system (that is, the way the essential system components are connected and interact) and its consequential behavior in order to understand and evaluate outcomes (Olsson & Sjöstedt, 2005). There are two major stages in developing a system dynamics model (Olsson & Sjöstedt, 2005). The first stage is to construct the CLD, which graphically portrays the cause-effect interrelationships arising from the behaviour of the system components or other exogenous factors relevant to the system. The second stage is to develop a quantitative model and represent it in terms of flow rates, levels and delays. In this Chapter, the focus was only on the first stage (i.e. CLD). The CLD (Figure 5-4) and its components are discussed in Section 5.4.4.

5.3 Results

5.3.1 Future Barley Production and Supplies for Domestic Uses

The projected area of land for barley production under the Mid scenario increases from 945 thousand ha in 2030 to 963 thousand ha in 2050 (Table 5-2). These areas of land are substantially lower than the current (BAU) area of land under barley production (1,026 thousand ha). The largest area of land for barley production will be about 1.2 million ha under the Mid+20% land use change scenario in 2050 whereas the lowest would be 756 thousand ha under the Mid-20% scenario in 2030.

Table 5-2: Projected area of land for UK barley production.

Land use scenario	Total area for barley production ('000 ha)		
	2030	2040	2050
BAU	1,026	1,026	1,026
Mid	945	954	963
Mid+5%	992	1,002	1,011
Mid+10%	1,040	1,049	1,059
Mid+15%	1,087	1,097	1,107
Mid+20%	1,134	1,145	1,156
Mid-5%	898	906	915
Mid-10%	851	859	867
Mid-15%	803	811	819
Mid-20%	756	763	770

Source: mid land use scenario data taken from Thomson *et al.* (2013).

Due to the combined effect of climate change on yield and change in area of land for barley production, total future UK barley production ranged between approximately 4.6 million tons (under the low emission scenario, LES, and Mid-20% scenario in 2030) and 9.0 million tons in 2050 under the Mid+20% and the high emissions scenario (HES) (Table 5-3). For the BAU, projected total barley production ranged from approximately 6.2 million tons in 2030 (under the LES) to 8.0 million tons in 2050 under the HES. The difference in maximum barley production (HES, 2050) under the BAU and Mid+20% is approximately 1.0 million tons. As would be expected, total barley production increases from the LES to the HES and from the 2030s to the 2050s for each land use scenario. However, using the medium emissions scenario (MES), the difference in total barley production between the BAU and Mid scenarios are 523,000 tons (2030), 482,000 tons (2040) and 456,000 tons (2050).

Table 5-3: Projected total UK barley production due to land use and climate change.

Land use scenario	Total barley production ('000 tons)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	6,197	6,628	6,700	6,402	6,874	7,326	6,607	7,428	7,972
Mid	5,708	6,105	6,171	5,953	6,392	6,812	6,202	6,972	7,483
Mid+5	5,993	6,410	6,479	6,251	6,711	7,152	6,512	7,321	7,857
Mid+10	6,279	6,715	6,788	6,548	7,031	7,493	6,822	7,669	8,231
Mid+15	6,564	7,020	7,096	6,846	7,351	7,833	7,132	8,018	8,605
Mid+20	6,849	7,326	7,405	7,144	7,670	8,174	7,442	8,367	8,979
Mid-5	5,422	5,799	5,862	5,655	6,072	6,471	5,892	6,624	7,108
Mid-10	5,137	5,494	5,554	5,358	5,753	6,130	5,582	6,275	6,734
Mid-15	4,852	5,189	5,245	5,060	5,433	5,790	5,271	5,926	6,360
Mid-20	4,566	4,884	4,937	4,762	5,113	5,449	4,961	5,578	5,986

Table 5-4: Projected UK barley supply from domestic production for domestic uses.

Land use scenario	Total barley supply for domestic uses ('000 tons)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	5,144	5,501	5,561	5,314	5,705	6,081	5,484	6,165	6,617
Mid	4,738	5,067	5,122	4,941	5,305	5,654	5,148	5,787	6,211
Mid+5	4,974	5,320	5,378	5,188	5,570	5,936	5,405	6,076	6,521
Mid+10	5,212	5,573	5,634	5,435	5,836	6,219	5,662	6,365	6,832
Mid+15	5,448	5,827	5,890	5,682	6,101	6,501	5,920	6,655	7,142
Mid+20	5,685	6,081	6,146	5,930	6,366	6,784	6,177	6,945	7,453
Mid-5	4,500	4,813	4,865	4,694	5,040	5,371	4,890	5,498	5,900
Mid-10	4,264	4,560	4,610	4,447	4,775	5,088	4,633	5,208	5,589
Mid-15	4,027	4,307	4,353	4,200	4,509	4,806	4,375	4,919	5,279
Mid-20	3,790	4,054	4,098	3,952	4,244	4,523	4,118	4,630	4,968

The pattern of projected barley supply for domestic use is similar to the total production as the former is a constant proportion of the latter. The largest quantity of barley that would be supplied for domestic uses would be approximately 7.5 million tons in 2050 under the HES and Mid+20% scenarios whereas the lowest would be approximately 3.8 million tons in 2030 under the LES and Mid-20% scenarios (Table 5-4). Under the BAU scenario, total barley supply for domestic uses ranged from

approximately 5.1 million tons under the LES in 2030 to 6.6 million tons in 2050 under the HES.

Projected feed barley supply from domestic production under the BAU ranged from approximately 3.2 million tons (under the LES in 2030) to 4.1 million tons in 2050 under the HES (Table 5-5). Under the Mid scenario, the values ranged from approximately 2.9 million tons to 3.8 million tons. The maximum feed barley supplies (Mid+20% scenario) ranged from approximately 3.5 million tons in 2030 to 4.6 million tons in 2050, whereas the minimum supplies (Mid-20%) ranged from approximately 2.3 million tons to 3.0 million tons. The difference between maximum feed barley supply under the BAU and Mid+20% and the HES in 2050 is 512 thousand tons whereas the difference between the BAU and Mid-20% is approximately 1.0 million tons.

Table 5-5: Projected UK feed barley supply from domestic production.

Land use scenario	Total feed barley supply ('000 tons)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	3,153	3,372	3,409	3,257	3,497	3,727	3,362	3,779	4,056
Mid	2,904	3,106	3,140	3,029	3,252	3,466	3,156	3,547	3,807
Mid+5	3,049	3,261	3,296	3,180	3,414	3,639	3,313	3,725	3,998
Mid+10	3,195	3,417	3,454	3,332	3,577	3,812	3,471	3,902	4,188
Mid+15	3,340	3,572	3,610	3,483	3,740	3,985	3,629	4,079	4,378
Mid+20	3,485	3,727	3,768	3,635	3,902	4,159	3,786	4,257	4,568
Mid-5	2,759	2,950	2,983	2,877	3,089	3,292	2,998	3,370	3,616
Mid-10	2,614	2,795	2,826	2,726	2,927	3,119	2,840	3,193	3,426
Mid-15	2,469	2,640	2,669	2,574	2,764	2,946	2,682	3,015	3,236
Mid-20	2,323	2,485	2,512	2,423	2,601	2,772	2,524	2,838	3,046

Projected malt barley supply ranged from approximately 1.3 million tons in 2030 (under the LES and Mid-20%) to 2.6 million tons in 2050 under the HES and Mid+20% (Table 5-6). Under the BAU scenario, projected malt barley supply ranged from approximately 1.8 million tons in 2030 under the LES, to 2.3 million tons in 2050 under

the HES. The difference in maximum possible supplies of malt barley between the BAU and Mid+20% is 570 thousand tons. It is noteworthy that for all barley production and supplies and for all scenarios, the value of barley supply under the BAU and the LES in 2030 is slightly higher than the value under the Mid-20% and HES in 2050.

Table 5-6: Projected UK malt barley supply from domestic production.

Land use scenario	Total malt barley supply ('000 tons)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	1,780	1,903	1,924	1,839	1,974	2,104	1,897	2,133	2,289
Mid	1,639	1,753	1,772	1,710	1,836	1,956	1,781	2,002	2,149
Mid+5	1,721	1,841	1,861	1,795	1,927	2,054	1,870	2,102	2,256
Mid+10	1,803	1,928	1,949	1,880	2,019	2,152	1,959	2,202	2,364
Mid+15	1,885	2,016	2,038	1,966	2,111	2,249	2,048	2,303	2,471
Mid+20	1,967	2,104	2,127	2,052	2,203	2,347	2,137	2,403	2,579
Mid-5	1,557	1,665	1,683	1,624	1,744	1,858	1,692	1,902	2,041
Mid-10	1,475	1,578	1,595	1,539	1,652	1,760	1,603	1,802	1,934
Mid-15	1,393	1,490	1,506	1,453	1,560	1,663	1,514	1,702	1,826
Mid-20	1,311	1,403	1,418	1,368	1,468	1,565	1,425	1,602	1,719

5.3.2 Projected Population, Feed Barley and Meat Demand

For all population projection scenarios, projected UK population ranged between 69.5 million in 2030 (low fertility scenario) and 82.2 million in 2050 (high fertility scenario) (Table 5-7). As a result of population growth, projected total meat demand ranged from approximately 6.7 million tons in 2030 to 8.0 million tons in 2050. Similarly, total feed grain demand ranged from approximately 27.5 million tons in 2030 (under the low fertility scenario) to 32.7 million tons in 2050 under the high fertility scenario. Under the constant population growth scenario, total population ranged from 71.9 million in 2030 to 80.3 million in 2050. Total meat demand for this scenario ranged from 6.9 million

tons in 2030 to 7.8 million tons in 2050, with total feed grain demand ranging from 28.5 million tons to 32.0 million tons for the same period.

Table 5-7: Projected UK population and total meat and feed grain demand.

Fertility scenario	Total population (million)			Total meat demand ('000 tons)			Total feed grain demand ('000 tons)		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
High	72.8	77.3	82.2	6,989	7,459	7,973	28,829	30,688	32,716
Constant	71.9	76.1	80.3	6,902	7,344	7,789	28,472	30,212	31,959
Low	69.5	72.0	74.0	6,672	6,948	7,178	27,522	28,584	29,452
Balanced long-term migration	70.3	71.5	71.9	6,749	6,900	6,974	27,839	28,386	28,616

Source: population data (Office of National Statistics); feed and meat data (de Fraiture *et al.*, 2007).

Projected feed barley demand (as a proportion of total feed grain demand) for all population projections ranged from approximately 10.6 million tons in 2030 to 12.6 million tons in 2050 (Table 5-8). Comparable values for feed barley equivalent meat demand ranged from approximately 2.6 million tons to 3.1 million tons. However, under the constant fertility scenario, total feed barley demand ranged from approximately 11.0 million tons in 2030 to 12.3 million tons in 2050 whereas feed barley equivalent meat demand ranged between 2.7 million tons and 3.0 million tons.

Table 5-8: Projected UK feed barley demand and feed barley equivalent meat demand.

Fertility Scenario	Total feed barley demand ('000 tons)			Feed barley equivalent meat demand ('000 tons)		
	2030	2040	2050	2030	2040	2050
High	11,099	11,815	12,596	2,691	2,872	3,070
Constant	10,962	11,632	12,304	2,657	2,827	2,999
Low	10,596	11,005	11,339	2,569	2,675	2,764
Balanced long-term migration	10,718	10,928	11,017	2,598	2,656	2,685

Projected UK deficits in feed barley supply from domestic production for all land use and climate change scenarios and time slices ranged from approximately 7.2 million tons in 2030 (under the HES, Mid+20% scenario) to 9.8 million tons in 2050 under the LES and Mid-20% scenario (Table 5-9). However, under the BAU, the deficits in feed barley supply ranged from 7.6 million tons in 2030 (under the HES) to 8.9 million tons in 2050 under the LES. Comparable values for the Mid land use scenario range from 7.8 million tons in 2030 to 9.1 million tons in 2050. The deficits under the Mid+20% scenario ranged from 7.2 million tons in 2030 to 8.5 million tons in 2050, whereas the deficits under the Mid-20% ranged from 8.5 million tons in 2030 to 9.8 million tons in 2050. It is important to indicate that these are the ranges of deficits under the constant fertility scenario of population growth.

Table 5-9: Projected deficits in UK feed barley supply from domestic production using constant fertility scenario of population growth.

Land use scenario	Total deficit in feed barley supply ('000 tons)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	-7,809	-7,590	-7,553	-8,374	-8,134	-7,904	-8,943	-8,525	-8,248
Mid	-8,058	-7,856	-7,822	-8,603	-8,379	-8,166	-9,149	-8,757	-8,497
Mid+5	-7,913	-7,701	-7,665	-8,451	-8,217	-7,993	-8,991	-8,580	-8,307
Mid+10	-7,767	-7,545	-7,508	-8,300	-8,054	-7,819	-8,833	-8,402	-8,117
Mid+15	-7,622	-7,390	-7,352	-8,148	-7,891	-7,646	-8,676	-8,225	-7,926
Mid+20	-7,477	-7,234	-7,194	-7,997	-7,729	-7,473	-8,518	-8,047	-7,736
Mid-5	-8,203	-8,011	-7,979	-8,754	-8,542	-8,339	-9,307	-8,934	-8,688
Mid-10	-8,348	-8,167	-8,136	-8,905	-8,704	-8,513	-9,464	-9,112	-8,878
Mid-15	-8,493	-8,322	-8,293	-9,057	-8,867	-8,686	-9,623	-9,289	-9,068
Mid-20	-8,639	-8,477	-8,450	-9,209	-9,030	-8,859	-9,780	-9,466	-9,259

Similarly, deficits in UK total meat supply (due to deficit in feed barley supply) ranged from 1.7 million tons in 2030 under the HES and Mid+20% scenario to 2.4 million tons under the LES and Mid-20% scenario in 2050 (Table 5-10). Under the BAU,

the deficits ranged from 1.8 million tons in 2030 to 2.2 million tons in 2050, compared to the Mid scenario which had a range of 1.9 million tons in 2030 to 2.2 million tons in 2050. However, for the Mid+20% scenario, the range of deficits in feed barley equivalent meat supply is 1.7 million tons in 2030 to 2.1 million tons in 2050, whereas the values for the Mid-20% scenario are 2.1 million tons in 2030 to 2.4 million tons in 2050.

Table 5-10: Projected deficits in UK supply of feed barley equivalent meat using constant fertility scenario of population growth.

Land use scenario	Total deficit in feed barley equivalent meat supply ('000 tons)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	-1,893	-1,840	-1,831	-2,035	-1,977	-1,921	-2,180	-2,078	-2,010
Mid	-1,953	-1,904	-1,896	-2,091	-2,037	-1,985	-2,230	-2,134	-2,071
Mid+5	-1,918	-1,866	-1,858	-2,054	-1,997	-1,943	-2,191	-2,091	-2,025
Mid+10	-1,883	-1,829	-1,820	-2,017	-1,958	-1,900	-2,153	-2,048	-1,978
Mid+15	-1,848	-1,791	-1,782	-1,980	-1,918	-1,858	-2,115	-2,005	-1,932
Mid+20	-1,812	-1,754	-1,744	-1,944	-1,879	-1,816	-2,076	-1,961	-1,886
Mid-5	-1,988	-1,942	-1,934	-2,128	-2,076	-2,027	-2,268	-2,178	-2,118
Mid-10	-2,023	-1,979	-1,972	-2,164	-2,116	-2,069	-2,307	-2,221	-2,164
Mid-15	-2,059	-2,017	-2,010	-2,201	-2,155	-2,111	-2,345	-2,264	-2,210
Mid-20	-2,094	-2,055	-2,048	-2,238	-2,195	-2,153	-2,384	-2,307	-2,257

5.3.3 Virtual Water Associated With Barley Imports

The total volume of virtual water associated with total UK barley production in the future ranged from 206 billion m³ (under the LES and Mid-20%) in 2030 to 350 billion m³ (under Mid+20% and both the medium emissions scenario, MES, and the HES) in 2050 (Table 5-11). Under the BAU, the values range from 280 billion in 2030 to 311 billion m³ in 2050, compared with 258 billion (2030) and 292 billion m³ (2050) for the Mid scenario (Table 5-11). Under the Mid+20% scenario, the volume of virtual water ranges from 310 billion (2030) to 350 billion m³ in 2050 whereas the values for the Mid-

20% scenario range from 206 billion in 2030 to 233 billion m³ in 2050. The total volume of virtual water here is entirely green water as the simulations of future barley production were done under rain-fed conditions.

Table 5-11: Virtual water associated with total barley production in the UK.

Land use scenario	Total virtual water associated with total barley production ($\times 10^6$ m ³)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	280	300	302	281	299	302	304	311	311
Mid	258	276	278	261	278	280	285	292	292
Mid+5	271	290	292	274	291	294	299	306	306
Mid+10	284	304	306	288	305	309	314	321	321
Mid+15	297	317	319	301	319	323	328	336	336
Mid+20	310	331	333	314	333	337	342	350	350
Mid-5	245	262	264	248	264	266	271	277	277
Mid-10	232	248	250	235	250	252	257	263	263
Mid-15	219	235	236	222	236	238	242	248	248
Mid-20	206	221	222	209	222	224	228	233	233

Table 5-12: Virtual water associated with projected feed barley supply in the UK.

Land use scenario	Total virtual water associated with domestic feed barley supply ($\times 10^6$ m ³)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	143	152	153	143	152	153	155	158	158
Mid	131	140	141	133	141	143	145	148	148
Mid+5	138	147	148	140	148	150	152	156	156
Mid+10	144	154	155	146	155	157	160	163	163
Mid+15	151	161	163	153	162	164	167	171	171
Mid+20	158	168	170	160	169	171	174	178	178
Mid-5	125	133	134	126	134	136	138	141	141
Mid-10	118	126	127	120	127	128	131	134	134
Mid-15	112	119	120	113	120	121	123	126	126
Mid-20	105	112	113	106	113	114	116	119	119

Similarly, the volumes of virtual water associated with projected feed barley supply from domestic production ranged from 105 billion m³ in 2030 (under the Mid-20% and LES) to 178 billion m³ in 2050 (Table 5-12). However, under the BAU, the volumes

of virtual water ranged from 143 billion in 2030 to 158 billion m³ in 2050. For the Mid+20% and Mid-20, the values ranged from 158 to 178 billion m³ and 105 billion to 119 billion m³ respectively from 2030 to 2050.

Table 5-13: Virtual water inflows to the UK due to feed barley import to balance deficit.

Land use scenario	Total virtual water inflows from feed barley import (x 10 ⁶ m ³)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	5,919	5,753	5,725	6,348	6,166	5,991	6,779	6,462	6,252
Mid	6,108	5,955	5,929	6,521	6,352	6,190	6,935	6,638	6,441
Mid+5	5,998	5,837	5,810	6,406	6,228	6,058	6,815	6,503	6,297
Mid+10	5,888	5,719	5,691	6,291	6,105	5,927	6,696	6,369	6,152
Mid+15	5,778	5,602	5,572	6,176	5,982	5,796	6,576	6,234	6,008
Mid+20	5,668	5,484	5,453	6,061	5,859	5,664	6,457	6,100	5,864
Mid-5	6,218	6,073	6,048	6,636	6,475	6,321	7,054	6,772	6,585
Mid-10	6,328	6,190	6,167	6,750	6,598	6,453	7,174	6,907	6,730
Mid-15	6,438	6,308	6,286	6,865	6,721	6,584	7,294	7,041	6,873
Mid-20	6,548	6,426	6,405	6,980	6,845	6,715	7,413	7,175	7,018

Note: Green water = 97%; blue water = 3%

Conversely, the total volumes of virtual water inflows to the UK, due to import of feed barley to balance the projected deficits in supply, ranged from approximately 5.5 billion m³ (under the Mid+20% and HES) to 7.4 billion m³ in 2050 under the LES and Mid-20% scenario (Table 5-13). The volumes of virtual water inflow under the BAU ranged from 5.7 billion m³ in 2030 to 6.8 billion m³ in 2050. Under the Mid scenario, the values ranged from 5.9 billion to 6.9 billion m³ from 2030 to 2050 respectively. This range decreased to 5.5 billion in 2030 and 6.5 billion m³ in 2050 under the Mid+20% scenario, but increased to 6.4 billion in 2030 and 7.4 billion m³ in 2050 under the Mid-20% scenario. The mean green and blue VWC of barley was respectively 737 and 21 m³ ton⁻¹. If total domestic barley production were used for feed, the deficits in feed barley supply would range from 3.3 to 7.3 million tons whereas the volumes of virtual water inflows

associated with imports would range from 2.6 to 5.6 billion m³ (data not shown). Blue and green water constitute 3% and 97% respectively of each total volume of virtual water.

Finally, the volumes of virtual water inflows to the UK, due to import of feed barley equivalent meat to balance deficit, ranged from 7.2 billion m³ in 2030 (under the Mid+20% and HES) to 9.9 billion in 2050 (under the Mid-20% and LES) (Table 5-14). The pattern of the volumes of virtual water inflow is similar to the inflows associated with feed barley imports. The volumes of virtual water inflow under the BAU ranged from 7.6 billion m³ in 2030 to 9.0 billion m³ in 2050. Under the Mid scenario, the values ranged from 7.9 billion to 9.3 billion m³. Under the Mid+20%, the total volumes of virtual water ranged from 7.2 billion to 8.6 billion m³, whereas the range for the Mid-20% is 8.5 billion to 9.9 billion m³. The average green and blue VWC of total meat were 3,905 and 243 m³ ton⁻¹ respectively. Assuming total domestic barley production were used as feed barley, the feed barley equivalent meat deficits would range from 0.8 million to 1.8 million tons and the associated volumes of virtual water inflows would range from 3.4 to 7.4 billion m³ from the 2030s to the 2050s (data not shown).

Table 5-14: Virtual water inflows to the UK due to import of feed barley equivalent meat to balance deficit.

Land use scenario	Total virtual water inflow from feed barley equivalent meat import (x10 ⁶ tons)								
	2030			2040			2050		
	LES	MES	HES	LES	MES	HES	LES	MES	HES
BAU	7,851	7,631	7,594	8,443	8,200	7,969	9,041	8,619	8,339
Mid	8,101	7,898	7,864	8,673	8,448	8,232	9,250	8,854	8,591
Mid+5	7,956	7,742	7,707	8,520	8,284	8,058	9,090	8,674	8,398
Mid+10	7,809	7,586	7,549	8,368	8,120	7,883	8,931	8,495	8,206
Mid+15	7,663	7,430	7,391	8,215	7,956	7,709	8,771	8,315	8,014
Mid+20	7,518	7,274	7,233	8,062	7,792	7,534	8,612	8,136	7,821
Mid-5	8,248	8,055	8,022	8,826	8,612	8,407	9,409	9,033	8,784
Mid-10	8,393	8,211	8,180	8,978	8,775	8,582	9,569	9,212	8,976
Mid-15	8,539	8,367	8,338	9,131	8,940	8,756	9,728	9,392	9,168
Mid-20	8,686	8,523	8,496	9,284	9,104	8,931	9,888	9,571	9,361

Note: Green water = 94%; blue water = 6%.

5.4 Discussion

Projections are not meant to forecast or predict the future, especially over long-time periods when uncertainties become greater, but to offer broad overviews of possible future states of what is being projected to serve as input for discussions regarding adaptive planning, policy, decisions and actions (Foresight, 2011). However, such projections should have a sound basis in past or current knowledge and practices in order to be credible. This study offers projections of UK barley production, supply and demand of feed barley, as well as the implications for meat supply and food security.

5.4.1 Future Barley Production and Supply

Domestic production would likely continue to be a major source of future supply of feed barley in the UK. Increase in crop yields will be a key determinant for increases in total production of crops in the future (Bruinsma, 2012). However, in spite of the projected increase in UK barley yields under projected climate change, land use change will largely dictate the final quantity of grain produced (all other things being equal). Assuming the current ratio of area of land under barley production to total cropland remains unchanged to 2050, then it is likely that policy-driven land use change alone (Mid scenario) could reduce the area of land for barley production (under the BAU) by as much as 81, 72 and 63 thousand ha respectively in 2030, 2040 and 2050 (Table 5-1). The corresponding reductions in total UK barley production would be equally substantial (Table 5-2).

The plausibility of this situation can be deduced from UK commitments and aspirations regarding reductions in greenhouse gas emissions and energy security. The Climate Change Act (2008) commits the UK to reduce greenhouse gas emissions by 80% from the 1990 baseline level by 2050. The Climate Change Act (2008) provides a basis for policy proposals and reporting of projected greenhouse gas emissions to 2050 for carbon budgets for the UK government, the European Union (EU) Monitoring Mechanism and the United Nations Framework Convention on Climate Change (UNFCCC) (Thomson *et al.*, 2013). The EU Renewable Energy Directive (2009) obliges the UK to have 10% share of biofuels in its transport fuel mix and 20% of total energy mix from renewable sources by 2020. These obligations will substantially affect agricultural land use futures adversely through a suite of policy and legal instruments, financial and tax incentives and market signals that, for example, encourage domestic production and constrain imports of biofuels (Durham *et al.*, 2012). While there is considerable amount of information on the link between biofuels and food prices (e.g. Oladosu & Msangi, 2013; Hochman *et al.*, 2012; Thompson, 2012 and references therein), there is little information on competition for land. Rowe *et al.* (2009) reported that, to meet projected energy targets, between 2.7 and 7.0 Mha of land would be required for bioenergy production in the UK by 2050. They concluded that land availability will constrain the contribution of biofuel to renewable energy targets (Rowe *et al.*, 2009). Figures quoted by Howard *et al.* (2009) fall within the range given by Rowe *et al.* (2009). The medium term cereal market outlook in the EU (European Commission, 2011) indicates that while the land area of cereals is likely to remain stable, barley would likely lose about 21% of its land area to other biofuel crops by 2020. Yang *et al.* (2009) reported that, depending on the type of feedstock, China would

have to allocate 5-10% of its total cultivated land to biofuels in order to meet its 2020 target. Historically, agricultural land use change in the UK has been driven primarily by government policy intervention, with other secondary factors being farm incomes, prices and land values (Foresight, 2011; Angus *et al.*, 2009). It is likely, therefore, that there will be reductions in the area of UK croplands (and possibly for barley) in future due to policies regarding climate change and energy (e.g. Angus *et al.*, 2009; Howard *et al.*, 2009; Rounsevell & Reay, 2009).

Short term changes in total barley production due to changes in area of land for barley production in future could also arise from non-policy factors, mainly market signals (demand, supply and prices of inputs and food commodities) (Huang *et al.*, 2010; Angus *et al.*, 2009). In the analysis presented in this thesis, assuming positive signals from non-policy sources cause a 20% increase over the projected area of land for barley production (and under the MES), the increase in total barley production (relative to BAU) would be 698, 796 and 939 thousand tons respectively in 2030, 2040 and 2050. Conversely, a 20% reduction in the area of land under the Mid scenario (and under the MES) would result in reductions of 1.7, 1.8 and 1.9 million tons in 2030, 2040 and 2050 respectively. The proportions will be the same for supply of total barley for domestic uses and feed barley. Thus, all things being equal, changes in the area of land for barley production will be a primary determinant of the total barley production in the UK and, for that matter, self-sufficiency in feed barley supply in the future.

5.4.2 Deficits in Feed Barley and Feed Barley Equivalent Meat Supply

Currently, barley grains constitute approximately 39% of total use of grains for feed (with wheat being dominant) in the UK (Table 5-1a). The UK has a high self-sufficiency rate in barley production and almost all its feed barley supply is produced domestically (Defra, 2011). All things being equal, increase in meat demand would result in a proportionate increase in animal feed demand and, for that matter, demand for feed barley. In the analysis presented in this thesis, the ranges of deficits in future feed barley supply under all land use change scenarios and the constant population growth scenario (Table 5-9) are substantially greater than current total barley production (Table 5-1a). Thus, within the limits of the current study, the UK is likely to incur huge deficits in feed barley supply from domestic production under all scenarios of population growth even if total domestic barley production is used for feed.

Whereas future growth in incomes is projected to be the principal driver of meat demand (and for that matter animal feed) in industrially advancing countries, population growth will be the main driver of meat demand in high income countries (Alexandratos & Bruinsma, 2012; Thornton, 2010; de Fraiture *et al.*, 2007). In the current study, even though the projected per capita meat demand for UK is high, the absolute increase in per capita meat demand from baseline is lower than projections for industrially advancing countries such as Brazil, Russia, India and China (Alexandratos & Bruinsma, 2012; Bruinsma, 2012; de Fraiture *et al.*, 2007). However, even though per capita meat demand stagnates between 2030 and 2050, the projected aggregate UK meat demand and associated feed barley demand are high due to increase in population. Under the constant population growth scenario, differences between future demand and current feed barley

use are 8.0, 8.6 and 9.3 million tons respectively in 2030, 2040 and 2050. The estimated feed barley equivalent meat demand for each future time slice and population growth scenario (Table 5-8) is greater than the current quantity of meat import (Table 5-1b). It must be pointed out that grain feed requirements and feed conversion efficiencies differ among animals (Pollock, 2011; Thornton, 2010). For example, for every unit kcal of meat produced, beef cattle require about 5 times the dietary energy required by poultry. Hence, differences in the proportions of different meat types demanded might alter the total quantity of feed barley demanded in the future. For example, it has been observed that the consumption of carcass meat (mainly beef and lamb) is on the decline while consumption of poultry, pig and processed meats (or non-carcass meat) is either stable or increasing in the UK (Defra, 2013; 2011) and the EU (European Commission, 2011). A similar trend has been observed in the USA (Andreyeva *et al.*, 2010). This trend, however, should be analyzed within the larger matrix of socio-economic conditions as it is believed that it might change with improvements in the economy (European Commission, 2011). Components of food have different price and income elasticities. A systematic review by Andreyeva *et al.* (2010) showed that carcass meat of beef and lamb has greater price elasticity than poultry and processed meats in the USA and changes in food prices and or disposable incomes have direct impact on the consumption of carcass meat. In the case of the UK, while the average quantity of carcass meat purchased per household is decreasing, the average expenditure on carcass meat is increasing (Defra, 2013). Hence, changes in prices of meat (for example, during the food crisis) and household disposable incomes (for example, during the economic recession), together with health considerations, might cause households to trade down some dietary components (Defra, 2013). Again, while per capita

consumption of carcass meat could be declining, aggregate consumption might increase due to population growth. These changes will have effect on overall future total meat demand and, for that matter, feed barley demand. Poultry meat production, for example, is more feed-efficient than beef production. It must also be pointed out that the ranges of feed barley deficits here are based on the assumption that the current ratio of feed barley to malt barley remains unchanged to 2050. Any change in this ratio will alter the quantity of feed barley demand and consequently the deficit.

It is projected that meat import to Europe will increase substantially in future and so will animal feed (Bruinsma, 2012; European Commission, 2011). This is probably because while the need for feed use of grains will increase, it is likely that the response to demand for bioenergy would be disproportionately higher due to initiatives to achieve renewable energy targets (Bruinsma, 2012; Durham *et al.*, 2012; European Commission, 2011). It is projected that, by 2020, barley will lose about 21% of its total area of land in the EU to other biofuel cereals (such as soft wheat and maize) (European Commission, 2011). Should this happen, it would have a cascading effect on UK's import of feed grains or meat from the EU and intensify competition on the world market. The question is: where will all this barley or feed barley equivalent meat import come from?

5.4.3 Virtual Water Flows

Faced with deficits, the UK would have the option to import feed barley, increase domestic barley production by expanding the land area for barley production or import the feed barley equivalent meat demand. Whereas the UK domestic production of barley is

totally rain-fed (green water), barley import would result in blue water inflows to the UK. The projected virtual water inflows to the UK through the import of feed barley or the equivalent meat in the future would be substantial given the scale of deficits in either feed barley or equivalent meat demand. Blue virtual water inflows, due to import of feed barley equivalent meat deficit, would range from 440 Mm³ in 2030 to 579 Mm³ in 2050 (under the constant population growth scenario). Unlike green water, blue water use is said to have high environmental and socio-economic impact (Aldaya *et al.*, 2010a; Hoff *et al.*, 2010; Chapagain & Orr, 2009; Yang *et al.*, 2006). However, the environmental and socio-economic impact of UK's imports would vary depending on the location of blue water withdrawal and the scale of water stress at that location. For example, the blue VWC of both barley and meat from Spain, where water scarcity is likely to intensify in future, was the highest among the exporting nations. It is noteworthy that, according to the analysis presented in this thesis, the projected virtual water inflows to the UK, regardless of the volumes, is due to land constraint and not domestic water scarcity. Because green water use occurs only through land occupation, reallocation of green water saved through food import can occur only through changes in land use or crop type. Thus, the UK can shift land from feed barley production to, say wheat, which is directly consumed by humans and can be used in feed and biofuel production. In that case, the UK can focus on production of wheat and malt barley and import feed barley if necessary. Therefore, the green water saved from such a shift in land allocation will mean a reallocation of the saved green water.

The mean virtual water content of meat (mainly beef and lamb) used in this study is lower than the virtual water content reported in the EBLEX study which assessed the

water footprint of English beef and lamb (Chatterton *et al.*, 2010). The differences emanate from differences in the models and parameter values used in estimating crop evapotranspiration and assumptions regarding intermediate water uses (Chatterton *et al.*, 2010; Hess, 2010). The blue VWC of English beef and lamb in the EBLEX report were 66.7 and 48.6 m³ ton⁻¹ respectively (Chatterton *et al.*, 2010). This means meat production in the UK might be more water efficient and have less environmental impact than imported meat.

5.4.4 Implications for Food Security

Figure 5-4 is a simplified causal loop diagram (CLD) indicating the most relevant interconnections underlying the UK future barley production, demand and supply of feed barley and meat, and consequences for food security. A positive sign indicates same direction, that is, an increase in one variable leads to a corresponding increase or a decrease leads to a corresponding decrease in the other variable to which it is linked. Conversely, a negative sign indicates opposite direction, that is, a decrease in one variable leads to an increase in the other variable to which it is linked and vice versa.

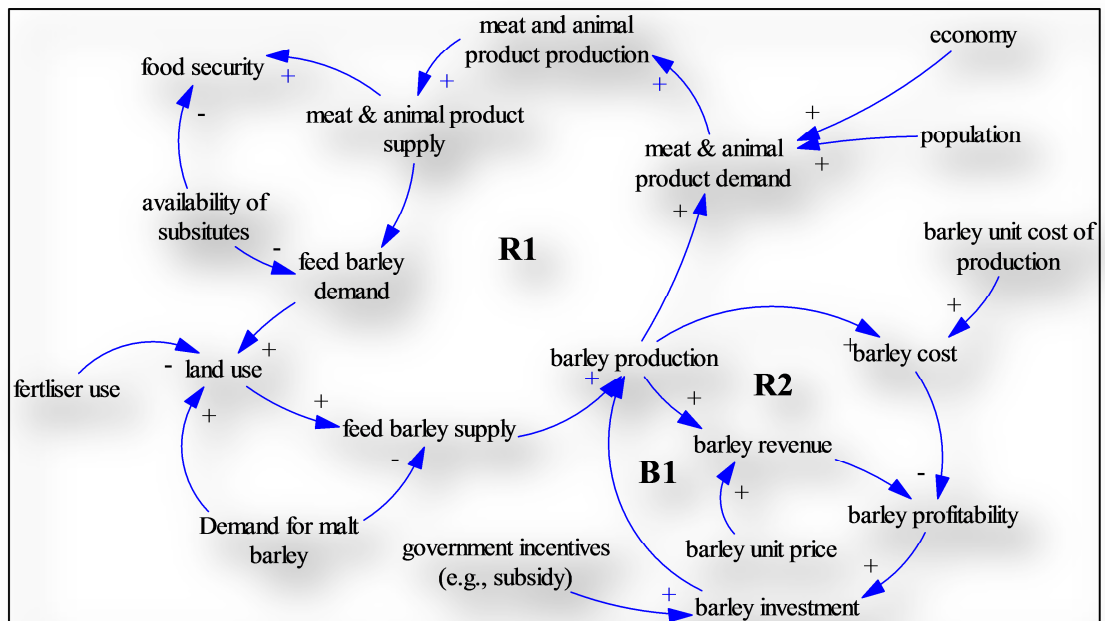


Figure 5-4: A simplified causal loop diagram showing the feed barley, meat and food security relationships.

There are two reinforcing feedback loops and one balancing loop in the CLD (Figure 5-4). In loop R1, an increase in population and economic welfare (exogenous factors) increases the demand for meat and animal products. In response, production increases to match supply to demand, which ensures food security. However, this also leads to increased feed barley demand, which, in turn, necessitates additional land requirements for production in order to deliver adequate supply and maintain high level of production. Loop R1 can thus be regarded as **resource requirement** feedback loop in barley production. This loop represents an example of positive feedback self-reinforcing process. However, the loop would be prevented from increasing the quantity of each factor indefinitely because other factors outside the loop such as *total production costs* actually influence the *barley price*. The price and availability of substitutes (such as soft wheat and

maize) could lower feed barley demand, just as increased demand for malt barley could lower feed barley supply. In lieu of adequate feed barley supply, however, use of substitutes could increase meat supply but lower food security by diverting grains for direct human consumption. Moreover, should those substitutes be used for bioenergy production, food security would also be adversely affected.

Loops B1 and R2 (**market signal loops**) consider the profitability of the barley production. In the case of B1, the higher the barley production, the more the barley production cost is incurred, which negatively influences the barley profitability. Lower barley profitability decreases investment in barley production, which, in turn, decreases barley production. This is an example of a self-balancing loop, where growth is attenuated and checked from within the loop. Such a subsystem would tend to be innately stable. On the other hand, R2 shows that increasing barley production positively influences the barley profitability. Higher profitability acts as an incentive for more barley investment, therefore increasing barley production. This is another self-reinforcing loop. Loops B1 and R2 thus operate to control the level of barley production and feed barley supply regardless of the scale of demand or land available for production in loop R1.

The UK Government defines food security as *ensuring the availability of, and access to affordable, safe and nutritious food sufficient for an active lifestyle, for all, at all times* (Defra, 2009). According to Newton *et al.* (2011), the food security status of a crop such as barley ought to be assessed in terms of its cultural, political, agronomic and economic value. For example, barley has certain end uses (such as malt whiskey production) which make it different from other cereals (Newton *et al.*, 2011). Meat and animal products (mainly dairy) are a rich source of high value protein and essential

micronutrients (iron, zinc and vitamin A) and are therefore key to food security (Foresight, 2011). As an important source of grain for animal feed, barley plays a crucial role in UK's food security as meat contributes a substantial proportion of daily calories. Hence, given the definition of food security adopted in this study and by Defra (2009), the projected deficits in UK feed barley supply from domestic production (as a result of land use and high demand) has direct, adverse implications for food security.

All things being equal, the projected large deficits in UK feed barley supply and reduction in EU-level production in the future could compel the UK to import feed barley or reduce domestic meat production and increase meat imports. Imports (and for that matter virtual water inflows) of either feed barley or meat could help ease the threat of food insecurity. However, this could expose the UK to the dangers inherent in the global grains and meat market. Uncertainties regarding global supply, demand, competition and prices of coarse grains and meat would have the potential to undermine the stability of UK's future supplies. The cost of animal feed is rising steadily due mainly to increases in prices of cereal grains (Defra, 2011). The cost of feed is projected to remain higher above long term EU average due to possible diversion of grains to bioenergy production (European Commission, 2011). High feed cost would increase the cost of meat production, price of meat to consumers and ultimately influence both the availability and access to meat. Already, the increasing preference for pig and poultry meat over beef and lamb across the EU is considered to be a matter of affordability (European Commission, 2011). Therefore, if measures are not adopted to address the projected deficits in feed barley supply, the availability and economic access to meat could be negatively affected.

5.5 Conclusions

1. Policies regarding food security, climate change and energy are likely to be key drivers of agricultural land use futures in the UK. Projected maximum area of land for barley production ranged from approximately 1,134 thousand ha in the 2030s to 1,156 thousand ha in the 2050s.
2. Total area of land allocated to barley production in the future, together with changes in population and per capita meat demand, will be the key determinants of UK's future self-sufficiency in feed barley supply. The highest projected total barley production was approximately 9 million tons in the 2050s with a corresponding feed barley supply of 4.6 million tons.
3. Within the limits of this thesis, the UK is projected to face substantial deficits in feed barley supply (ranging from approximately 7.5 to 9.3 million tons) from domestic production from 2030 to 2050.
4. The projected deficits in feed barley supply indicate possible risks to UK's future food security due to potentially large deficits in feed barley equivalent meat supply.
5. Imports of feed barley or feed barley equivalent meat supply to offset food security risks would lead to substantial volumes of virtual water inflows to the UK, including blue water. Blue virtual water inflows could have high socio-economic and environmental impacts in exporting countries depending on the location of withdrawal and the extent of water stress at that location.

CHAPTER 6**‘AGRI-COMPATIBILITY’: A FRAMEWORK FOR EVALUATING THE ROLE OF VIRTUAL WATER IN WATER-FOOD SECURITY POLICY**

This chapter is based on the paper: *Yawson, DO, Mulholland B, Ball T, Mohan S, White P (2013). Food security in a water-scarce world: making virtual water compatible with crop water use and food trade. Scientific Papers Series “Management, Economic Engineering in Agriculture and Rural Development”, 13(2), 431 – 443. E-ISSN 2285-3952. See Appendix 4 for the full paper.*

6.1 Introduction

Since its introduction, the term ‘virtual water’ and its associated hypothesis, that water-intensive food commodities can be imported from water-rich areas to offset local water scarcity in the importing country (Allan, 1998a; 1998b; 2003; Yang *et al.*, 2006; Liu *et al.*, 2007b; Aldaya, 2010a), have attracted criticisms and generated debate along two main lines. One, on a conceptual level, Merrett (2003a, 2003b) argued that there is nothing *virtual* about virtual water and that the term is redundant as it duplicates the pre-existing term *crop water requirement*. He also argued that use of the phrase *virtual water trade* is misleading as it is not the water that is traded but the food crop. However, Allan (2003) refuted Merrett’s view as incomplete as it focused only on the intensive aspect (i.e. water and crop production) of virtual water and not on the extensive aspect (i.e. the impact of food trade on the water economies of the trading nations and the water policies of water deficit economies). Thus, from the extensive (consumption) perspective, virtual water

analysis should include the volume of water *virtually* saved by importing food, which has been called theoretical virtual water (Hoekstra, 2003) or water savings (Chapagain & Hoekstra, 2008; Chapagain *et al.*, 2006; Yang *et al.*, 2006) or exogenous water (Haddadin, 2003). Two, on the practical usefulness of virtual water for water management decisions and policy, there are suggestions that virtual water suffers conceptual and practical limitations. Here, the main questions have been whether water scarcity is the main driver of the structure and direction of virtual water flows; and if it is consistent with trade theories (see Chapter 2, Section 2.5.2; Ansink, 2010; Ramirez-Vallejo & Rogers, 2010; Wichelns, 2010a; 2010b; 2004), or virtual water export can be linked to a specific environmental impact category (Ridoutt & Pfister, 2010; Pfister *et al.*, 2009).

The aim of this chapter is to contribute to, and advance, the debate on the role and usefulness of the virtual water concept for informing water-food security management and policy decisions. It is argued that the role or usefulness of virtual water in water-food security management and policy decisions can be understood by analysing its components, which must be conceptually compatible. It is argued that current limitations of the concept of virtual water to inform policy arise from the conceptual incompatibility among its main components. Therefore, in order to advance the debate, this chapter draws on literature and concepts or findings of the previous chapters to promote the concept that ‘agri-compatibility’ is required to understand the link between water scarcity and food security through the movement of virtual water. The objective of this chapter is therefore to present the conceptual outlines of ‘agri-compatibility’ (Section 6.2) and a framework for its evaluation (Section 6.3). In Section 6.4, a discussion of the implications of the proposed

'agri-compatibility' for virtual water analysis is presented and, finally, conclusions are drawn.

6.2 'Agri-compatibility'

Virtual water has an agronomic (or production) component, which concerns crop-water use, and a socio-economic (or consumption) component with regard to food security and the two are linked by trade. On the production side, the key issue is the consumption of a productive resource (water), or the constraint thereof (water scarcity). On the consumption side, the key issue is sufficient availability of food (hence, food security). The two parts, however, require detailed examination so that the ability to match sustainable water use to food security needs, and the role of trade, can be evaluated accurately. To achieve this, the two components (water scarcity and food security) should be conceptually compatible to justify and strengthen the link provided by virtual water (food trade). If this conceptual compatibility is achieved for a given crop, area and time, the situation can be referred to as agri-compatible connections among water scarcity, virtual water and food security (or simply 'agri-compatibility').

In the context of crop production and food security, 'agri-compatibility' refers to the condition in which a food crop commodity is imported to fill actual or potential food security gaps created by insufficient aggregate water supply from all relevant sources to satisfy the water requirements for the production of the given food commodity in the importing area. Figure 6-1 is an illustration of the idea of 'agri-compatibility'. Thus, virtual water can be said to be agri-compatible if conditions 'X' and 'Y' (agri-compatible

water scarcity and agri-compatible food imports respectively) are satisfied. Otherwise, it is non-agri-compatible (that is, food import is driven by factors other than water scarcity).

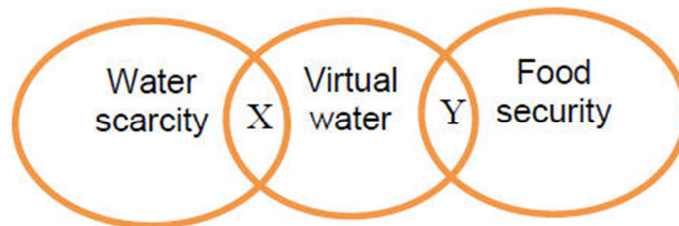


Figure 6-1: An illustration of agri-compatible connections between water scarcity, virtual water and food security. *X* denotes agri-compatible water scarcity; *Y* denotes agri-compatible food import. Figure adapted from Yawson *et al.* (2013).

6.2.1 Agri-compatible Water Scarcity

Depending on the source, there are two main types of water used by crops (as defined in Section 1.3.1): blue (from irrigation) and green (from precipitation) (Hoff *et al.*, 2010; Chapagain & Orr, 2009). The actual or potential use of harvested rainwater by direct interception or by collecting runoff, which is at the interface between green and blue water (Hoff *et al.* 2010; Wisser *et al.*, 2010), and desalinated water in crop production has not yet been included in these types of water. ‘Agri-compatible water scarcity’ refers to the condition where there is insufficient water availability from all relevant sources to satisfy the water requirement of a given crop at a particular area and time. This means that, to achieve ‘agri-compatibility’, water scarcity should be defined with reference to a crop, location and time.

As pointed out earlier (see Chapter 2, Section 2.2.3.2), current concepts of water scarcity focus on blue water availability for human populations and the associated socio-

economic impacts. They do not adequately capture water availability and use in agro-ecosystems and are therefore limited when applied to virtual water and food security. Available evidence suggests that, on average, green water constitutes over 80% of global water use in crop production (e.g. Aldaya *et al.*, 2010a; Hanasaki *et al.*, 2010; Hoff *et al.*, 2010; Liu & Yang, 2010; Thenkabail *et al.*, 2010; Liu, 2009; Liu *et al.*, 2009; Rockström *et al.*, 2010; 2009; Molden, 2007) although there can be large variations within and between countries, as well as between crop types. Consequently, green water dominates global virtual water flows (Aldaya *et al.*, 2010a; 2010b; Liu *et al.*, 2009; Chapagain & Hoekstra, 2008; Yang *et al.*, 2006; Hoekstra & Hung, 2005). This means that, for water scarcity to be meaningful to virtual water and food security analysis, it must account for green water available to a target crop. In other words, water scarcity should be analysed through agricultural systems and expressed in terms of normal water balance concepts and its effect on food security understood by considering the role of the target food crop in the water consumption and food balance sheet of the country or region of interest. The main conventional indicators of water scarcity fail to capture this fact (Rockström *et al.*, 2010; 2009; 1999; Oki & Kanae, 2006; Vörösmarty *et al.*, 2005; ; Rockström, 2003; 2001; Sullivan *et al.*, 2003; Ohlsson, 2000; Falkenmark *et al.*, 1989), yet, any reference to water scarcity is indiscriminately linked to food insecurity. Thus, as shown in Figure 6-1, not every type of water scarcity is relevant to or compatible with crop production or food security needs. ‘Agri-compatible water scarcity’, therefore, provides insight into the contribution of a given food crop to water scarcity in a given crop-producing area at a given time, or food insecurity in a given nation or region.

6.2.2 Agri-compatible Food Import

This is the second condition for achieving ‘agri-compatibility’ (Figure 6-1). Once ‘agri-compatible water scarcity’ is defined or established, it is possible to assess its effect on food security. The gap in food security here then becomes “*water-dependent*” (Aldaya *et al.*, 2010b), necessitating the import of food. ‘Agri-compatible food import’ refers to the total amount of food imported to fill actual or potential gaps in food security created by insufficient available water from all relevant sources for food crop production (all other things being equal). In other words, it is the import of food to fill a gap in food security created by agri-compatible water scarcity. Virtual water flows associated with such food imports can be referred to as ‘ecological virtual water flows’. While food import generally satisfies food security needs, it can only be agri-compatible when it is driven by agri-compatible water scarcity. Moreover, import of crop commodities for non-food security purposes (e.g. biofuel production) will also fall outside the scope of ‘agri-compatibility’ or can be referred to as ‘economic virtual water flows’. Thus, making water scarcity agri-compatible is the key to achieving agri-compatible virtual water which can be more useful to the analysis of water-food security policy needs than the current understanding or approaches used. Therefore, instead of conflating all food imports in virtual water analysis, a distinction between agri-compatible and non-agri-compatible virtual water flows will help to clarify the role and usefulness of virtual water for policy in the nexus of water and food security.

6.3 A Framework for Evaluating ‘Agri-compatibility’

The previous section has described the conceptual outlines of ‘agri-compatibility’. It has been indicated that ‘agri-compatible water scarcity’ is the primary requirement for defining agri-compatible virtual water. A framework for evaluating agri-compatible virtual water flows is proposed (Figure 6-2). The base of Figure 6-2 shows the factors of agri-compatible water scarcity (crop type, soil, climate and water type). Each factor has elements that are relevant for quantifying or analysing agri-compatible water scarcity.

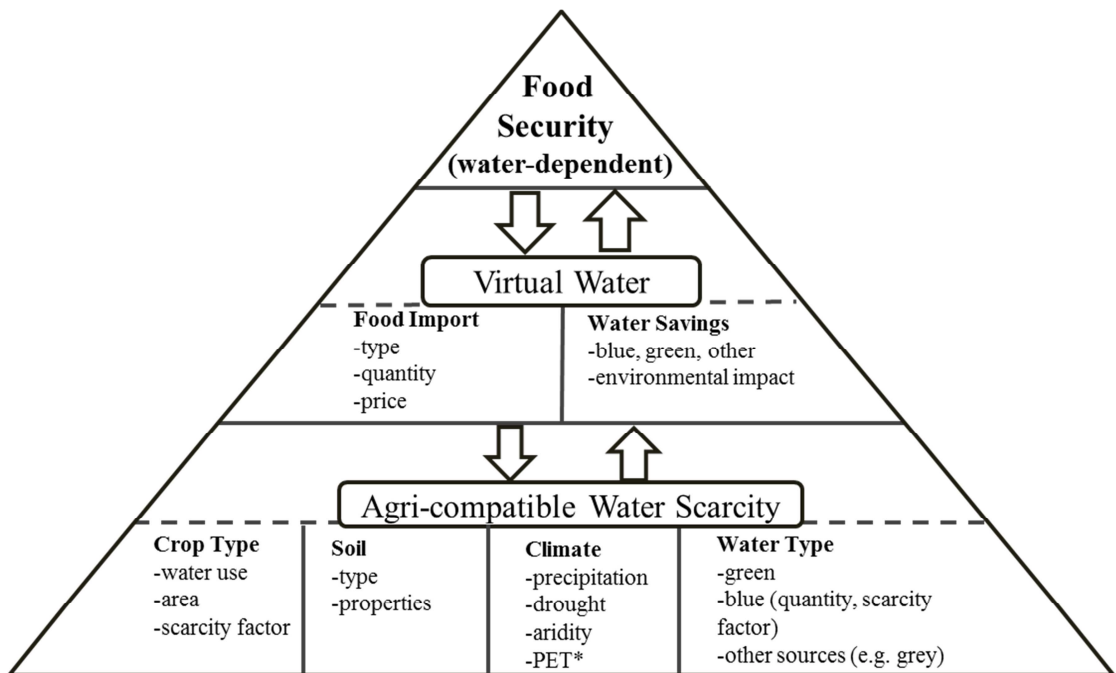


Figure 6-2: A framework for evaluating agri-compatible virtual water flows and understanding the role of virtual water in achieving food security in a water-scarce area. The base of the triangle shows the factors of agri-compatible water scarcity which limits crop production and necessitates food import (virtual water). The apex of the triangle shows food security achieved through water-dependent food import. Conversely, food security, achieved through virtual water, also affects water availability and impacts the environment in the crop production area. * Potential Evapotranspiration. Figure taken from Yawson *et al.* (2013).

Agri-compatible water scarcity should account for the totality of environmental water availability (green, blue and other sources) and consumption in relation to specific crop water requirement (CWR) at a given crop-producing area and time (for e.g. at a given catchment or sub-national scale). The CWR is affected by crop type, climate, soil and agronomic practices regarding management of the soil-water-crop continuum (e.g. soil water conservation and irrigation practices) (Raes *et al.*, 2009; Barnabàs *et al.*, 2008; Shahin, 2003; Allen *et al.*, 1998). Crops can also suffer genotype-specific water scarcity or stress under the same production conditions due partly to differences in water use efficiency (Anjum *et al.*, 2011a; Barnabàs *et al.*, 2008; Blum, 2005; Sumner & Jacobs, 2005). The total volume of water consumed by a crop increases with the area of land for its production. The main climatic factor that influences the magnitude of CWR is the reference evapotranspiration, which indicates the evaporative demand of the atmosphere (Hess, 2010; Raes *et al.*, 2009; Shahin, 2003; Allen *et al.*, 2006; 1998). The type of soil and its hydraulic properties also control the amount of water available to crops and surface evaporation but this can be influenced by agronomic practices (Raes *et al.*, 2009; Shahin, 2003). It is proposed that ‘agri-compatible water scarcity’ should capture three key elements: (i) quantification of CWR and total water resource available from all sources to the given crop to identify gaps in supply, (ii) where irrigation is involved, the use of crop- and catchment-specific water scarcity factors to evaluate the contribution of the crop to water scarcity, and (iii) the contribution of aridity or drought (from a temporal perspective) to crop yield losses and consequently food import.

6.3.1 Quantification of Water from Different Sources

A comparison of CWR and water available to a crop from all sources will reveal if there is insufficient water availability to constrain the production of the given crop. In most agricultural areas, green and blue water are the main sources of water for crop production (Hoff *et al.* 2010; Aldaya *et al.* 2010b). However, even though green water dominates crop production in most agro-ecosystems (Figure 6-3; Hoff *et al.* 2010; Aldaya *et al.* 2010b), green water volumes and consumption are rarely measured (Hess, 2010). Even in the arid Middle East and North Africa (MENA) region, which depends largely on irrigation, green water could account for 50% of total water consumption by all crops, either in rain-fed production or from precipitation over irrigated land (Hoff *et al.* 2010). Rockström *et al.* (2009) suggested that estimates of the adverse effect of blue water scarcity on crop production, even under future climate change, can be significantly diminished when green water is properly estimated, sourced and managed. The accurate quantification of especially green water availability and use in crop producing areas is therefore important in the analysis of agricultural water scarcity.

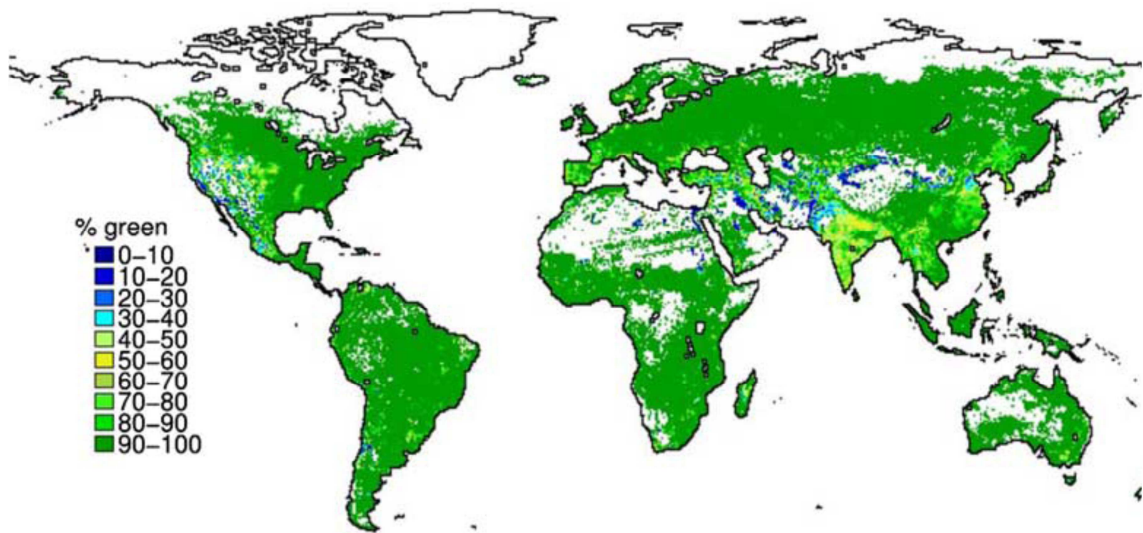


Figure 6-3: Green water use as a proportion of total water use (green + blue) on global croplands and pasture (1995-2005 average). Source: Rockström *et al.* (2009).

6.3.2 Crop and Catchment Water Scarcity Factors

Allan (2003) argues that the virtual water concept is both intensive and extensive, meaning that it carries implications for water resources availability and management for both sites of production and consumption. Estimates of either virtual water flows or water footprint are not indicators of any environmental damage or stress. They only quantify consumptive use of water, a situation that limits their usefulness for policy. Water scarcity is an environmental phenomenon that has biophysical and socio-economic drivers and impacts. However, current water scarcity indicators are not only inadequate for gauging water availability for agriculture, but they also fail to capture the impact of food consumption on water scarcity of production communities. If the analysis of drought must be specific to a given crop type or land use to be meaningful and purposeful (Allan, 2000), then, similarly, agri-compatible water scarcity must be specific to a particular crop or

catchment and time in order to be meaningful and purposeful. By making water scarcity specific to a given crop, the contribution of that crop to water scarcity or the effect of water scarcity on that crop can be isolated and analysed.

Pfister *et al.* (2009) developed a method that uses water stress characterization factors to assess the environmental impacts of water consumption. Subsequently, Ridoutt & Pfister (2010) applied the water stress characterization factors of Pfister *et al.* (2009) to weight the water footprint of Dolmio™ pasta sauce and Peanut M&M™ produced in Australia. In that study (Ridoutt & Pfister, 2010), the location of water consumption at each point in the product's life cycle was defined. However, the water consumption at the production phase was equated to the crop water requirement. The water consumption at each phase was then multiplied by the relevant water stress factor. The results were then linearly summed to produce product-level water footprint. The results showed that while the conventional water footprint of Dolmio pasta sauce was less than one-fifth that of Peanut M&M's, the stress-weighted water footprint of Dolmio pasta sauce was over 10 times higher in magnitude (and for that matter impact) than that of Peanut M&M's. Ridoutt & Pfister (2010) argued that the significance of their study lies in its potential to minimize the difficulties associated with partitioning water input into blue and green in water footprint accounting, as well as giving a single value that is associated with an environmental impact category (water scarcity). This study, however, did not include green water on the premise that green water has low opportunity cost and does not contribute to environmental flows or directly to water scarcity. Thus, while the work of Ridoutt & Pfister (2010) is significant as it creates opportunity for quantifying the specific contribution of each product, through its life cycle, to water scarcity at the location of

production, it does not fully capture agri-compatible water scarcity. Therefore, a calculation scheme for agri-compatible water scarcity factors at crop and catchment levels is proposed (Table 6-1).

Table 6-1: A scheme for calculating crop- and catchment-specific water scarcity factors.

(i) CROP FIELD	(ii) CATCHMENT
<p>Per unit time (t):</p> $BWRi[t] \text{ (m}^3\text{)} = (ETc[t] - P_{eff}[t]) \times A$ <p>[where $ETc \geq P_{eff}$]</p> <p>Per season:</p> $BWRi[season] = \sum_{t=1}^l BWRi[t]$ <p>Scarcity factor (Cfi) = $\frac{BWRi[season]}{BWfi}$</p>	$BWRc[t] = \sum_{i=1}^n BWRi[t]$ $BWRc[season] = \sum_{i=1}^n BWRi[season] = TBWR$ <p>Scarcity factor (Cfc) = $\frac{TBWR}{\sum_{i=1}^n BWfi}$</p>

NOTE:

(i) $BWRi$ denotes blue water requirement of crop i per unit time (t) (m^3); P_{eff} denotes effective rainfall or soil water content (mm); ETc denotes crop evapotranspiration (mm); A denotes area covered by crop i (m^2); $BWfi$ denotes the amount of blue water in the catchment applied to crop i (m^3); l denotes length of crop growing period (days); (ii) $TBWR$ denotes total blue water requirement of all crops considered in the catchment (m^3); n denotes number of crops considered; and c denotes catchment.

A scarcity factor (Cf) ≤ 1 implies no scarcity; $Cf > 1$ implies water scarcity.

Thus, taking $Cf = 1$ as the threshold for water scarcity, it implies water scarcity increases as Cf increases from 1 and vice versa. The development or use of these crop and catchment specific scarcity factors is important for the following reasons:

- a) Knowing the crop and catchment water scarcity factors will help match crops to catchments in order to save water or reduce the effect of the production of a particular crop on a given catchment. This will, in turn, aid

the analysis of the effect of land cover change on water scarcity in a given catchment.

- b) Not all catchments in a country might have agricultural abstractions of blue water.
- c) Different catchments will have different scarcity factors with respect to agriculture and overall withdrawal; and for different crops grown in the catchment.
- d) There can be water scarcity in a particular area without there being water scarcity for a particular crop in the same area. Thus, green water availability could be sufficient to support the production of some crop(s) in a catchment that might be suffering blue water scarcity.
- e) Intra-seasonal dry spells might adversely affect crop yield in a country or an area that is not considered as water-scarce in the conventional sense.
- f) The equations also have operational significance as they can be used to monitor temporal water scarcity (for only green water, blue water or both) at crop, field and catchment scales.
- g) The crop- and catchment-specific scarcity factors can be used in calculating crop water footprints and related effects on humans and ecosystems at both sites of production and consumption. The virtual water content of a crop is similar to its water productivity. In the conventional analysis of virtual water, water savings occur in the importing region if the water productivity of the given food crop is less than that of the source of import (Yang & Zehnder, 2007; Yang *et al.*, 2006). Such water savings can be a

justification for promoting import of the given food crop from the given source of import. However, a comparison of the crop or catchment water scarcity factors between the two trading regions could suggest that greater environmental damage is done due to greater water scarcity factors at the source of import.

6.3.3 Aridity and Drought

Numerical indices of aridity (obtained as the quotient of precipitation and PET) describe the extent of dryness of the atmosphere of agro-ecosystems (Rockström *et al.* 2010). Arid agro-ecosystems (where PET substantially exceeds effective rainfall) are characterized by high spatial and temporal variability of rainfall and frequent drought or dry spells (Rockström *et al.* 2010). There is therefore a high potential for physical water scarcity in such environments. Drought is a temporary shortage of water, over periods of months to years, due to below-normal precipitation (Dai, 2011). Within a growing season, crops can suffer water stress due to agricultural drought (or dry spells) even in the absence of meteorological drought (Dai, 2011), a situation that is common in many rain-fed crop production systems (Barnabàs *et al.*, 2008; Gardner & Gardner, 1983; Boyer, 1982). Depending on the timing and intensity, dry spells can ultimately impair crop growth and yield if not addressed in a timely manner. Drought is a complex abiotic stress and difficult to predict because of the interaction of multiple factors related to crop, climate, soil and agronomic practices (Richards, 2006; Blum, 2005). Assessment of the effects of drought on yield is further complicated by the varying effectiveness of different crop response and

adaptive mechanisms, the time of incidence in the crop cycle and the severity of the drought (Blum, 2005). Aridity and drought increase CWR and the need for irrigation. Thus, imports of water-intensive food crops might help save scarce blue water in arid countries. Similarly, Allan (2000) argues that the virtual water concept is particularly effective and efficient in addressing *progressive and occasional local agricultural drought*. Drought can compel a relatively water-secure economy to restrict food export or increase food import in order to maintain food security. Therefore, in a temporal sense, agri-compatible water scarcity should incorporate the role of aridity and drought in creating crop-specific water stress at a particular area and time and, thereby necessitating food import. This provides a more rigorous basis for evaluating the significance of virtual water for water-food security.

The role of aridity in understanding agri-compatible virtual water flows can be illustrated using cereals, which have the largest water use in global crop production (de Fraiture & Wilchens, 2010) and are the most traded crop commodity (de Fraiture & Wilchens, 2010; Hoekstra & Chapagain, 2008; Chapagain *et al.*, 2006; Yang *et al.* 2006). In the year 2000, for example, cereals accounted for 57% of total crop water use in the world (over 7000 km³) and over 70% of total crop water use in the MENA region (Figure 6-4). The aridity of the MENA region largely accounts for the high irrigation water requirement of cereal production (de Fraiture and Wilchens, 2010; Allan, 1998a; 1998b), giving rise to agri-compatible water scarcity. Cereals constitute the largest food import to the MENA region. According to de Fraiture & Wilchens (2010), in 2000, Egypt alone imported 8 million tonnes of grains from the USA. As a result of the grain import, Egypt saved 8.5 billion m³ blue water which could have been used to produce the imported

grains (de Fraiture & Wilchens, 2010). The analysis of Allan (1998a; 1998b) suggests that import of cereal grains (especially wheat) to the MENA region serves the purpose of water-dependent food security as water availability for cereal crop production is limited substantially by aridity and competition.

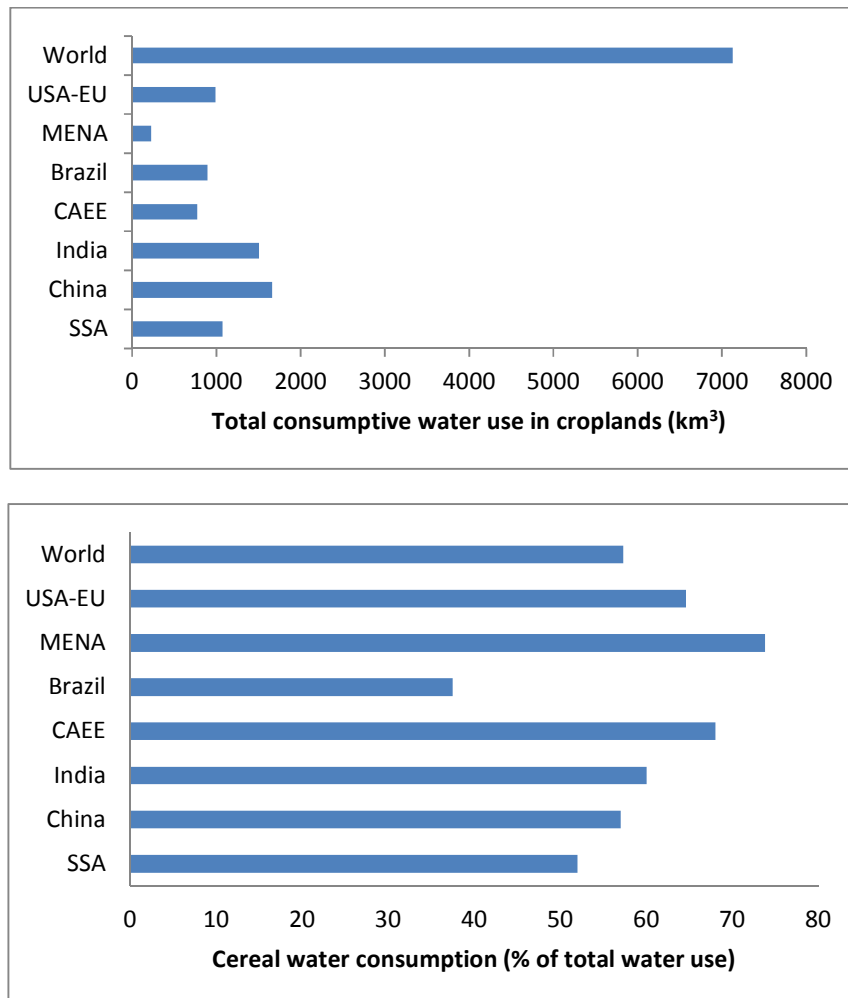


Figure 6-4: Top: total water used for crop production in the world and selected major crop production regions in the year 2000. Bottom: total water used by cereals as a percentage of total crop water used in the world and selected major crop production areas in 2000. MENA, CAEE and SSA denote Middle East and North Africa, Central Asia and Eastern Europe, and Sub-Saharan Africa respectively. Data taken from de Fraiture & Wilchens (2010).

6.4 Discussion

A number of factors (economic, ecological, technical, political and socio-cultural) operate singly or in combination to limit or enhance crop production in a particular geographic region, resulting in the creation of surpluses or deficits in food production across space and time. Food commodity trade enables the transfer of food from regions with food surplus to regions with food deficits. Trade theories such as the Heckscher-Ohlin theorem or the Ricardian comparative advantage suggest that trading a commodity invariably constitutes an indirect trade of the factors or resources consumed in the production of that commodity (Ansink, 2010; Hakimian, 2003; Krugman & Obstfeld, 1991). Hence, in the context of trade theories, the virtual water concept has been interpreted and reduced to relative water endowments between trading nations. Trade theories, such as comparative advantage and opportunity cost, have therefore been used or proposed as tools for testing the virtual water concept or evaluating its usefulness for policy (Ansink, 2010; Wichelns, 2010a; 2010b; 2004; Hakimian, 2003; Allan, 1999).

Just like any commodity, food is produced with several productive factors including water. However, when the availability of a particular resource such as water becomes the main constraint to the production of a commodity, such as a food crop, the effects of the resource scarcity can be isolated and analyzed to identify solutions. Even in conventional trade analysis, single factor and single commodity analysis is common (Ansink, 2010; Krugman & Obstfeld, 1991). Hence, scarcity of water can be considered as a main resource constraint to food production or food security in certain areas and, by isolating the resource problem, virtual water proposes a possible solution for food security in water-scarce areas. However, just as for industrial commodities, applications of trade

theories to virtual water analysis have largely exhibited the Leontief Paradox where relatively water-rich countries import crop commodities from relatively water-poor countries (Seekell *et al.*, 2011; Ansink, 2010; Ramirez-vallejo & Rogers, 2010; Verma *et al.*, 2009; Kumar & Singh, 2005; Lant, 2003; Earle, 2001) and sometimes lead to the conclusion that the virtual water concept has limited use for policy (Ansink, 2010; Wichelns, 2010a; 2010b). Moreover, both water (as a productive resource) and food do not bear a true economic cost to the consumer (Allan, 2003; Hakimian, 2003), a situation that further confounds any economic (or cost-based) analysis.

‘Agri-compatibility’ can help explain why the application of trade theories to virtual water analysis has largely yielded poor results and diminished the usefulness of the virtual water concept for policy. As suggested by Hakimian (2003), analysis of the virtual water hypothesis is sensitive to the definition and measurement of water employed. Using ‘agri-compatibility’ would mean distinguishing between areas that suffer agri-compatible water scarcity from others and distinguishing between agri-compatible food imports from other food imports. Thus, using conventional water scarcity renders the analysis incompatible with the virtual water concept. The ‘agri-compatibility’ framework also supports the suggestion that, if properly applied, the virtual water concept can be useful in informing optimal design of water right systems, management and policy decisions on agricultural water use (El-Sadek, 2011; Aldaya *et al.*, 2010b; Brown *et al.*, 2009).

The requirements for the application of the ‘agri-compatibility’ framework will differ depending on geographic area or scale of analysis, crop production system (rain-fed versus irrigated systems) and time. A dynamic application of the ‘agri-compatibility’ framework will show its usefulness. For example, in the case of UK barley production, the

results in Chapters 3 and 4 generally showed that rainfall is and will be sufficient to support barley production. In that case, the projected barley imports by the UK (Chapter 5) will not be due to water deficit limiting barley production but by other factors. The virtual water inflow associated with such barley imports would not be agri-compatible as it will not be driven by agri-compatible water scarcity. The UK can, however, use the ‘agri-compatibility’ framework (crop or catchment specific water scarcity factors) to import barley sustainably from where barley production does not contribute substantially to water scarcity. Conversely, the results in Chapter 4 also showed that future UK regional barley yields could also be reduced substantially (see Tables 4-6 to 4-8) due to water deficits (in combination with heat stress). In that case, the water-limited yield would raise the UK barley imports and render the associated virtual water inflows agri-compatible. This shows that both water-rich and water-scarce countries can use the ‘agri-compatibility’ framework to inform water-food security management and policy decisions in the context of climate change and over varying temporal scales.

‘Agri-compatibility’ requires a re-statement of the virtual water hypothesis to aid clarity in interpretation and application. That is, *through the instrument of food import, agri-compatible water-scarce areas can maintain food security and allocate water virtually saved to alternative uses*. The implication is that ‘agri-compatibility’ shifts the focus of virtual water analysis or discussion from mere quantification of virtual water flows or water endowment (static or permanent water scarcity) to understanding the spatio-temporal dynamic relationships in the continuum of water availability, crop water use and import of food crop commodities, and how these interact over space and time to affect water resources and food security. This shift in focus makes the virtual water

concept relevant for both rain-fed and irrigated production systems, as well as for both water-poor and water-rich agro-ecosystems. It also exposes the importance of green water in water-food security and policy. The shift in the focus of virtual water analysis is consistent with the suggestion that, to ensure food security in the face of water scarcity, a hydro-centric view is not sufficient for policy and that there is the need to integrate food production and consumption into frameworks for water management and policy (Brichieri-Colombi, 2004). ‘Agri-compatibility’ combines the intensive and extensive dimensions of virtual water to provide a more rigorous basis for evaluating the usefulness of virtual water to inform management and policy decisions on water-food security. It adds to the call for a paradigm shift in water resources management towards accurate measurement or estimation, dynamic monitoring and effective management of green water availability and consumption in crop production areas (Hess, 2010; Rockstrom *et al.*, 2010; 2009). Roth & Warner (2007) suggested that, for nations faced with food insecurity induced by water scarcity, virtual water is a key component of a wider palette of policy choices. ‘Agri-compatibility’ expands this suggestion and clarifies the role and usefulness of virtual water for water-food security in both water-scarce and water-rich economies as demonstrated using results from Chapters 3, 4 and 5.

6.5 Conclusions

- a) The ‘agri-compatibility’ framework uses the fundamental and dynamic relationships among water availability, crop water use and food import to

clarify the role and utility of the virtual water concept in water-food security and policy.

- b) For virtual water to be agri-compatible, two conditions must be met. One, water scarcity ought to be compatible with water availability and consumption in crop producing areas (i.e. agri-compatible water scarcity). Two, food crops that suffer agri-compatible water scarcity are imported to fulfill water-dependent food security needs (i.e. agri-compatible food import).
- c) Establishment of agri-compatible water scarcity is the key requirement of making virtual water agri-compatible.
- d) Agri-compatible water scarcity has three main elements: accounting for water available to crops from all possible sources, use of crop and catchment-specific water scarcity factors to show the scale of crop and land use effect on local hydrological system and, finally, a consideration of the effects of aridity or drought on crop-specific water stress and yield that necessitate food imports.
- e) While all food imports serve, to a considerable extent, food security purposes, not all can be agri-compatible.
- f) Countries, such as the UK, can use the framework to support or inform decisions and policies on sustainable food production and trade, especially in the context of projected climate change.

CHAPTER 7**SYNTHESIS, CONCLUSIONS AND RECOMMENDATIONS****7.1 Introduction**

Demand for food is projected to increase substantially in the next four decades (Alexandratos & Bruinsma, 2012; Foresight, 2011). Due to the interlocked relationship between water availability and crop production, projected climate change and water scarcity pose a direct threat to future food security across varying spatio-temporal scales. Food trade can play a key role in ensuring food security at times when water stresses limit the yields of food crops substantially. However, the magnitude and direction of future food trade and its impact on water resources and food security, rationalized in the ‘virtual water’ concept (Allan, 1999; 1997), require a detailed examination of the local environmental water availability to crops to inform policy and management decisions. The overall aim of this thesis was to improve understanding of the relationship between future crop-water availability, crop production and food trade and how their interactions will impact water resources and food security, using the UK as a model country and barley as a model crop. The key findings and emergent issues of the thesis are synthesised in the sections that follow.

7.2 Synthesis

7.2.1 Predicted Barley Water Use Differs Between Models But Not Among Genotypes

This thesis has shown that, within the same production environment and under adequate soil water supply conditions, the barley genotypes studied might not differ substantially in their patterns or quantities of water consumption (Chapter 3, Figures 3-3a,b,c, 3-4). This observation was consistent for all the three models used (AquaCrop, CropWat and WaSim). Canopy temperature profiles of the genotypes (which can be a proxy for ET_c or water stress, Leinonen & Jones, 2004) also did not show substantial variation among the genotypes studied (Figure 3-5). The similarity in water consumption patterns among barley genotypes in the presence of adequate soil water supply has been observed in other environments (e.g. González & Ayerbe, 2011; Alderfasi, 2009). The similarity in water use found in this thesis was attributed to the similar abilities of the genotypes to acquire water from the soil. This is consistent with the findings of Alderfasi (2009) and McKenzie *et al.* (2009). The climate change simulation study also shows that green water availability will be sufficient for future barley production (Chapter 4, Figure 4-4).

However, the predicted seasonal water use of barley can differ substantially between models. This thesis has shown that CropWat can underestimate the water use of barley genotypes (Figure 3-4, 3-7). CropWat also performed poorly, according to the RMSE and D-Stat values, compared with AquaCrop and WaSim (Table 3-5). The data presented in this thesis (Figure 3-4, 3-7) suggest that CropWat might not be an appropriate model for quantifying the virtual water content (or flows) of crops in northern temperate

environments, or indeed the world. This observation has been made previously by Hess (2010) and Chatterton *et al.* (2010). Models can give different results due to differences in their structure and underlying assumptions. Apart from its ease of use, CropWat has limitations that make it unsuitable for estimating crop water use over larger spatial scales. CropWat uses a fixed rate of change in the crop coefficient (K_c , the crop-specific coefficient that relates to the crop's soil water depletion potential, Allen *et al.*, 1998) with time even though ET_c actually varies over short time scales with weather or ET_o , canopy cover and alternating wetting and drying of the soil surface. Further, CropWat is limited by its use of the effective rainfall method and its inability to separate water depletion at different depths in the soil, which can affect the accuracy of blue water requirement (Hess, 2010). The development of AquaCrop was partly informed by these deficiencies in CropWat (Raes *et al.*, 2009). The poor performance of CropWat in this thesis has implications for the wider use of CropWat in estimating the virtual water content and flows of crops at a global scale. Specifically, poor estimates of green water use of crops will have a cascading effect on the estimates of blue (irrigation) water requirement and, consequently, the perception of water scarcity in crop producing areas. There is the need, therefore, for best estimates of green water availability and consumption for different crops in different crop producing areas, based on best or most suitable models, to inform decisions or discussions on water scarcity and food security at large spatial scales.

7.2.2 UK Barley Yields are Projected to Increase under Climate Change

The results of the simulations described in Chapter 4 show that projected spring barley yields are substantially greater than the yields in the baseline period in all UK regions, time slices and under all emission scenarios (Figure 4-9). The greatest increase in yields occurs under the high emission scenario (HES) in the 2050s and the magnitude of the projected yields is considered as plausible. This finding suggests that climate change will likely have a net positive effect on barley yields in the UK and probably northern temperate environments. This finding is consistent with similar studies using barley in Denmark (Clausen *et al.*, 2011), Finland (Rötter *et al.* 2011), Germany (Manderscheid *et al.*, 2009), Ireland (Holden *et al.*, 2003) and Norway (Sæbø & Mortensen, 1996), or wheat in England and Wales (Richter & Semenov, 2005), Norway (Sæbø & Mortensen, 1996) and Europe (Semenov & Shewry, 2011).

This thesis has also shown that elevated atmospheric CO₂ concentrations ([CO₂]_{atm}) can substantially explain the variations in projected UK barley yields. Elevated [CO₂]_{atm} explained 30–80% of variations in projected yields of UK regions under all emission scenarios and time slices, and 30–50% of variation in projected UK yields (Table 4-9). While the direct effect of changes in individual climatic factors on crops can be readily understood, it is not clear what the net effect of their interactions, together with elevated [CO₂]_{atm}, would be. The findings in Chapter 4 suggest that elevated [CO₂]_{atm} would be important in reducing the effect of warmer temperatures and rainfall variability, as well as raising yields of barley across the UK. This potential role of elevated [CO₂]_{atm} in northern temperate environments has been reported in previous studies (Rötter *et al.*, 2011; Richter & Semenov, 2005; Holden *et al.*, 2003). Similar observations have been

made in China (Erda *et al.*, 2005). While elevated $[\text{CO}_2]_{\text{atm}}$ might have several positive effects on C_3 crops (Burkart *et al.* 2011; Robredo *et al.* 2011; 2007), more studies are required to understand its effects on crops over long time durations of exposure to inform adaptation planning. This is because acclimation to elevated $[\text{CO}_2]_{\text{atm}}$ can reduce the rate of photosynthesis to a level equal to or lower than the rate under ambient conditions (Erda *et al.*, 2005; Tang & Liren, 1998).

The results described in Chapter 4 also show that projected rainfall under all emission scenarios (Figure 4-4), regardless of the reductions from the 2030s to the 2050s and from the LES to the HES, will be sufficient for UK barley production. Generally, a reduction in ETc (Figure 5-4), as well as improvement in water productivity, was observed from the 2030s to the 2050s and from the LES to the HES. This confirms the belief that projected changes in temperature and elevated $[\text{CO}_2]_{\text{atm}}$ might increase radiation use efficiency, water use efficiency and photosynthesis in C_3 crops assuming there is no severe water stress and nitrogen is not limiting (Robredo *et al.* 2011; 2007; Manderscheid *et al.*, 2009). In this thesis, water stress was rare but soil fertility stresses were not considered in the simulations. It has been reported, however, that nitrogen stress could substantially reduce the positive effect of elevated $[\text{CO}_2]_{\text{atm}}$ on crops (Erda *et al.*, 2005). This indicates, regardless of models used, a need for future studies to incorporate an improved understanding of the effect of climate change and elevated $[\text{CO}_2]_{\text{atm}}$ on nitrogen dynamics and acquisition from soil by different crops in different environments. This is particularly important for barley as grain nitrogen content is a key determinant of quality for either animal feed or malting (Robredo *et al.*, 2011).

In this thesis, even though water stress was only occasionally encountered among the model variants, it still constitutes a potential risk to stable barley yields, especially in the East and South East English regions. Other important sources of risks identified include heat stress and saturated soil conditions (Section 4.4.3, Figure 4-11a, b). While barley can tolerate soil water deficit well, it can be vulnerable to heat stress in spite of elevated $[\text{CO}_2]_{\text{atm}}$ (Clausen *et al.*, 2011; Rötter *et al.* 2011). The adverse effect of heat stress on C_3 crops has been emphasized in previous studies (e.g. Clausen *et al.*, 2011; Rötter *et al.* 2011; Semenov & Shewry 2011; Richter & Semenov 2005; Fuhrer, 2003). In this thesis, however, anaerobiosis stress was found to be an equally important source of potential risk to barley yields (Section 4.4.3). Thus, future management of soil water should not be aimed at minimizing only the risk of deficit but also the risk of excess supply. In all, this thesis has shown that barley will remain a viable rain-fed crop in the UK under projected climate change.

7.2.3 Land, Not Climate Change, Will Limit UK Barley Production Capacity

This thesis has shown that UK barley production capacity will be constrained by reductions in the area of land allocated to barley production (Chapter 5) but not by climate change or water scarcity (Chapter 4). The large deficits in UK future feed barley supply suggested in Chapter 5 arise from projected reductions in the area of croplands in general and barley in particular in the face of increased demand due to increase in population and per capita demand (Tables 5-2, 5-7, 5-8). Feed barley demand increases by approximately 8.0 million, 8.6 million and 9.3 million tons in 2030, 2040 and 2050 respectively over that

in the baseline period (Table 5-1a, 5-8). Thus, the expected increase to satisfy projected demand is approximately three times the quantity used in the baseline period. Using barley yields under the HES (Chapter 4, Tables 4-6, 4-7 and 4-8), approximately 1.7 million ha of land will be required from 2030 to 2050 to meet the projected feed barley demand (Table 5-8). This implies additional 700 thousand ha of land over current area of land under barley production will be required by 2050 if the UK is to maintain a 100% self-sufficiency rate in feed barley supply (assuming total domestic barley produced is allocated to feed). Additional land would surely be required to produce malt barley (as a competitive end use) or wheat (as either a complementary or substitute feed grain). The question remains whether the UK would be able to allocate sufficient land for the production of barley or find alternative means to address the deficit.

In 2011, total agricultural land in the UK (including common rough grazing) was 18.3 million ha (Defra, 2011). Total utilized agricultural area (UAA, comprising arable and horticultural crops, uncropped arable land, common rough grazing, temporary and permanent grassland and land used for outdoor pigs) was 17.2 million ha, representing 70% of total land area in the UK (Defra, 2011). Of this, arable cropping accounted for 36%, distributed according to Figure 7-1. Of the cereals, wheat covered nearly 2.0 million ha (64%) whereas barley occupied 970 thousand ha (31.5%). Uncropped arable land (including uncropped set-aside land and all other arable land not in production, such as wild bird and game cover and land managed in Good Agricultural and Environmental Condition – GAEC12) was 156 thousand ha. Contrasting the current land use with the projected land requirement for barley, it becomes clear that it would be difficult to increase barley production through expansion of cropped area.

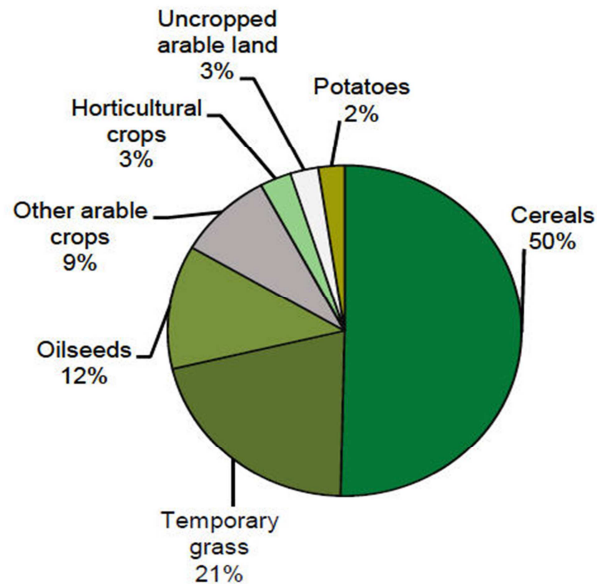


Figure 7-1: Distribution of total croppable land area in 2011. Figure taken from Defra (2011).

Croplands are projected to decrease not only in the UK (Thomson *et al.*, 2013; Angus *et al.*, 2009; Rounsevell & Reay, 2009) but also across the EU (European Commission, 2011; Rounsevell *et al.*, 2006) and the industrialized countries (Alexandratos & Bruinsma, 2012). As a result, it has been projected that, by 2050, the global area of cereals could suffer a net reduction of 28 million ha after adjusting for expansion in other regions (Rosegrant *et al.*, 2008). Analysis of the current global agro-ecological zones data suggests that the net balance of global prime and good arable land potentially available for agricultural expansion is about 1.4 billion ha, of which 960 million ha are located in developing countries (Alexandratos & Bruinsma, 2012; Fischer *et al.*, 2011). Africa and Latin America account for 450 and 360 million ha respectively (about 85%) of the 960 million ha located in developing countries (Alexandratos & Bruinsma, 2012; Fischer *et al.*, 2011). There is almost no prime or good arable land

remaining in many countries in the Near East and North Africa, South Asia, Central America and the Caribbean (Alexandratos & Bruinsma, 2012; Fischer *et al.*, 2011). This suggests that the UK, like many industrialized countries, might face *land scarcity* for crop production, which occurs when more than 60% of a country's prime and good arable land is actually cultivated (Alexandratos & Bruinsma, 2012). Moreover, because agriculture is the dominant land use in the UK (Angus *et al.*, 2009; Rounsevell & Reay, 2009) and Europe (Audsley *et al.*, 2006), changes in land use in the interest of climate change mitigation and energy security policy goals will likely affect crop production. In all, the potential land scarcity found in this thesis agrees with the conclusion of the Foresight Regional Case Studies R1 (*the UK in the context of North-West Europe*) that the most plausible effect of land use changes in the UK would be a net reduction in the area of croplands and production penalties (Pollock, 2011). Although allocation of land to a particular crop will be dictated by interaction of policy, profitability and domestic imperatives, this thesis has shown that projected reductions in land allocation to barley, rather than climate change, will be the key constraint to UK's future barley production capacity and self-sufficiency rate in feed barley supply.

7.2.4 Risk of Deficits in Feed Barley or Meat Supply

This thesis has shown that the UK faces risks of large deficits in feed barley and meat supply from the 2030s to the 2050s (Table 5-9, 5-10). The projected deficits in feed barley supply range from 7.2 to 9.8 million tons (Table 5-9) while the projected deficits in feed barley equivalent meat demand range from 1.7 to 2.4 million tons in the 2050s (Table

5-10). The deficit in meat supply is due to projected increase in population and per capita meat demand (Table 5-7) in combination with reductions in the area of land allocated to barley production (Table 5-2). Meat constitutes an important component of the UK diet or food balance sheet (FAOSTAT, 2009). However, aggregate meat production in the UK already lags behind aggregate demand, resulting in the import of 2.4 million tons of meat largely from the EU (Table 5-1b; Defra, 2011; FAOSTAT, 2009). This means the UK consumes the bulk of its locally-produced meat.

On the balance of such supply deficits and land constraint found in this thesis, the UK might have to rely on increased imports of either feed barley or meat to offset the deficits. The questions that need to be addressed are (1) where the imports will come from, (2) what the security of supply will be and (3) what will be the cost implications for domestic production and the consumer. First, the area of barley is likely to reduce in the EU in favour of biofuel grains (European Commission, 2011) and meat import to Europe, as well as animal feed, is projected to increase substantially in the future (Bruinsma, 2012; European Commission, 2011). This suggests uncertainties regarding the ability of traditional sources of imports to generate substantial surpluses (after satisfying their domestic demand) to sustain exports to the UK in future. Second, EU-level biofuel production might intensify competition for grains that can either substitute or complement feed barley unless second generation biofuel technologies become operational. Third, sustainability and regulatory pressures on livestock production in the EU might intensify to reduce the environmental footprints of meat production and consumption (Foresight, 2011). Fourth, globally, potential yield gains from climate change in notably northern temperate regions might be neutralized by losses in other regions (Alexandratos &

Bruinsma, 2012; Foresight, 2011; Rosegrant *et al.*, 2008; IPCC, 2007). Finally, overall global area of cereals might reduce substantially (Rosegrant *et al.*, 2008) while feed use of grains might also increase substantially in developing countries (Alexandratos & Bruinsma, 2012; Kruse, 2011), suggesting a potentially tight grains market. Overall, given the socio-economic importance of barley, it is likely that the UK would respond through appropriate domestic adjustments to moderate the risk of large deficits and its cascading effect on meat production. Such a response would help the UK contribute to future global food security substantially.

7.2.5 Rethinking Water Scarcity and Food Security

This thesis has argued that the conventional concepts of water scarcity (which are essentially based on the socio-economics of blue water supply) are not compatible with water availability and consumption in crop producing areas (Chapter 6, Section 6.2.1). To address this deficiency, the concept of ‘agri-compatible water scarcity’ was introduced and elaborated in Section 6.2.1. Due to the predominance of green water in crop production, it is appropriate to quantify the totality of water availability and consumption from all sources by a given crop at a given area and time. By so doing, water scarcity is rendered compatible with a specific crop over a given spatio-temporal scale. Throughout this thesis, it has been shown that green water is and will be sufficient, even under climate change, for barley production in the UK. It will not be exaggerating to extend this finding to the production of cereals in northern temperate environments.

The spatio-temporal scale in agri-compatible water scarcity is important as yield-limiting crop water stress can occur over either short time periods (within the crop growing season) or long time periods (due to meteorological drought) even at a conventionally water-rich location. It makes a difference when one says there is drought or water shortage in the UK, or in England or in South-East England. Similarly, potato and barley in the same environment will make different demands on water and respond differently to different degrees of soil water deficits. While at the moment, using a specific water scarcity indicator, the UK or a part thereof might be considered water-scarce, such water scarcity might not be entirely agri-compatible. For example, only about 2% of total UK water withdrawal is allocated to irrigation, mainly horticulture, in the driest parts of England and Wales (Knox *et al.*, 2010; 2009; Weatherhead & Howden, 2009; Weatherhead, 2008) where water scarcity issues are prominent (Charlton & Arnell, 2011). This suggests that demand for irrigation water during summer droughts in these parts of the UK can have profound localized effect on water resources and crop production (Hess *et al.*, 2011). Agriculture (largely cattle production) accounts for about 0.2% of blue water withdrawal in Scotland (Moran *et al.*, 2007). Hence, discussions on UK water scarcity and food security (or any other country) ought to be crop- and location-specific in order to be agri-compatible and meaningful. Moreover, water scarcity due to socio-economic constraints (economic water scarcity,) has little or nothing to do with food production as this type of water scarcity is caused by low investments in water resources development and not by agricultural withdrawals (Rijsberman, 2006). Therefore, the idea of agri-compatible water scarcity and the calculation scheme proposed (Table 6-1) to quantify crop- or catchment-specific water scarcity opens up opportunities for analyzing or

thinking about the effect of crop production on water scarcity and vice versa. Use of agri-compatible water scarcity will reveal the true extent of the effect of water scarcity on the production of specific crops or vice versa in a given area and time. This shows a need to match crops to suitable environments according to their physiology, water requirements and root systems to allow them to exploit water and nutrients in the soil effectively and efficiently. Agri-compatible water scarcity therefore draws attention to the need to incorporate soil and green water management in an integrated framework for water-food security and policy.

7.2.6 Rethinking the Role of Virtual Water in Policy

The concept of virtual water will continue to attract conflicting views regarding its relevance for policy. Progress in this debate might depend on defining what ‘policy’ is being considered, what are its goals and requirements and at what spatio-temporal scale it is being considered in order to determine the fitness of applying the concept of virtual water to a specific problem. Hitherto, these have been the missing elements in the debate which is too focused on water resource endowment or policy at national scale (Roth & Warner, 2007). In Chapter 6, it was shown that the primary purpose of food import is to serve food security needs, whereas savings in virtual water are only a secondary benefit (Figure 6-1, Section 6.2.2). However, food import can be necessitated or driven by several factors including water scarcity (Ramirez-vallejo & Rogers, 2010; Verma *et al.*, 2009; Roth & Warner, 2007). In the context of water scarcity, the proposed ‘agri-compatibility’ framework (Figures 6-1 and 6-2) can be used to analyze or understand the role of food

trade in ensuring food security and mitigating the effect of water scarcity on food security in the importing economy, as well as the effect on the water resources of the exporting economy. In the context of agri-compatibility, food import should be driven mainly by agri-compatible water scarcity and should serve water-dependent food security. Thus, the proposed agri-compatibility addresses or harmonizes the conflicting views by combining both the intensive and extensive dimensions of the virtual water concept (Allan, 2003).

It was argued in Section 6.4 that the application of economic or trade theories to the virtual water concept in order to explain the structure and flow of virtual water is inappropriate and would often yield undesirable result because both water (as a productive resource) and food do not bear a true economic cost or value. Moreover, whatever cost or value attached to water and food, and conditions of access to water for food production, will differ considerably between nations and over time. Further, food production or trade serves one or more of cultural, socio-economic and political purposes, which are consistent with food security goals (McIntyre *et al.*, 2009). Consequently, it is not surprising that the application of trade theories based on relative water endowments to virtual water often does not yield the desired results (Seekell *et al.*, 2011; Ansink, 2010; Ramirez-vallejo & Rogers, 2010; Wichelns, 2010a; 2010b; Verma *et al.*, 2009).

Agri-compatibility essentially shifts the focus of the policy debate from water (hydrocentricity, Bricchieri-Colombi, 2004) to food security goals by strengthening the practical and conceptual relationship between water availability and crop production. It enables the identification and quantification of water resource constraint to food production and the consequent import of food as a basis for distinguishing between agri-compatible and non-agri-compatible food import (or ecological and economic virtual

water flows, respectively). Moreover, it introduces a temporal aspect to virtual water analysis which is important with regard to crop production. That is, the virtual water concept could be temporarily applicable to a relatively water-secure economy in the event of, say, a severe drought. In that case, positive application of the virtual water concept becomes instrumental in transitioning from food insecurity to food security, a situation that has hitherto been neglected in virtual water analysis (Allan, 2003). Agri-compatibility, therefore, narrows and focuses the scope of application of the virtual water concept in order to expose its usefulness to water-food security policy. The agri-compatibility framework can be used to analyze the role of, or effect of water scarcity on a crop, the main driver of food import and the effect of food import on the water resources of the exporting economy.

7.2.7 Implications for Food Security and Policy

In this thesis, food security was defined as “*the risk of adequate food not being available*” (Chakraborty & Newton, 2011; Newton *et al.*, 2011). This thesis has shown that the UK faces the risk of large deficits in feed barley supply (Table 5-9) with a cascading effect on domestic meat production. Because meat constitutes a substantial source of calorie and nutrients in the UK diet (FAOSTAT, 2009), the projected shortfall in feed barley and meat supply will clearly have an adverse effect on food security. Altering demand for food in a consumerist-oriented world is difficult but not impossible (Gerbens-Leenes *et al.*, 2010; Ingram *et al.*, 2010; Kearney, 2010). Food demand and consumption levels can be altered through a suite of policy, legal and market instruments, as well as

public educational campaigns aimed at desirable behavioural changes (Gerbens-Leenes *et al.*, 2010; Kearney, 2010). For example, efforts can be made to keep per capita meat demand well below projected levels, ensure efficient use of meat or alter the composition of total meat consumption. Options for dealing with the projected supply deficits and their implications are discussed below.

Future increase in crop production is expected to arise mainly from productivity gains per unit area and the expansion of croplands (Alexandratos & Bruinsma, 2012; Pollock, 2011; Araus *et al.*, 2002). It was concluded earlier in this discussion that the ability of UK to expand the area of barley production in future would be limited (Section 7.2.3). Since the mid-1980s, declines in areas of croplands in high income countries have been more than compensated for by productivity gains per unit area and very intensive use of land (Alexandratos & Bruinsma, 2012; Pollock, 2011; Rounsevell *et al.*, 2006; Araus *et al.*, 2002). These mitigation options have sustained agricultural growth, lowered food prices and are likely to continue to 2050 due to increasing pressures on land (Alexandratos & Bruinsma, 2012; Pollock, 2011).

Apart from potential gains from climate change, there are opportunities for increasing barley yields per unit area and overall production through crop improvement, intensification and alterations in agronomic management practices (Pollock, 2011; Araus *et al.*, 2002). The same can be said of animal production where there is still scope for improving carcass yield per unit feed intake (Pollock, 2011; Godfray *et al.*, 2010). Assuming the projected maximum UK barley yield is raised from 8 tons ha⁻¹ (Table 4-8) to 10 tons ha⁻¹, together with the projected land area under the BAU or Mid+20% scenario (Table 5-2), it will almost neutralize the feed barley deficit. This yield increase is

achievable through a combination of conventional breeding (complemented with genomics and molecular techniques) and suitable agronomic practices (Pollock, 2011; Zwart *et al.*, 2004; Araus *et al.*, 2002). A yield of 10 tons ha⁻¹ has been observed in a field experiment with the genotype Westminster in South-east Scotland (Chapter 3, Table 3-6; McKenzie *et al.*, 2009). Obviously, even if this yield level is achieved, any reduction in the area of land for barley below the current level will result in a proportional production penalty. However, as indicated in Chapter 2 (Section 2.4), there are constraints and limits to the extent of genetic or physiological improvement and there is yet to be a compelling evidence for *sustainable* intensification in relation to biodiversity and ecosystem services. Cereal yields seem to have already plateaued in Europe and yields cannot be raised indefinitely even if other factors are not limiting (Brisson *et al.*, 2010). Nonetheless, given the socio-economic importance of barley and the scale of projected deficits, raising the yield of barley remains the most likely and viable option if the UK is to maintain self-sufficiency in feed barley supply.

Other measures could include exploring alternative production systems that require less land, upgrading low productive land uses to more productive uses, reducing the rate of degradation and loss of agricultural lands, substantially reducing food waste along the entire food chain, and using waste or by-products across production systems or sectors (Alexandratos & Bruinsma, 2012; Pollock, 2011). Shuffling around the components of current production might also help. For example, given the increasing preference for poultry, pig and processed meat in the UK (Defra, 2013; 2011) and the EU (European Commission, 2011), one can imagine that increasing poultry and pig production at the expense of other animals might help address the surging demand for meat in the UK. The

observed decline in the consumption of carcass meat (mainly beef and lamb) and preference for poultry (Defra, 2013; 2011) can have implications for future meat demand and production mix, and therefore feed grain demand. This is because poultry, for example, requires about 5 times less kcal of feed grain to produce a unit kcal of meat compared to beef cattle. However, the socio-economic consequences of this for the supply of, example, beef and dairy products and their related economic activities would require a careful examination. The implications for production cost due to, for example, bought-in feed (especially concentrates) and final price to the consumer equally require attention as the cost of feed has been rising steeply in recent years (Defra, 2011). Increasing grazed production might reduce dependence on prepared feed but this would require accepting a certain overall production penalty.

The UK could be exposed to several risks if it becomes a net importer of feed barley or its meat production capacity is substantially reduced due to unavailability of feed. Projections of world demand for meat and demand for grains for biofuel and feed (see Chapter 5, Section 1.1) suggest that future global meat and grain markets could be tighter. Across the EU, where the UK's imports largely come from, the UK is the 5th largest cereal producer (but with the 7th largest cereal area), second largest producer of poultry meat, the largest producer of sheep and goats, the 4th largest producer of cattle and 9th largest producer of pig meat (Eurostat, 2012). These statistics give a general impression of the UK's position and the scale of meat production and trade flows in the EU. A linear extrapolation might suggest that a future increase in import of grains or meat from the EU could be difficult (Section 7.2.4). Moreover, without substantial subsidies, UK and European agriculture could have a limited capacity to absorb increased costs and

regulatory burdens unless profitability remains high (Pollock, 2011). Demand for biofuel might also add to the pressure on croplands and grains that could complement or substitute feed barley (Rounsevell *et al.*, 2006). Consequently, the UK might have to import more from markets other than the EU and thereby expose its farmers to global competition where profitability is the key determinant of what and how much is produced. This will raise the additional challenge of sustaining a highly regulated agricultural system that delivers food and ecosystems services and remain globally competitive and profitable in the absence of trade barriers and other market distortion mechanisms. In the event of acute deficit in domestic production of feed barley or meat, availability and affordability could be contingent on the profit interest of supply chains and retailers. In this regard, uncertainties regarding global supply and demand of meat and grains for feed and biofuel, driven by competition, prices and asymmetric productivity and policies, would profoundly influence the stability of UK's future food security.

To reduce the insecurity of a potentially tight global supply, the UK can adopt measures to influence proactively regional or global food production and land use. There is considerable potential to increase food production in areas where there are yield gaps due to inefficient farming practices or where there is potentially available arable land for expansion (e.g. Eastern Europe and Africa; Alexandratos & Bruinsma, 2012; Pollock, 2011). From a global sustainability perspective, the UK can influence and drive genuine investments in research and development, development of functional markets and related services, as well as appropriate institutional frameworks and support services to increase productivity and effectiveness of land use governance in such areas. Whatever the future

turns out to be, the UK would remain an integral part of the global food system and the earlier these measures are employed the better it could be for the UK in the future.

7.3 Conclusions

This thesis evaluated water availability for barley production under future climate change and the effects on UK feed barley supply, food security and trade in order to examine the role and usefulness of the virtual water concept for policy. Like all futures analyses, the results of this thesis indicate a future possibility within the boundaries of the prevailing circumstances or assumptions employed. Therefore, within the limits of this thesis, and based on its findings, the following conclusions can be drawn.

One, the evaluation of the water-driven models using the RMSE and D-Stat (Chapter 3) showed that AquaCrop and WaSim performed excellently, while CropWat performed poorly in estimating the green water use of 10 barley genotypes. The seasonal water use simulated using WaSim was greater than that of AquaCrop which was greater than that of CropWat. These differences appeared to arise from differences in the sensitivity of the models to (a) crop development and (b) partitioning of rainfall. CropWat might not be suitable for estimating crop water use under Scottish or northern temperate environments. Even though WaSim performed slightly better than AquaCrop, AquaCrop is recommended for studying crop water use and the effect of water stress or climate change on yields, as it simulates canopy development more realistically and also incorporates atmospheric CO₂ concentration. The ten barley genotypes studied did not show substantial differences in their pattern of either daily or seasonal water use. The

consistency of this finding across the models and the canopy temperature profiles indicates that, under sufficient soil water supply, barley genotypes might not differ substantially in their water use in a northern temperate environment.

Two, future climate change would have positive effect on UK barley production. For all UK regions, barley yields were predicted to increase substantially over baseline yields for all time slices and emissions scenarios (Chapter 4). The magnitudes of increase in yield were greatest under the high emissions scenario (HES) in 2050 and lowest under the low emissions scenario (LES) in 2030. For all time slices and emissions scenarios, atmospheric CO₂ concentrations explained about 80% of variations in regional barley yields and 50% of UK national yield. This suggests that future increases in atmospheric CO₂ would be beneficial to the production of barley or C₃ crops in the UK and northern temperate environments. Even though barley would remain a viable rain-fed crop, the potential for occasional yield dips due to heat stress or soil water stress (from both deficit and excess) should be integral to the portfolio of risk management. Other biotic or abiotic stresses that might potentially reduce barley yields were beyond the scope of this thesis but would be worthy of consideration in future work.

Three, regardless of projected increase in UK barley yields, the UK faces a risk of large deficits in feed barley supply from domestic production from the 2030s to the 2050s (Chapter 5). This deficit translates, proportionately, to a large deficit in meat production. The deficit in feed barley supply arises from projected reductions in the area of land for barley production in the face of escalated aggregate demand for meat. This suggests that future feed barley capacity of the UK will not be limited by water availability or climate change but by land use change and increase in population and per capita meat demand.

Therefore, the total area of land allocated to barley production in the future will largely determine UK's self-sufficiency in feed barley supply and, for that matter, domestic meat production. The area of barley production will be determined largely by future policy goals regarding mainly energy and climate mitigation and, to some extent, market signals. Currently, the UK is self-sufficient in barley supply but a net importer of meat. Given the potential for land scarcity and the scale of the projected deficit, the options available to the UK include further increasing barley yield per unit area or carcass yield per unit feed intake, intensifying production, increasing imports of feed barley or the equivalent meat, slowing down increase in per capita meat demand and encouraging genuine investments to raise productivity and effectively govern land use where there is available arable land. Given its high agricultural capability, the UK could be expected to increase global food security rather than diminish it through large imports.

Finally, this thesis has shown that virtual water can be a useful tool in water-food security policy if properly applied (Chapter 6). However, its conceptual basis requires a refinement. To this end, agri-compatibility was proposed as a simple but powerful way to address the policy-deficiency of virtual water. Agri-compatibility better aligns the virtual water concept with water availability and consumption in crop producing areas on one hand and food trade on the other hand. The agri-compatibility framework allows not only the quantification of water-dependent food import but also the crop-specific impact on water resources at the location of production. By distinguishing between agri-compatible and non-agri-compatible virtual water flows in a given spatio-temporal context, agri-compatibility enhances understanding and evaluation of the role or usefulness of virtual water for water-food security policy in both water-scarce and water-rich countries.

Countries such as the UK can use the calculation scheme of agri-compatible water scarcity as a tool for environmentally responsible food import. In the case of countries in the position of the UK as shown in this thesis, it is probably helpful to begin to pay attention to *virtual land* (the area of land virtually saved which could have been used to produce a given quantity of a given food commodity that is imported). The agri-compatibility framework can be adjusted to analyze or isolate and quantify the virtual flows of scarce productive resources that are difficult to transport physically (for example, land).

7.4 Recommendations for Future Work

1. Due to constraints of data and time, the evaluation of the models (AquaCrop, CropWat and WaSim) employed limited calibration. For a crop like barley that has much wider geographic coverage, a robust calibration with multi-site and multi-temporal data is required. AquaCrop has limited calibration information on barley. Future work should therefore consider a robust calibration with locally-generated and multi-year data. Moreover, in wet environments, such as Scotland or the UK, drainage is important to estimating soil water balance and crop water use. Future work should test and compare the suitability of the drainage sub-models in these models.

2. The sensitivities of simulated crop water use to different phenophases employed by different crop growth simulation models should be explored in future work to identify effects on final estimate of crop water use.

3. The barley genotypes studied could be exposed to water deficit conditions to test the similarity in their water use under contrasting water availabilities.

4. Revised projections of atmospheric CO₂ concentrations, together with other climatic variables, as they become available, should be employed to assess the consistency of the findings described in this thesis.

5. There is a need to study the effect of climate change on both winter and spring barley production and how this will affect the scale of future feed barley deficits.

5. There is little information on agricultural land use futures in the UK and globally (Foresight, 2011; Angus *et al.*, 2009; Rounsevell & Reay, 2009). In this thesis, the current ratio of area of barley to total croplands was assumed to remain unchanged to 2050. Future work can focus on how much land could be available to a given crop given a matrix of production targets of several crops and areas of croplands under different land use change scenarios.

6. The proposed agri-compatibility framework requires further applications to different areas and crops to test its robustness for analyzing and understanding the role of virtual water in water-food security policy.

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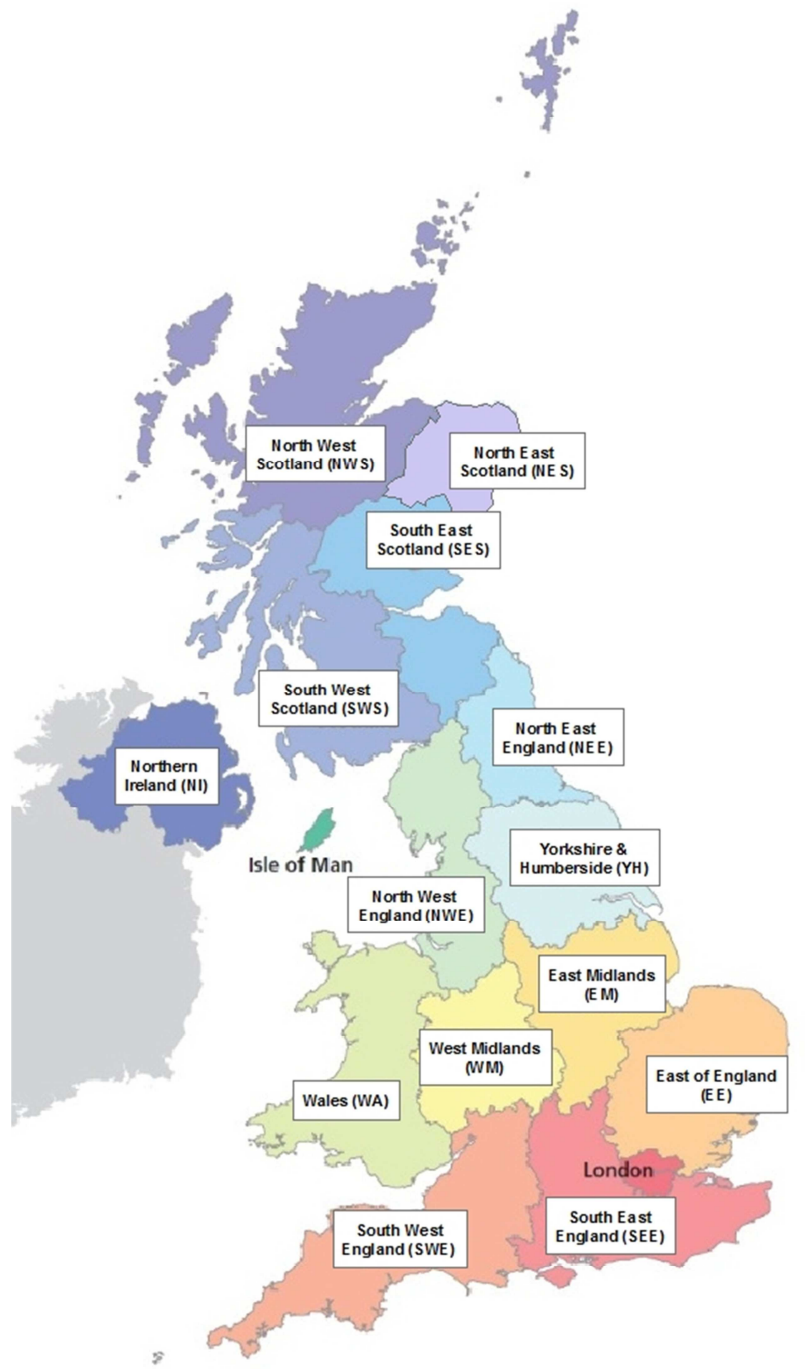
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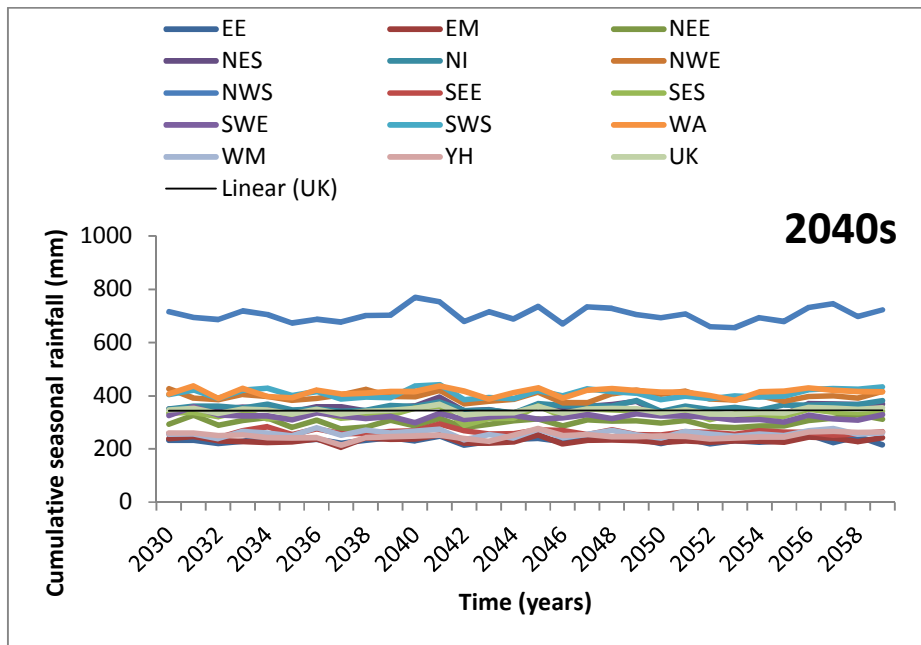
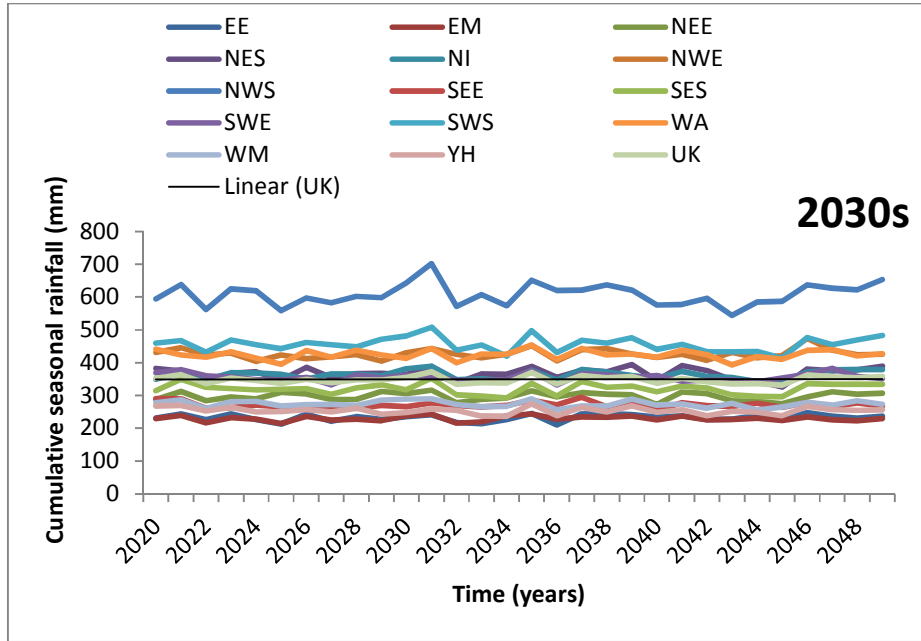
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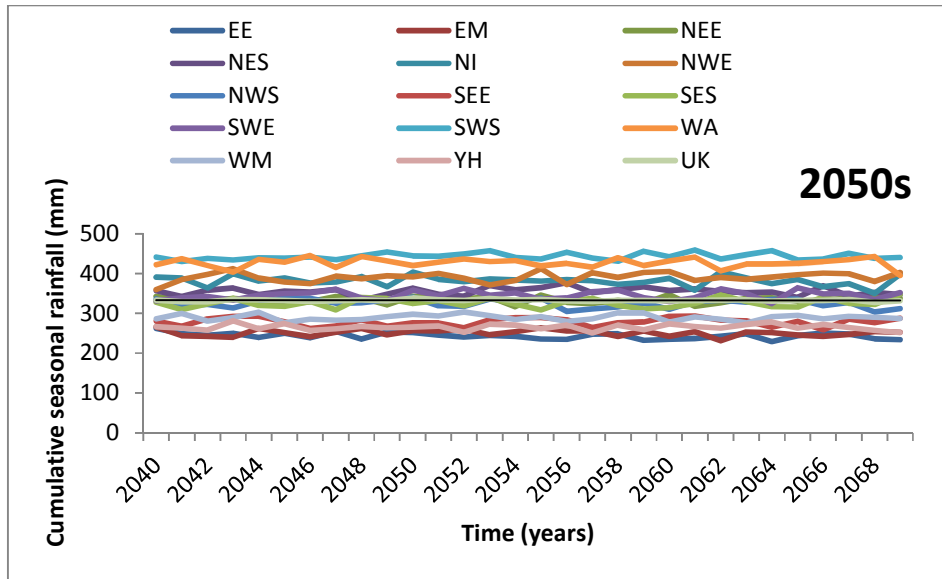
APPENDICES

Appendix 1: Geographic locations of the 14 UK administrative regions

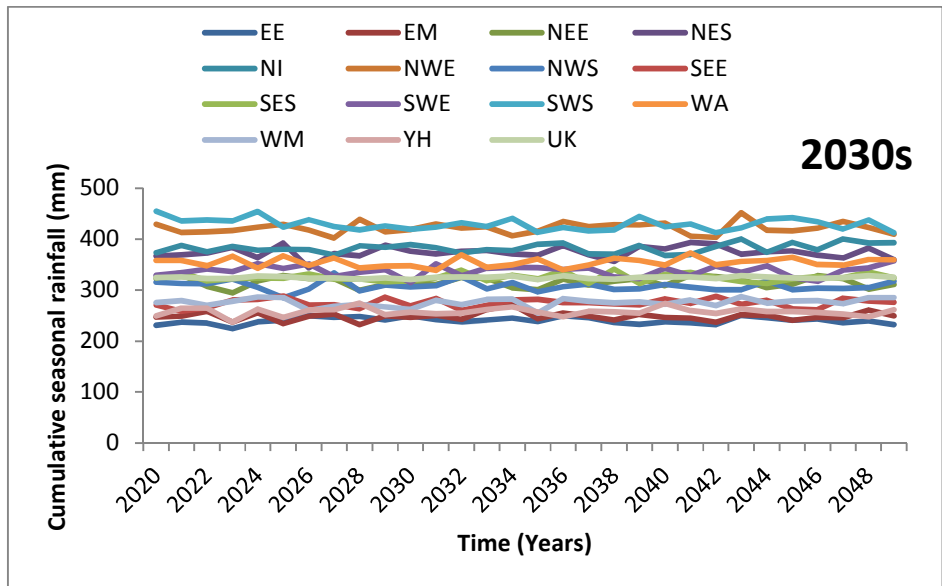


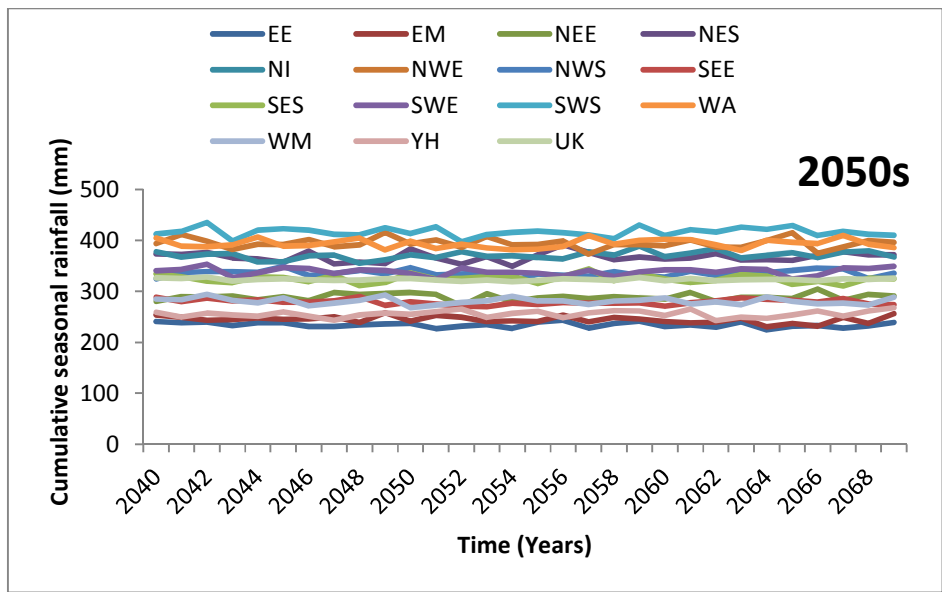
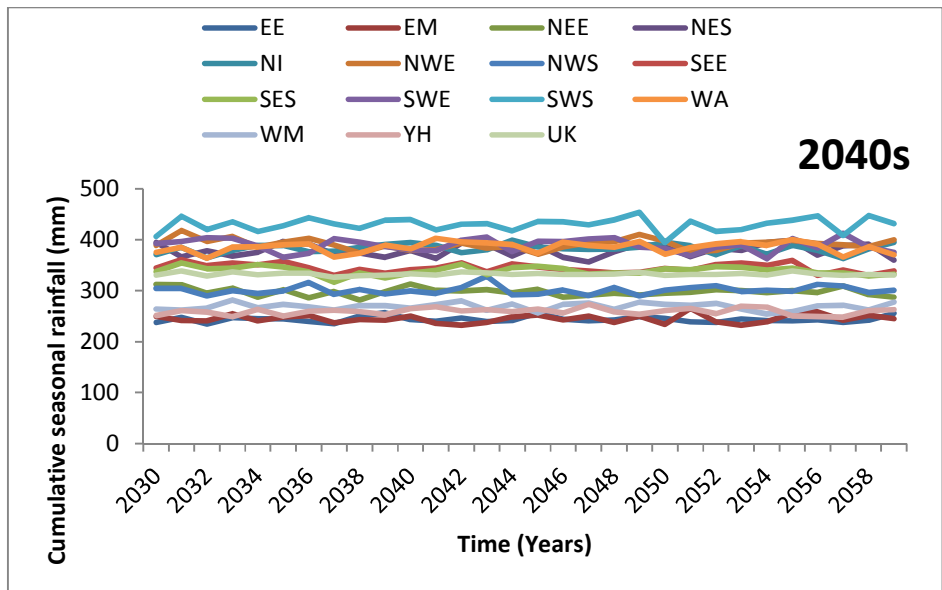
Appendix 2A: Temporal variations in total seasonal rainfall under the LES in the 2030s, 2040s and 2050s.



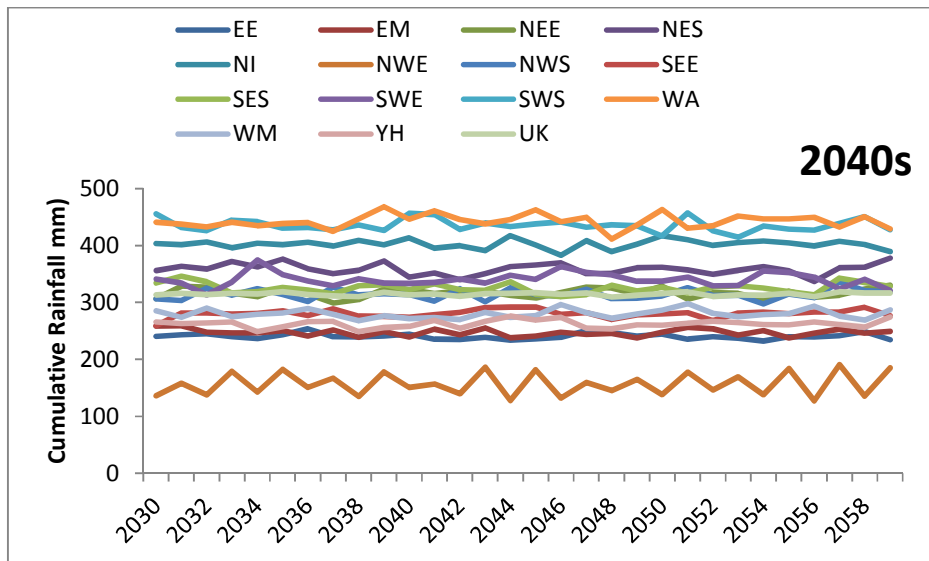
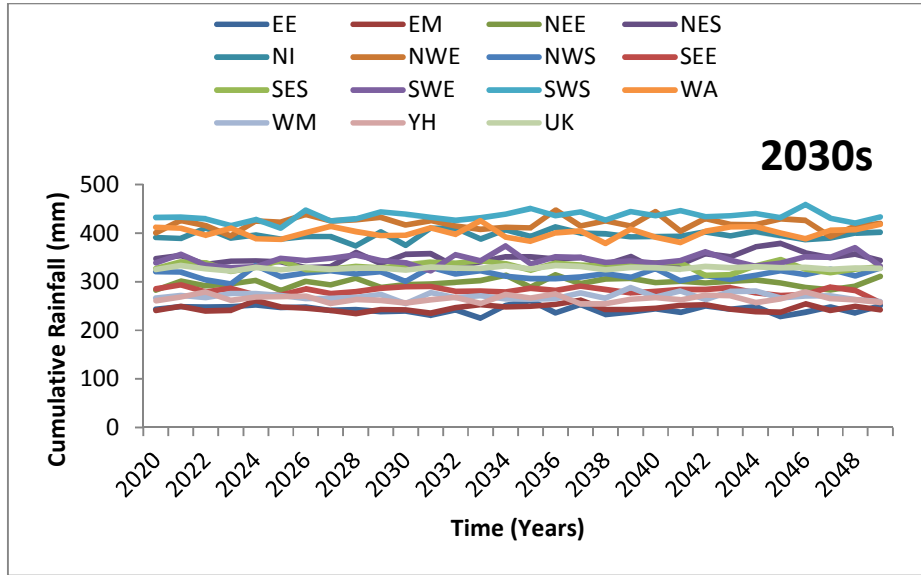


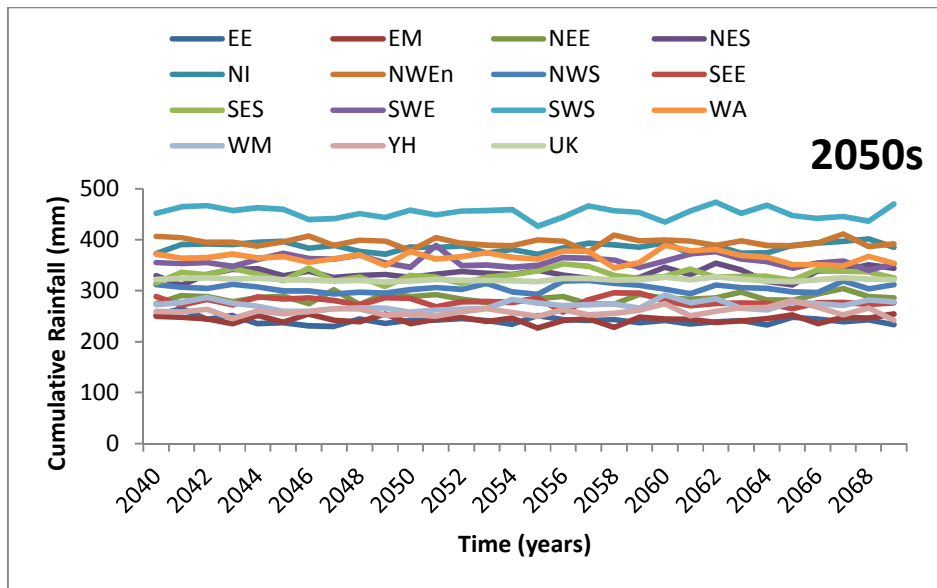
Appendix 2B: Temporal variations in total seasonal rainfall under the MES in the 2030s, 2040s and 2050s.



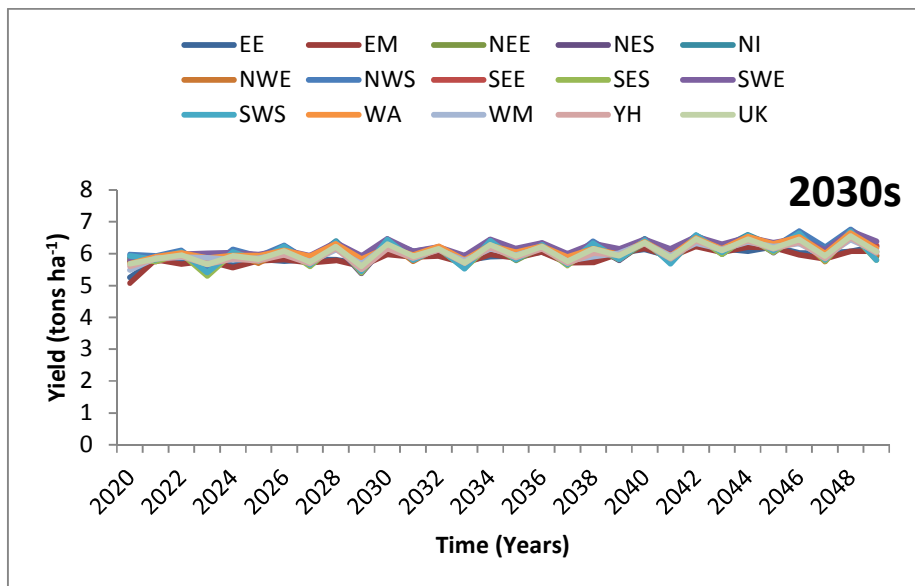


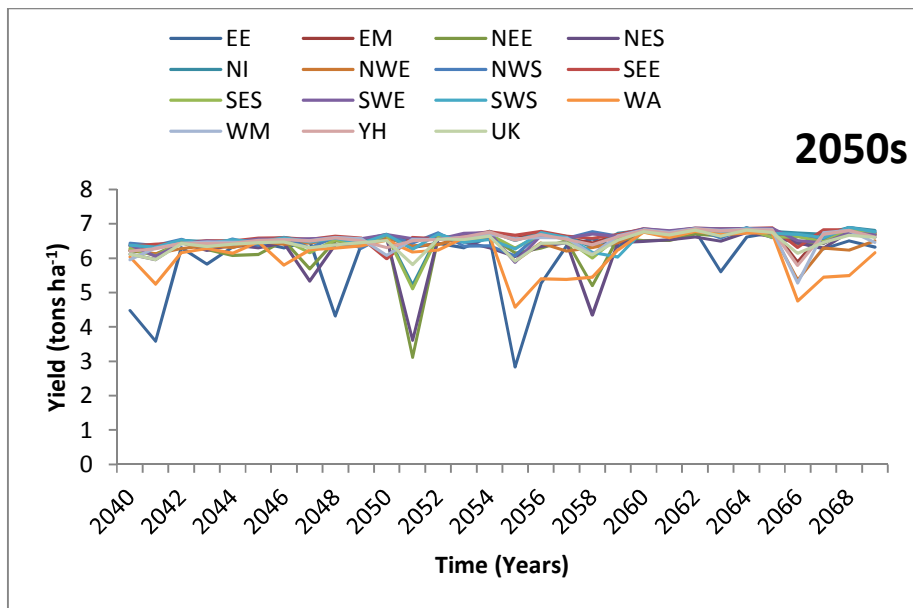
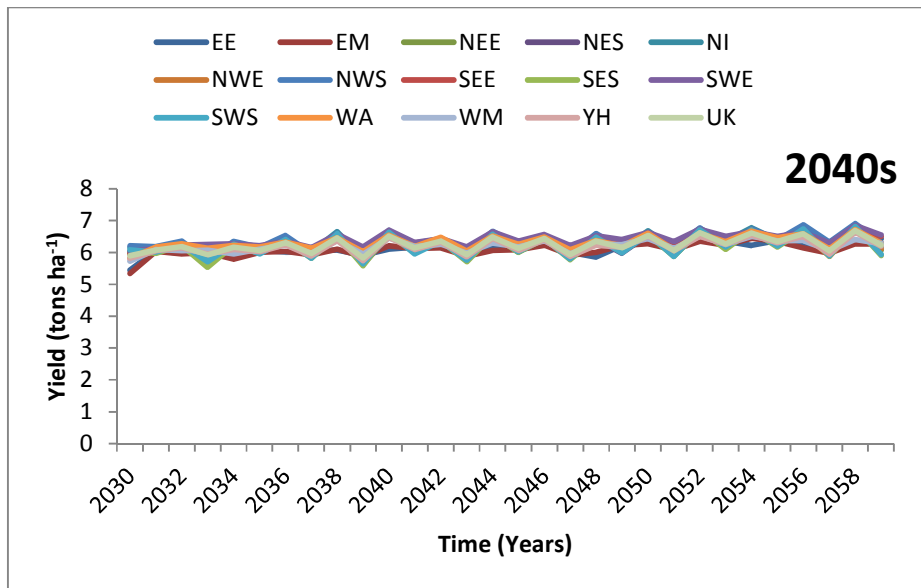
Appendix 2C: Temporal variations in total seasonal rainfall under the HES in the 2030s, 2040s and 2050s.



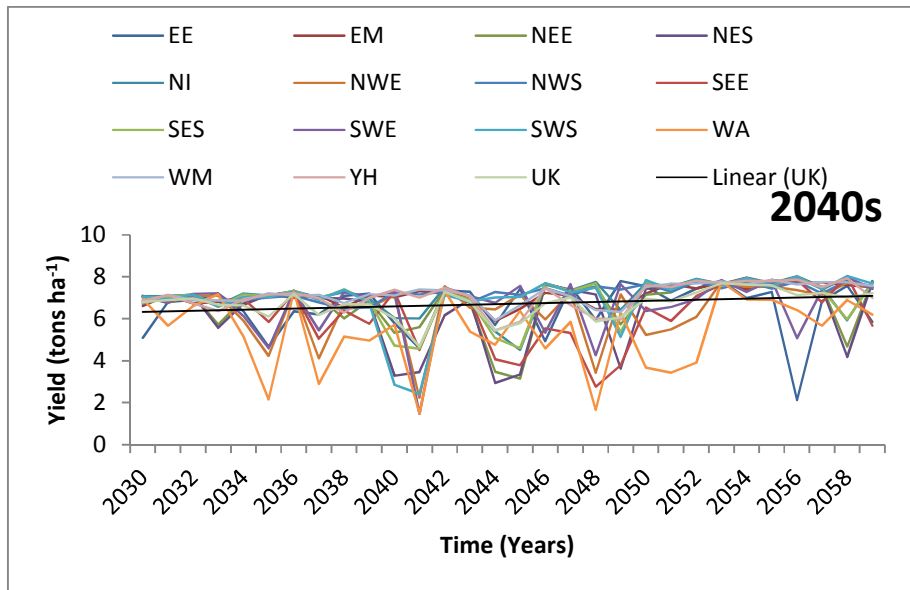
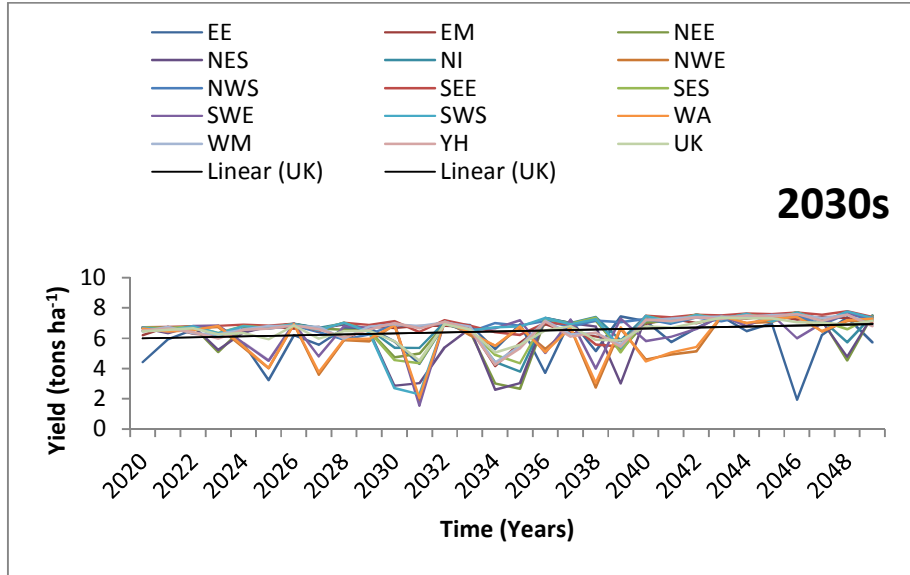


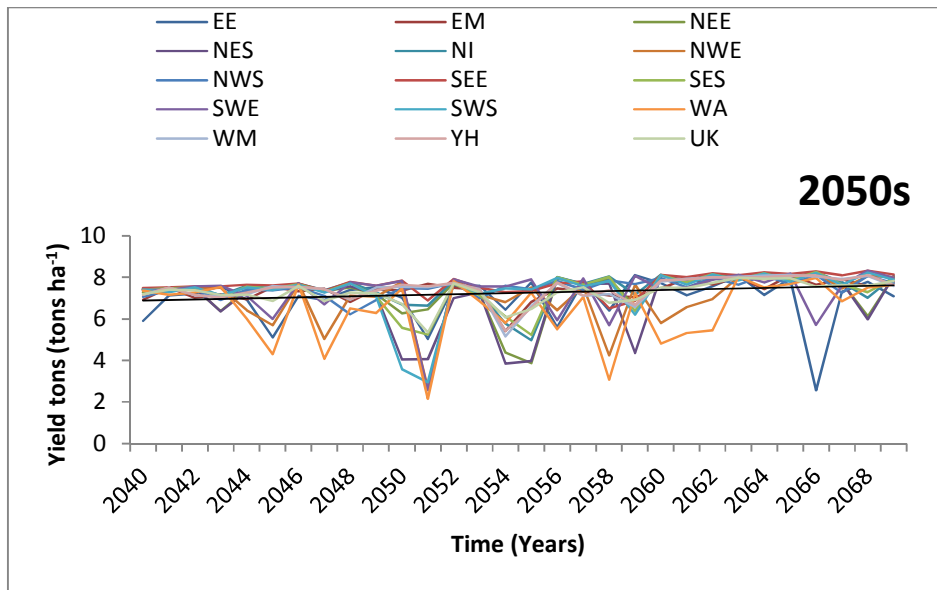
Appendix 3A: Temporal variations in yield under the LES in the 2030s, 2040s and 2050s.



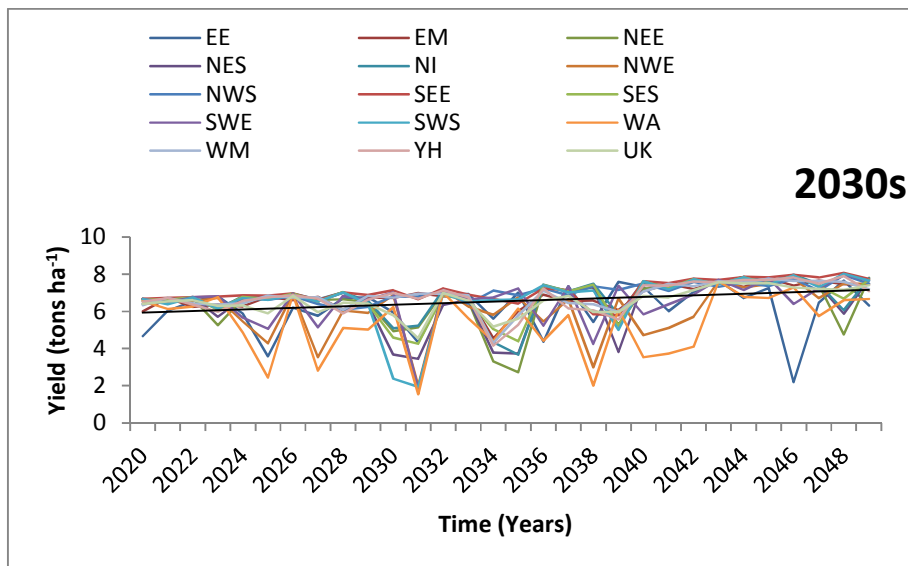


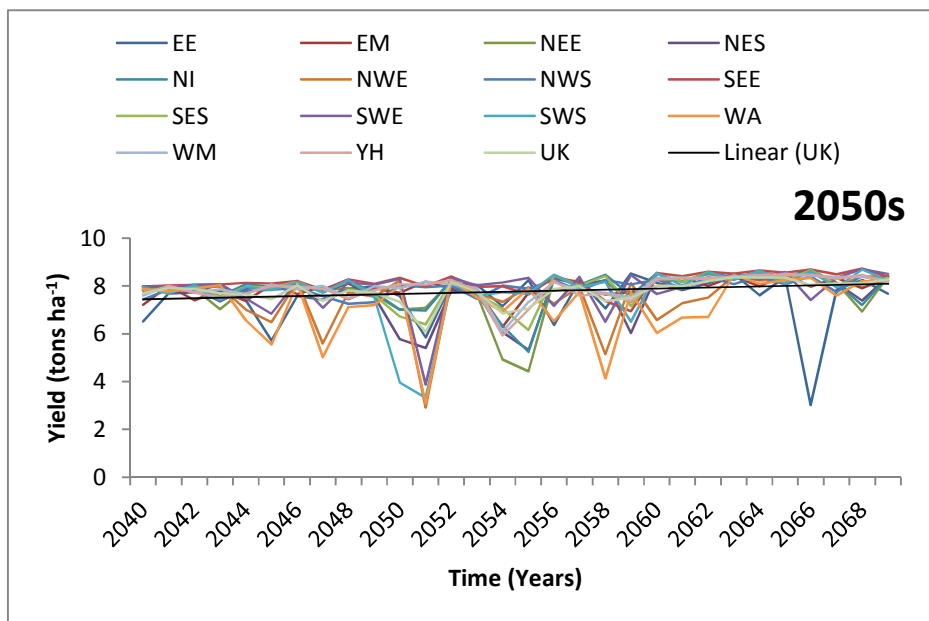
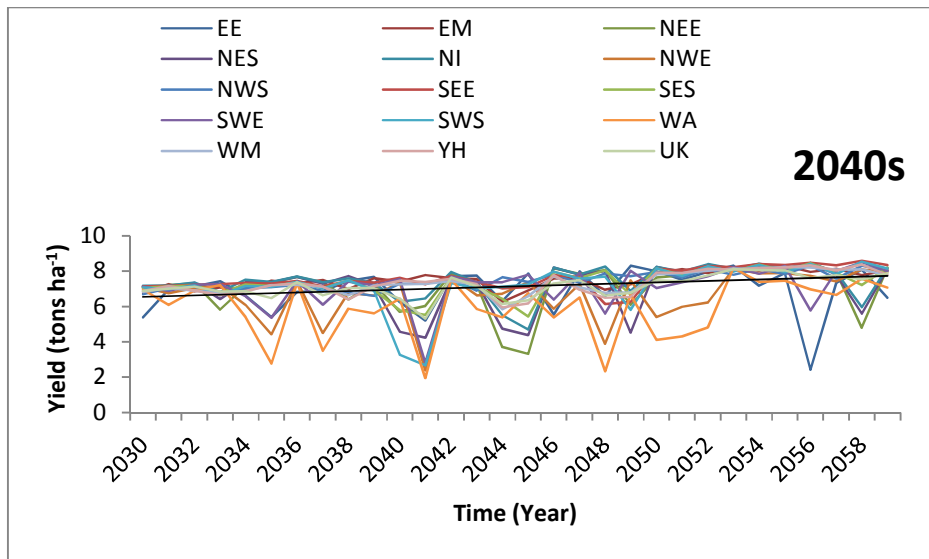
Appendix 3B: Temporal variations in yield under the MES in the 2030s, 2040s and 2050s.





Appendix 3C: Temporal variations in yield under the HES in the 2030s, 2040s and 2050s.





Appendix 4: Published paper.**Food security in a water-scarce world: making virtual water compatible with crop water use and food trade****David Oscar YAWSON^{1,2,3*}, Barry MULHOLLAND⁴, Tom BALL¹, Sushil Mohan⁵, Philip WHITE²**

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Abstract

Virtual water has been proposed as a mechanism with potential to reduce the effects of water scarcity on food security. To evaluate the role of virtual water in reducing the effect of water scarcity on food security, all components of the available water resource in agricultural areas must be quantified to provide a basis for evaluating food imports driven by water scarcity. We refer to this situation as ‘agri-compatible connections’ among water scarcity, virtual water, and food security. To date, this has not been captured in the literature on water scarcity, virtual water flows and food security. The lack of agri-compatibility has rendered the virtual water concept seemingly inconsistent with trade theories and water-food security policy needs. We propose two requirements for achieving agri-compatible connections: (i) the limit of crop production imposed by water scarcity should be captured by quantifying all components of the water available to satisfy specific crop water requirement in the importing economy, and (ii) food import should satisfy ‘water-dependent food security’ need, which is the actual or potential food security gap created by insufficient available water from all sources for crop production (all other things being equal). Further, we propose that agri-compatible water scarcity should capture three key elements: (i) a reflection of aridity or drought potential, (ii) quantification of all the components of water resource available to a given crop at a given locality and time, and (iii) use of crop- and catchment-specific water scarcity factors to evaluate the effect of crop production and virtual

water on water scarcity. In this paper, we show the conceptual outlines for the proposed agri-compatible connections. Achieving agri-compatible connections among water scarcity, virtual water and food security will enhance the analysis and understanding of the role of virtual water for food security in the importing economy and water scarcity in the exporting economy. We suggest that achieving agri-compatibility will improve the use of virtual water as a mechanism to reduce existing and future pressures on global food security.

Key words: water scarcity, food security, virtual water, agri-compatibility, crop water use

1. INTRODUCTION

Access to water and food is essential to human survival and is recognized as a fundamental human right (UN, 1948; Dubreuil, 2006). Water scarcity is however projected to be a key limiting factor to food production and development in the 21st century (WRI, 2003; UNDP, 2007). Many reports highlight the precariousness of global water security as water scarcity increases in scale and scope due to increasing demand for water (e.g. de Fraiture and Wichelns, 2010; Falkenmark et al. 2009; Falkenmark and Molden, 2008; Oki and Kanae, 2006). Projected changes in the global population, climate, economic growth and urbanization are expected to exacerbate water scarcity and further destabilize food security (Gregory et al. 2005). The economic theory of efficient allocation of resources tells us that as water becomes scarce, its allocation increasingly shifts from low economic-value activities (agriculture and other primary sectors) to relatively high-value activities (industrial and service sectors) (Ohlsson and Turton, 1999). This potential shift of water away from crop production raises concerns over the destabilizing effect of water scarcity on food security.

Food security is fundamentally linked to water availability for crop use as it is known that, on a global average, crop production is the largest water use sector (Thenkabail et al. 2010). Globally, the volume of water loss through crop evapotranspiration (ET) ranges from 6,685 to 7,500 km³ year⁻¹ (Thenkabail et al. 2010), accounting for over 70% of global water abstraction (e.g. de Fraiture and Wilchens, 2010; Hamdy et al. 2003; Yang et al. 2006). For example, in 2000, the global crop water abstraction amounted to 7,130 km³ (of which irrigation accounted for 2,630 km³) and total abstraction for domestic and industrial use was 877 km³ (de Fraiture and Wilchens, 2010). However, soil water deficit experienced under drought conditions during crop growing season is one of the major threats to achieving high and stable crop yields (Boyer, 1982; Rockstrom et al. 2009), making food security overly vulnerable to water scarcity (Liu, 2009). Water scarcity will, however, never be globally homogenous; it will always be geographically differentiated due to differences in climate and the management of different stocks and flows of water in the local hydrological system and differences in usage of water in economic activities.

To address the uneven distribution of global water reserves and increasing demand of water for food production, the movement of water through the trade of food commodities has been rationalised into the concept of virtual water. Virtual water refers to

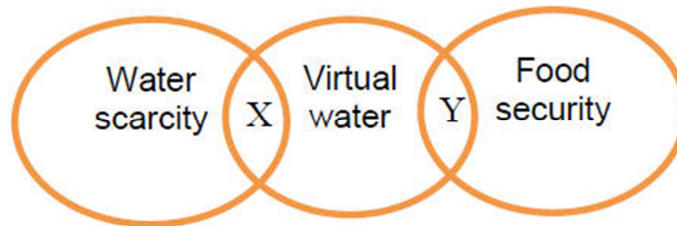
the volume of water used in the production of a unit crop commodity traded (Allan, 1998a, 1998b; 2003). The virtual water concept hypothesises that, by importing water-intensive food products from water-rich areas, water-scarce communities can offset local water scarcity and maintain food security (Allan, 1998a; 1998b; 2003; Yang et al., 2006; Liu et al., 2007; Aldaya, 2010a). It is this hypothesis that gives virtual water the potential to link water scarcity and food security through trade. Thus, importing food products saves the volume of water equivalent to the crop water requirement under the local conditions of production while augmenting domestic food security. Contrasted to engineering solutions, which move water to people, virtual water is an agro-economic mechanism that moves water embedded in traded food commodities from production sites to people in a water-scarce economy (Allan, 1998a). A large body of literature exists on virtual water, highlighting the utility of the concept as a potentially useful policy instrument for addressing the coupled problem of food-water insecurity (see e.g. Allan, 1998a; Hoekstra and Hung, 2005; Chapagain et al. 2006; Chapagain and Orr, 2009; Yang et al. 2006; de Fraiture and Wilchens, 2010). Virtual water is, therefore, now regarded as a key component of the options available to economies actually or potentially exposed to food insecurity as a result of water scarcity (Roth and Warner, 2008; Allan, 1998a).

Some studies (e.g. Ansink, 2010; Ramirez-Vallejo and Rogers, 2010) have, however, shown that some water-abundant countries import water-intensive crop commodities from water-scarce countries. Based on this evidence, these authors argue that food commodity trade is not motivated by water endowment and, therefore, the virtual water concept is insufficient for addressing policy requirements for improved food and water security. Wilchens (2010) also argued that virtual water does not offer sufficient insight for important policy questions regarding water security as it suffers conceptual limitations regarding relative water endowments and opportunity costs of production among trading countries. This paradox emanates from a lack of agri-compatible connections (or agri-compatibility) among water scarcity, the virtual water concept and food security (Figure 1). Specifically, the water scarcity considered excludes some components of the water resource (mainly soil water) in crop producing areas and its evaluation is entirely from an economic perspective.

Virtual water is a dual concept that has a crop-water use component and a trade component. The two parts, however, require detailed examination so that the ability to match sustainable water use to food security can be evaluated accurately. In this paper, we concentrate on the crop specific elements of virtual water. We promote the concept that agri-compatibility is required to understand the link between water scarcity and food security through the movement of virtual water and to render virtual water more amenable to water and food security policy. To date, this has not been attempted and this paper proposes to show the requirements for agri-compatible connections by (i) demonstrating the need for such agri-compatible connection, (ii) providing a formula for calculating crop- and catchment-specific water scarcity (iii) showing the use of agri-compatible water scarcity in the evaluation of the effects of virtual water movements on water and food security.

Definition of Terms

Agri-compatibility: refers to the condition in which food is imported to fill the food security gap created by insufficient aggregate water supply from all relevant sources to satisfy the water requirements of crop production in the importing economy. The idea of agri-compatible connections is illustrated below.



X = agri-compatible water scarcity

Y = water-dependent food import

Agri-compatible water scarcity: insufficient water availability from all relevant sources (blue, green, grey) to satisfy the water requirement of a crop or crops at a particular area.

Water-dependent food import: import of food to fill potential or actual food security gap resulting from insufficient water from all relevant sources to meet the water requirement of crops.

Figure 1: Definition of terms

2. FOOD SECURITY

Food security must necessarily refer to a state in which the food system is secured. Food systems include production and related supply chains of commodities and foods in the production-consumption nexus (Gerbens-Leenes et al. 2010; Gregory et al. 2005). Food security is complex as a number of biophysical and socio-economic factors interact in dynamic and complex ways to affect food systems that underpin food security (Gregory et al. 2005). Food security is generally defined as “availability of and assured access to sufficient food that is nutritionally adequate, culturally acceptable, safe and which is obtained in socially acceptable ways” (Gorton et al. 2009). The most widely used definition of food security emerged from the World Food Summit (1996): “*food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*”. The components of food security are availability, accessibility, utilization and stability of access (FAO, 2006).

The preceding definitions of food security reveal little of the issue of food crop production, but the ability to supply food relies on the availability of harvested food crops produced domestically or imported. In this paper, food security is equated to food availability in sufficient quantity to satisfy the dietary requirements of a given population and is understood to have a specific spatio-temporal context. Water is a key factor that links crop system productivity with food availability. Consequently, domestic food

production to satisfy food security is subject to the constraint of water availability but food security is achievable through domestic production or import.

3. WATER SCARCITY

Water used in crop production is classified into three main colours: blue, green and grey (Chapagain and Orr, 2009). Blue water refers to groundwater and surface water (streams, lakes, rivers, dams) available for human use that is introduced into crop production systems through irrigation. There is greater competition for blue water from all water use sectors compared with the other water colours. Green water refers the fraction of precipitation that infiltrates and remains in the unsaturated zone of the soil after drainage and is available for crop evapotranspiration. Grey water represents recycled water that is used in crop production after treatment. In assessing the effect of crop production on water availability, grey water is defined as the water required for diluting pollutants from agro-chemical inputs in crop production (Chapagain and Orr, 2009). These definitions, however, leave out or mask the use of rainfall harvesting by collecting runoff or by direct interception from roof for crop production (but the latter is also used to augment domestic water use in developing countries) and desalinated water that can potentially be used in agriculture. Perhaps, these can be referred to as ‘yellow water’ and ‘red water’ respectively. We label the former ‘yellow’ water because, in terms of crop production, it is considered to be at the interface between blue and green water (Wisser et al. 2010; Hoff et al. 2010); and the latter ‘red water’ because it is expensive and difficult to obtain, particularly in terms of energy consumption.

3.1 Types of Water Scarcity

According to Rijsberman (2006), an individual who is unable to access safe and affordable water to meet personal basic requirements is said to be “water insecure”. An area is “water scarce” when a significant proportion of the population become water insecure for a prolonged period. In the European Environment Outlook (2005), water scarcity is defined as the incidence of insufficient water resources (as a result of low availability or demand exceeding the supply capacity of the natural system) to satisfy long-term average requirements. Rockstrom et al. (2009) state that ‘water scarcity is a general collective term used when water is scarce for whatever reason’. In this paper, water scarcity is defined as insufficient water availability from all sources to satisfy long-term average crop water requirement.

A distinction exists between economic and physical water scarcity. Physical water scarcity refers to inadequate quantity of available water to satisfy demand or water requirement. Economic scarcity or social water scarcity relates to constrained access to water as a result of limited investment in water infrastructure or socio-economic constraint (Rijsberman, 2006). A third type of water scarcity, hybrid water scarcity, relates to a combination of physical and economic scarcity where over-abstraction combines with limited socio-economic adaptive capacity. Ohlsson and Turton (1999) argue, however, that these are not distinctive types of water scarcity, but progressive orders or levels which are emergent from immediately lower orders. Thus, physical scarcity is first order scarcity. An effort to resolve this scarcity, through engineered systems to augment supply, leads to

the emergence of a second order economic type scarcity. Addressing a second order scarcity through enhanced water conservation and use efficiency leads to the possibility of a third order scarcity which is a combination of physical and economic scarcities and signals a shift in water allocation from low-value to high-value use. It can also be argued, however, that economic scarcity can be first order scarcity which, when resolved, can lead to the second order physical scarcity. Rijsberman (2006) provided a comprehensive overview of water scarcity indicators, discussing their merits, demerits and potential uses. On the basis of computational approaches and inherent assumptions, three broad types of water scarcity indicators can be distinguished: withdrawal to availability ratio, per capita water availability, and hybrid water scarcity indicators.

3.1.1 Withdrawal to Availability Ratio

This indicator compares water withdrawal with the renewal capacity of a watershed or natural system of a given geographic area. A widely used method for calculating scarcity is the Water Resources Vulnerability Index (WRVI) developed by Raskin et al. (1997). This technique computes scarcity as the proportion of total annual withdrawal to total available water resources. When annual withdrawal is 20-40% of renewable water supply, the region suffers water scarcity. When the value is above 40%, the region suffers severe water scarcity. Other approaches include the criticality ratio (Alcamo et al. 1997) which is the quotient of water withdrawal to total renewable water supply. A value of 0.4 indicates high water scarcity. Similar methods of calculating water scarcity can be found in Vorosmarty et al. (2000), Alcamo et al. (2003), and Oki and Kanae (2006). Another variant is the Water Exploitation Index (WEI) which is used to gauge water scarcity in Europe (European Environment Outlook, 2005). The WEI is the quotient of total water abstraction and the long term annual average water resources. A WEI value of 0.2 is the threshold that indicates water scarcity. A value higher than 0.40 indicates severe water scarcity.

3.1.2 Per Capita Water Availability

This category of indicators presents the amount of water potentially available to an individual in a given population that depends on a given amount of water resources in a particular geographic area (Rockstrom et al. 2009). An example of such a method is the Falkenmark indicator (Falkenmark et al. 1989). The Falkenmark indicator is commonly used because it is easy to measure and is readily understandable and meaningful, even though it also has certain limitations such as masking variability across spatial-temporal scales, infrastructural capacity and demand due to differences in socio-economic contexts (Rijsberman, 2006). According to the Falkenmark indicator, a country is suggested to suffer water stress if its per capita annual renewable water supply (surface water and groundwater) is less than 1700 m³, water scarcity if its per capita available water is 1000 m³ or less, and absolute scarcity when its per capita water availability is less than 500 m³. It is easy to deduce from this indicator that an increase in population automatically increases water scarcity as the same amount of water circulates within the local hydrological cycle.

3.1.3 Hybrid Water Scarcity Indicators

Hybrid indicators combine physical and economic water scarcity into a single value. Examples include the water poverty index (Sullivan, 2002) and the social water stress index (SWSI) (Ohlsson, 1999). Ohlsson (1999), for example, generated the SWSI by weighting the Falkenmark indicator using the United Nations Development Program (UNDP) human development index and, thereby, incorporated social adaptive capacity (Rijsberman, 2006). Seckler et al. (1998) incorporated social adaptive capacity into their analysis to distinguish physical water scarce countries from economic water scarce countries.

4. TOWARDS AGRI-COMPATIBLE VIRTUAL WATER

4.1 Scope for Agri-compatibility

Currently, any reference to water scarcity is arbitrarily linked to food insecurity and any food import qualifies as virtual water. This limits the utility of virtual water for addressing specific water and food security policy. We therefore present and elaborate a framework for agri-compatible virtual water (Figure 2).

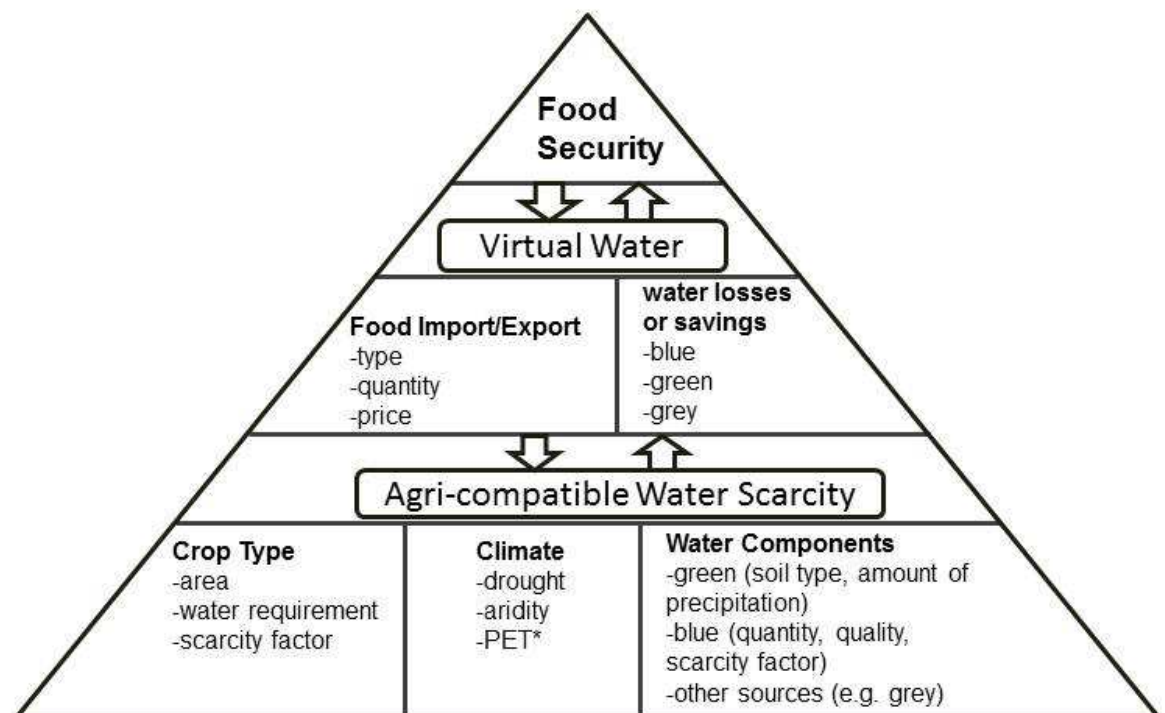


Figure 2: Agri-compatible framework for understanding the role of virtual water in achieving food security in a water-scarce community. The base of the triangle captures the elements of agri-compatible water scarcity which limits crop production and necessitates food import (virtual water). The apex of the triangle shows food security achieved through virtual water. Conversely, food security, achieved through virtual water, also affects water scarcity in the crop production area from which food crops are imported.

* Potential Evapotranspiration

Current methods of calculating water scarcity are not compatible with environmental water availability for crop production and therefore do not reflect crop water scarcity. These methods are limited by the following factors: i) current water scarcity indicators are based on blue water and socio-economics but do not capture green water availability and use, as well as yellow water or the possibility of red water use. The potential of deep groundwater as a buffer has received scant attention (Koehler, 2008); ii) increasing water scarcity in a certain area may have a high potential to cause a shift in water allocation from agriculture to non-agricultural uses even though the contribution of actual crop water use to overall water scarcity is rarely considered; iii) it is rare to include climatic variables such as temporal changes in precipitation which is critical for crop performance; iv) not all water scarcities are of significance for crop production, e.g. economic water scarcity has little relevance for rain-fed agricultural systems; (v) the scale of analysis is often too coarse to reveal important spatial, temporal and socio-economic differences within a given country, region or catchment.

Figure 2 shows that virtual water can be used as a mechanism to bolster food security while offsetting water scarcity in an importing economy, but can also affect water scarcity in the exporting economy. Figure 2 shows the two requirements for evaluating agri-compatible virtual water estimates. One, water scarcity must be agri-compatible, the other, food importation should serve “*water-dependent*” food security requirement (Aldaya et al., 2010b). Water-dependent food security refers to actual or potential food security gap created by insufficient available water from all relevant sources for crop production (all other things being equal) to meet food security requirement.

4.2 Agri-compatible water scarcity

Agri-compatible water scarcity refers to insufficient water availability from all relevant sources to satisfy crop water requirement to the extent that food security is undermined. The components of agri-compatible water scarcity (crop type, climate and water components) are shown at the base of Figure 2. Existing water scarcity indicators give useful information on water availability for use by human populations. There is, however, relatively scant information on the link between water scarcity for food production and security. For water scarcity to be meaningful for virtual water and food security, the concept must be agri-compatible. In other words, water scarcity should be analysed through agricultural systems and expressed in terms of normal water balance concepts and the role of imported food commodities in the food balance sheet and water consumption in the importing economy. Agri-compatible water scarcity, therefore, accounts for the totality of environmental water availability (green, blue and other sources) and consumption in relation to specific crop water requirement (CWR) at a particular place and time. CWR, usually equated to crop evapotranspiration, is a function of climatic and weather conditions, soil properties, agronomic practices and crop factors. As a result and due partly to differences in crop water use efficiency (amount of water used per unit yield), crops can suffer genotype-specific water scarcity under the same production conditions. Agri-compatible water scarcity should capture three elements as discussed in the next sub-sections.

4.2.1. Aridity and Drought

Aridity describes the extent of dryness of the atmosphere, in terms of the relationship between precipitation and potential evapotranspiration (PET), of a given agro-ecosystem (Rockstrom et al. 2010). In arid agro-ecosystems, PET exceeds effective rainfall, spatial-temporal variability of rainfall is high and drought and dry spells are frequent (Rockstrom et al. 2010). The occurrence of seasonal and intra-seasonal water deficit for crops is therefore high and frequent, underscoring a high potential for physical water scarcity. Drought is a temporary shortage of water, over periods of months to few years, due to below-normal precipitation (Dai, 2011). The occurrence of drought during the growing season of crops can ultimately impair crop growth and yield if not addressed.

While aridity is a permanent climatic feature of certain geographic regions, periodic and seasonal drought is common in many crop production areas of the world. Drought is a complex abiotic stress and difficult to predict because of the interaction of multiple factors related to crop, climate, soil and agronomic practices (Richards, 2006). Assessment of the effects of drought on yield is further complicated by the varying effectiveness of different crop response and adaptive mechanisms, the time of incidence in the crop cycle and the severity of the drought. Under rain-fed systems, drought can seriously decrease yield and can necessitate food import even though some crops have a physiological capacity to maintain high plant water status and minimize yield loss under short term water stress conditions (Blum, 2005). Aridity and drought increase CWR and increases the need for irrigation. These features make virtual water particularly relevant for regions with arid and semi-arid agro-ecosystems due to the high potential for agri-compatible water scarcity. Thus, in evaluating virtual water flows, it is important to consider the contribution of aridity and drought to water scarcity for crop production and, consequently, food import.

Allan (2000) argues that virtual water is particularly effective and efficient in addressing *progressive and occasional local agricultural drought*. Drought can compel a relatively water-secure economy to restrict food export and increase food import in order to maintain food security. Consequently, agri-compatible water scarcity estimates should reflect the effectiveness of the climate and weather in relation to the specific water requirement and phenology of a particular crop in a given area and time. Understanding the environmental effects of periodic and seasonal drought on crop yield response constitutes a more rigorous basis for evaluating the significance of virtual water for food security and water savings.

Cereal grains have the largest water use in global crop production, can fail due to seasonal drought and are the most traded crop commodity (Yang et al. 2006). World crop water use was over 7000 km³ in 2000 (Figure 3a), of which cereals accounted for 57% (Figure 3b). Cereals also accounted for over 70% of total crop water use in the Middle East and North Africa (MENA) region in 2000 (Figure 3b). The higher aridity of the MENA region largely accounts for the high irrigation water requirement of cereal production (de Fraiture and Wilchens, 2010; Allan, 1998a; 1998b), giving rise to agri-compatible water scarcity. Not surprisingly, cereals constitute the largest food import to

the MENA region. According to de Fraiture and Wilchens (2010), in 2000, Egypt alone imported 8 million tonnes of grains from the USA. As a result of the grain import, Egypt saved 8.5 billion m³ blue water which could have been used to produce the imported grains (de Fraiture and Wilchens, 2010). Evaluations of virtual water show that the higher import of cereals and grains to the MENA region serves the purpose of water-dependent food security (Allan, 1998a; 1998b) as water availability is limited substantially by aridity. Therefore, it is important that the analysis of agri-compatible water scarcity incorporates a ‘climate’ factor that reflects the effect of aridity or drought potential.

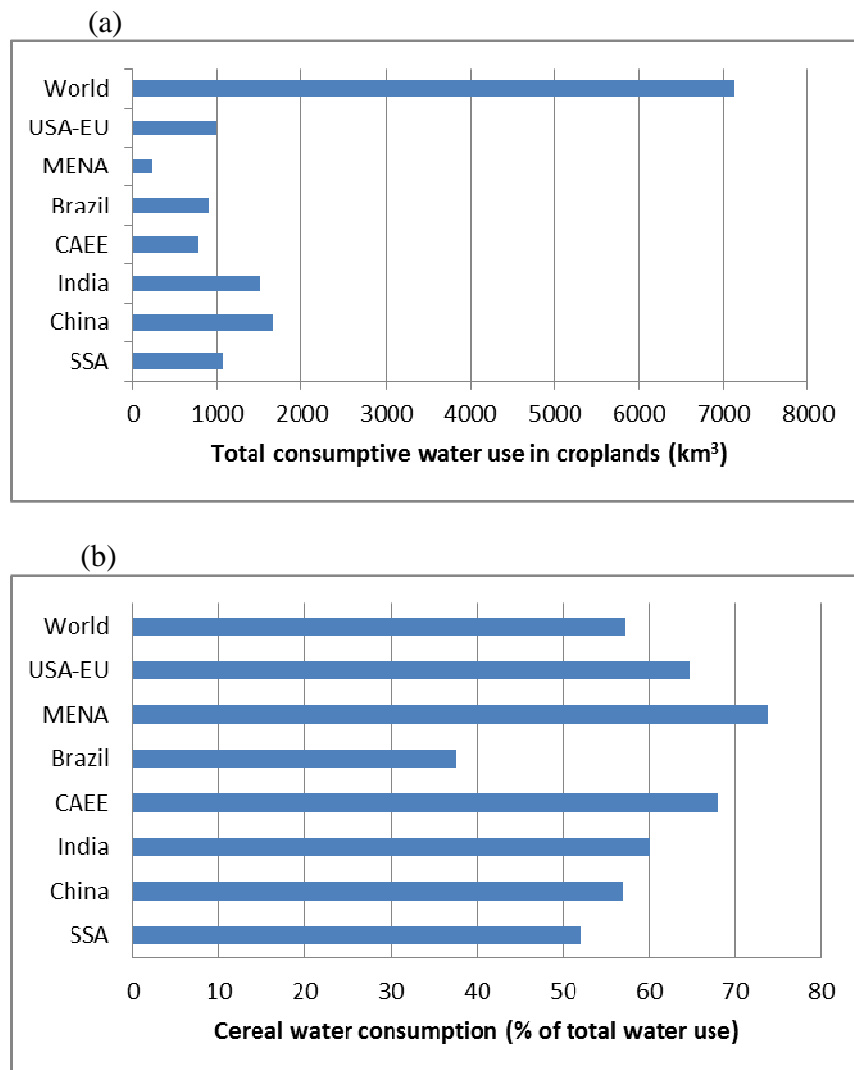


Figure 3: (a) Total crop water use in the world and selected major crop production regions in the year 2000 and (b) water used by cereals as a percentage of total crop water use in the world and selected major crop production areas in 2000. Data from de Fraiture and Wilchens (2010). MENA, CAEE and SSA denote Middle East and North Africa, Central Asia and Eastern Europe, and Sub-Saharan Africa respectively.

4.2.2 Green and Blue Water Availability

Green and blue water are the main components of water resource that serves specific crop water requirements in crop producing areas, even though other components may exist in some other crop producing areas. A number of studies highlight the dominance of green water in global crop production by indicating that green water consumption is about 4-5 times higher than blue water consumption (Hoff et al. 2010; Aldaya et al. 2010b), yet green water volumes and consumption are rarely estimated (Hess, 2010). Hoff et al. (2010) suggest that two-thirds of global precipitation is stored as green water while the remaining third is blue water. Even the MENA region, which depends largely on irrigation, meets 50% of their total crop water requirement from green water, either in rain-fed agriculture or from precipitation over irrigated land (Hoff et al. 2010).

Rockstrom et al. (2009) showed that global water scarcity for crop production can be significantly diminished when green water is properly sourced and managed. Liu and Yang (2010) undertook a spatially-explicit assessment of global green and blue water use on croplands and pasture fields. Their work demonstrated that high water use occurs in China and India, the southern part of West Africa, the mid-belt of USA and parts of South America. However, while blue water use could be substantial in global crop production (figure 4a), its proportional contribution to total water use is small (figure 4b). Green water therefore significantly moderates water scarcity and should be reflected in agri-compatible water scarcity.

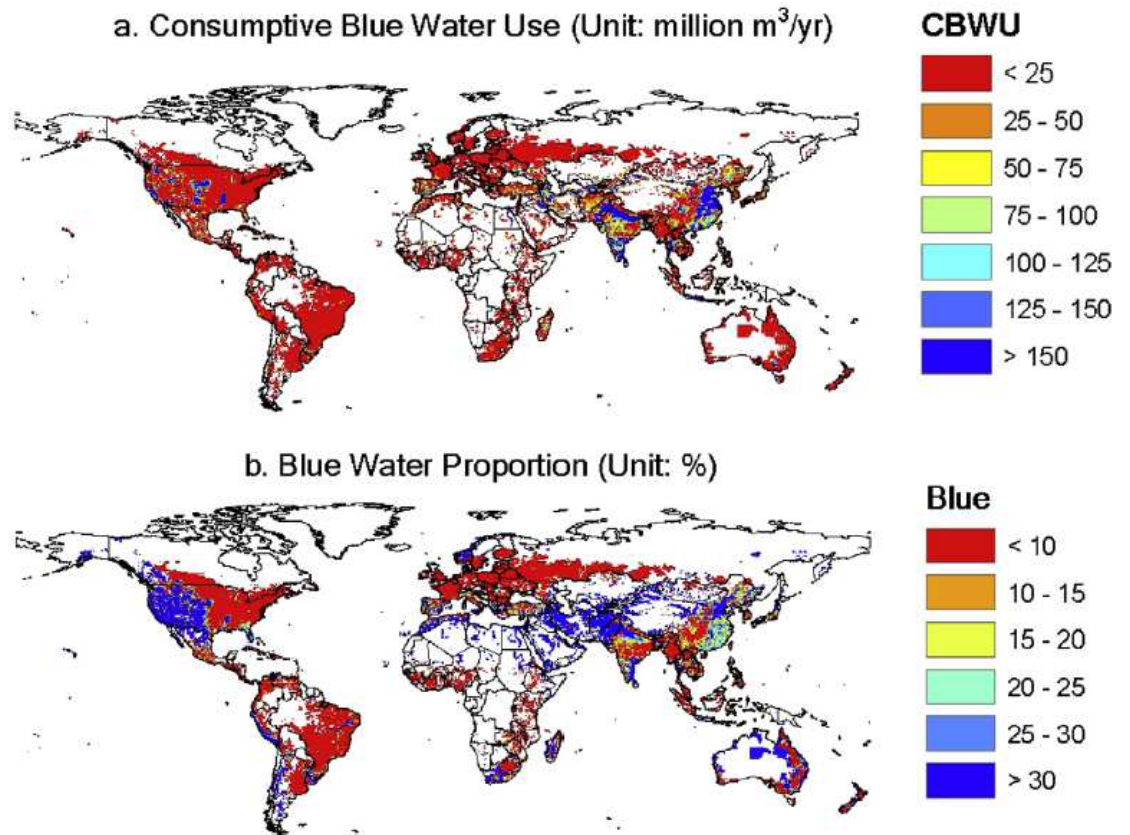


Figure 4: Global pattern of (a) blue water use in crop production (b) blue water use as a proportion of total water use in crop season (Liu and Yang, 2010).

3.2.3 Calculation of Crop and Catchment Water Scarcity Indicators

Allan (2000) asserted that analysis of drought must be specific to a given crop type or land use. Similarly, agri-compatible water scarcity must be specific to a particular crop and catchment at a particular area and time in order to be meaningful and purposeful. The work of Ridoutt and Pfister (2010) is significant as it creates opportunity for quantifying the specific contribution of each product to water scarcity, through its life cycle, and the location of water scarcity. Nevertheless, it does not fully capture agri-compatible water scarcity. We propose a calculation scheme for agri-compatible water scarcity factors at crop and catchment levels (Table 1).

Table 1: A scheme for calculating agri-compatible water scarcity at crop and catchment scales. Note:

(i) BWR_i denotes blue water requirement of crop i per unit time (t) (m³); P_{eff} denotes effective rainfall (mm) (effective rainfall is the proportion of rainfall that remains in the root zone after runoff and deep percolation); ET_c denotes crop evapotranspiration (mm); A denotes areal coverage of crop i (m²); BW_f denotes the fractional amount of blue water in the catchment available for to crop i (m³); l denotes length of crop growing period (days).

(ii) *TBWR* denotes total blue water requirement of all crops considered in the catchment (m^3);

n denotes number of crops considered; and c denotes catchment.

(i) CROP FIELD	(ii) CATCHMENT
<p>Per unit time (t):</p> $BWR_i[t] (m^3) = (ET_c[t] - P_{eff}[t]) \times A$ <p>[where $ET_c \geq P_{eff}$]</p> <p>Per season:</p> $BWR_i[season] = \sum_{t=1}^l BWR_i[t]$ <p>Scarcity factor (Cf_i) =</p> $\frac{BWR_i[season]}{BW_{fi}}$	$BWR_c[t] = \sum_{i=1}^n BWR_i[t]$ $BWR_c[season] = \sum_{i=1}^n BWR_i[season] =$ <p>TBWR</p> $Scarcity\ factor\ (Cf_c) = \frac{TBWR}{\sum_{i=1}^n BW_{fi}}$

Scarcity factor (Cf) < 1 implies no scarcity; $Cf > 1$ implies water scarcity.

Thus, taking $Cf = 1$ as the threshold for water scarcity, it implies water scarcity increases as Cf increases from 1 and vice versa.

The development or use of these crop and catchment specific scarcity factors is important for the following reasons:

i) not all the catchments in a country might have agricultural withdrawals or abstractions of blue water

ii) different catchments will have different scarcity factors with respect to agriculture and overall withdrawal; and for different crops grown in the catchment

iii) there can be water scarcity in a particular area without there being water scarcity for a particular crop in the same area. Thus, green water availability could be sufficient to support the production of some crop(s) in a catchment that might be suffering blue water scarcity.

iv) intra-seasonal dry spells might adversely affect crop yield in a country or an area that is not considered as water-scarce in the conventional sense.

v) knowing the crop and catchment water scarcity factors will help match crops to catchments in order to save water or reduce the effect of the production of a particular crop on a given catchment. This will, in turn, aid the analysis of the effect of land cover change on water scarcity in a given catchment.

vi) the equations also have operational significance as they can be used to monitor temporal water scarcity (for only green water, blue water or both) at crop, field and catchment scales.

vii) the crop- and catchment-specific scarcity factors can be used in calculating crop water footprints and related effects on humans and ecosystems at both sites of production and consumption.

4. SUMMARY AND CONCLUSIONS

Virtual water has been proposed as an essential component of the policy toolkit available to water-scarce communities to reduce the effect of water scarcity on food security. As water scarcity becomes more widespread and crop production becomes increasingly constrained, interest in virtual water is growing in the water research and policy community. However, the connection and the mechanism by which virtual water can reduce the effect of water scarcity on food security remains unclear and contested. We attribute this situation to a lack of agri-compatibility, which should provide a basis for evaluating the role of virtual water in reducing the effect of water scarcity on food security. To evaluate the role of virtual water in the global issue of water scarcity and food security, all components of the available water in crop producing areas need to be quantified to provide a basis for evaluating food imports necessitated by water scarcity. This makes virtual water agri-compatible.

The agri-compatibility framework improves understanding of the connections among water scarcity, virtual water and food security; and shows the relevance of virtual water as a mechanism for reducing the effect of water scarcity on food security. This paper shows scope for agri-compatibility and has argued, that, to ensure agri-compatibility, two key requirements must be met. First, water scarcity should be agri-compatible and, second, food importation should serve “water-dependent” food security requirement. Addressing the former significantly improves overall agri-compatibility. Agri-compatible water scarcity must capture three elements: i) It should account for the totality of water availability and consumption from all relevant sources in crop production. This requires further research effort in the accurate measurement and monitoring of the dynamics of green water availability and consumption in croplands; ii) The analysis of water scarcity for food production should incorporate a ‘climate’ factor that reflects aridity and drought potential; iii) Water scarcity factors should be specific to crops and catchments to show the scale of crop and land use effect on local hydrological system and, therefore, water scarcity. A conceptual framework for analysing agri-compatible connections among water scarcity, virtual water and food security has been presented and a scheme for calculating agri-compatible water scarcity at crop and catchment scales has been proposed. Making virtual water agri-compatible will require a multi-disciplinary research effort that spans socio-economics, hydrology, soil-water-crop-atmosphere dynamics, spatially-explicit modelling and policy analysis. Nevertheless, achieving such agri-compatibility will significantly advance the utility of virtual water for policy in addressing the effect of water scarcity on food security.

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