CLIMATE AND ITS EFFECTS ON CROP PRODUCTIVITY AND MANAGEMENT

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Summary

Crops are dependent on light, temperature, moisture and carbon dioxide (CO_2) concentration to produce the grains and other crop products that are so essential to our nutrition, health and well-being. However, the levels of these climate inputs, particularly rainfall, vary between locations and years, in part due to climate variability. Temperature and water supply also vary over the long-term, including in response to climate change, with major implications for crop production, and the livelihood of crop producers. Crop management is therefore very much about managing climate risk so as to have financially viable and sustainable agricultural systems. Climate and management also impact on the spread of weeds, pests and diseases, which in turn affects crop yields and harvests and producers' costs and returns. These climatic effects on crop production around the world impact on global trade, with implications for net exporters, net importers and consumers, as well as for national and global food security.

1. Introduction

Cropping is practiced over a wide range of agroecosystems, field crops being grown in climates ranging from very hot to very cold, and from very wet to very dry, across temperate, tropical and semi-arid zones. We draw in particular on the literature addressing cropping in Australia given that cropping activities there happen over many such agro-climatic zones. Additionally, Australia has the highest climate variability of any continent in the world with a sound science and farmer base for managing this, and is particularly exposed to climate change. Consequently it is highly suitable for studying the major determinants of climate on crop productivity, with the experience and information gained in Australia having relevance for other cropping countries throughout the world.

Cropping is highly sensitive to climate, crops having a limited environment in which they are productive and profitable. Professor Henry Nix of the Australian National University (ANU) posed three questions that need to be addressed when considering what crops can be grown where:

1. For any given crop which areas offer the greatest biophysical advantages,
2. For any given area which crops offer the greatest advantages, and
3. For any given crop or area how may productivity be raised and sustained?

In this chapter we focus on the climatic determinants of crop productivity by first considering how the climate envelopes of different crops based on light, temperature and moisture influence the distribution of cropping and other land uses around the world. We then discuss how these and other climatic variables influence the growth and yield of crops, interannual variability in grain production and associated risks (Figure 1). Cropping in a variable climate presents many challenges, particularly in the more arid regions of the world, so ways of reducing losses in adverse seasons are addressed.

Global change, including climate change, means that the environmental limitations to crop growth will inevitably be modified. This in turn will affect the choice of crop species and cultivars and other farm management decisions. A sound knowledge of the basic processes by which climate impacts on crops is therefore required in order to understand the changes taking place.

Climate change threatens to modify both the envelopes that characterize different crop production systems, and the associated yield variability and production and financial risk. Adaptation strategies are discussed that will assist crop producers to cope with rising global temperatures and carbon dioxide levels, along with often reduced rainfall, soil moisture and water availability. The need to improve productivity or efficiency is driven not only by economic pressures, but also by the need to mitigate greenhouse gas emissions (per kg of product), to conserve biodiversity and address rising global demand for food, particularly if the area under crop cannot be increased. However, there can be a risk of substantial losses if inappropriate adaptation strategies are selected. Finally, we focus on the implications of climate change for global food supply, food security and grain exports.

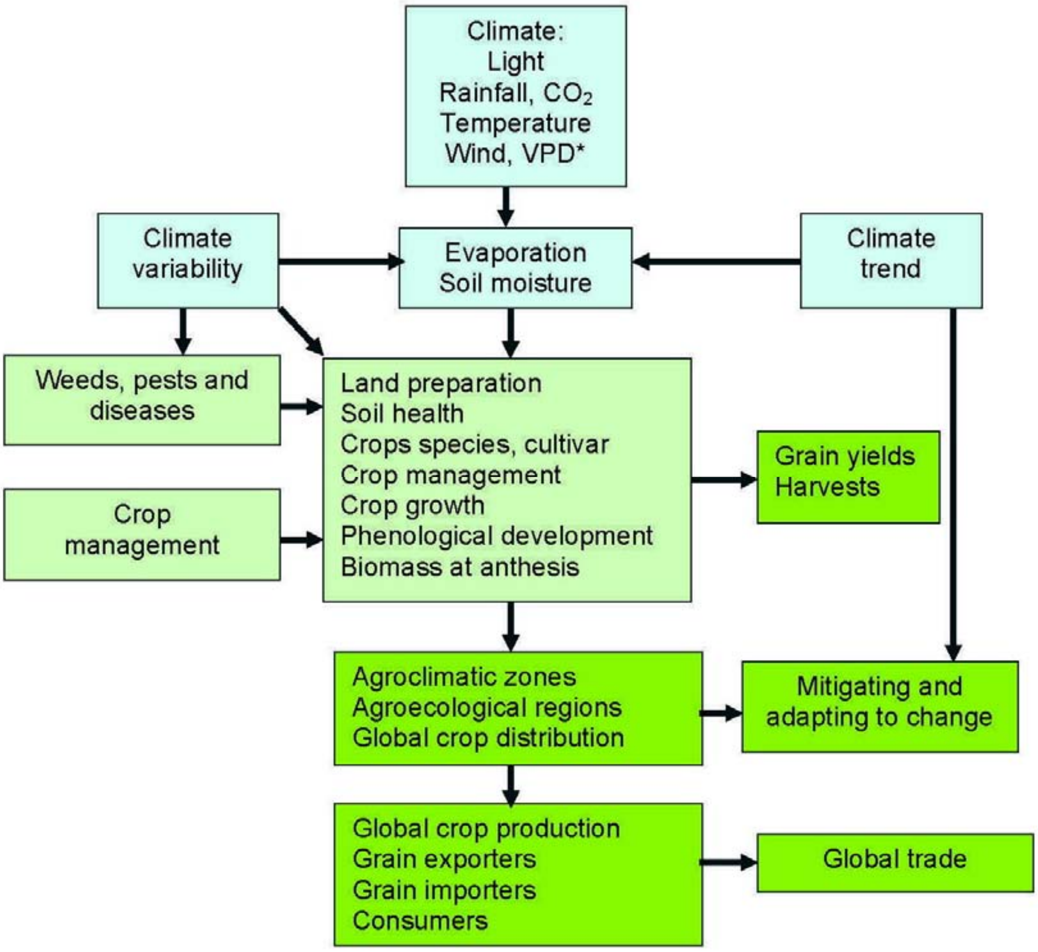

Figure 1. Climate impacts on the agricultural sector
* VPD = vapor pressure deficit

2. Major Climatic Determinants of Plant Productivity

Climate is fundamental to crop growth. Moisture stimulates seeds to germinate, the time to emergence being temperature-dependent. The rate of growth of roots, stem and leaves depends on the rate of photosynthesis, which in turn depends on light, temperature, moisture and carbon dioxide (CO_2), as discussed in detail in the following sections. Temperature and daylength also determine when plants produce leaves, stems and flowers, and consequently the filling of grain or the expansion of fruit. The yield of grain crops depends on grain number and grain weight at harvest, which in turn depends on biomass at anthesis and the availability of moisture post-anthesis. In this section we explore how light, temperature and moisture and other climatic factors determine land use, crop emergence and growth and saleable product.

Many of these relationships are described in extensively-tested computer-based simulation models. These models have an integral role in modern-day science, not only for exploring feasible future scenarios, but by providing a framework to improve our understanding of very complex problems. They are necessary for studying complex systems, whereby our current understanding of the complex interrelationships and feedbacks between the major system components are described mathematically, and the model’s behavior tested against real-world systems. They can then be used to predict the likely responses to different system inputs or management strategies, analyze the consequences in terms of likely benefits and risks of implementing particular strategies, and the transferability of simulated strategies and performance to other cropping locations or regions and years. Incorporating both physiological knowledge and genetic information into crop models should help identify suitable genotypes for different environments and how they may best be exploited. There are now identified genes for photoperiod, vernalization and leaf emergence rate that could be used to underpin model determinations of when flowering will occur, which in turn is an important determinant of crop adaptation and yield. Providing that sufficient work has been put into their development and validation, crop models are effective tools for relating crop growth, development and yield to actual climate data.

The level of detail and structure in any model is determined primarily by its objectives. A range of options is available, allowing us to select a suitable approach where an acceptable compromise is found between model simplification, date of availability and the desired level of accuracy.

The relative importance of light, temperature and moisture in different environments and seasons can be illustrated using the relatively simple CROPEVAL model described by Professor Nix whereby the weekly growth index (GI) is the product of the three primary climate indices, light, temperature and moisture, such that $GI = LI \times TI \times MI$. The significance of light, temperature and moisture as determinants of plant growth are briefly discussed in the following sections.

2.1. Significance of Light

Solar radiation is the primary driver of plant photosynthesis, and the radiation levels in the upper atmosphere may be estimated mechanistically as a function of latitude and time of year. Solar radiation at the crop surface differs from incident radiation in the upper atmosphere according to the daily atmospheric transmissivity, determined in part by cloud cover that can vary substantially within and between years (for example, El Niño years in Australia typically have much less cloud cover and rainfall than La Niña years). The broad relationship between mean daily solar radiation at the crop surface and fractional dry matter of a crop (LI, the light index) described by Professor Nix is shown in Figure 2.

Figure 2 shows that the effect of reducing the light reaching the crop canopy on plant growth is most pronounced at low levels of solar radiation. Consequently, in many countries and environments light will often not be the most limiting factor affecting crop growth and yield. However, in mid- to late winter, at very high latitudes or on shaded slopes, or in countries where airborne pollutants cause a substantial reduction in atmospheric transmissivity (a phenomenon known as global dimming), then photosynthetic activity and crop yields can be significantly diminished.

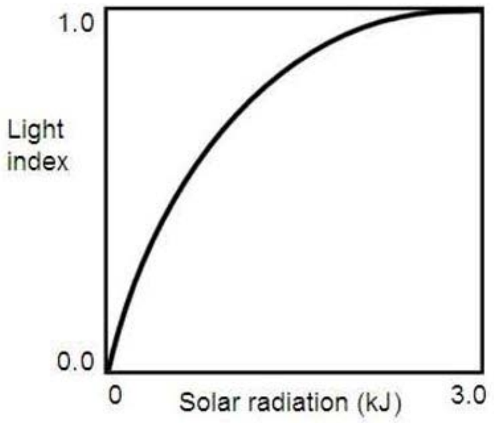

Figure 2. Light index (LI) (Nix 1981)

2.2. Significance of Temperature

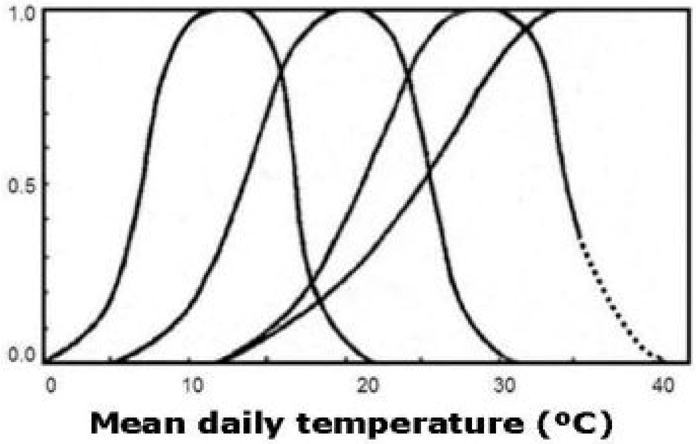

Figure 3. Thermal index (TI) (Nix 1981)

Temperature has major effects on photosynthesis and respiration, plant growth and phenological development. Phenology is particularly important in cooler regions and at higher altitudes. As a rough guide, atmospheric temperatures experienced by crops decrease by about 1°C for each 2° increase in latitude, or for each 100 m increase in altitude. The bell-shaped responses to temperature shown in Figure 3 indicate just how severely growth is limited at low temperatures, whereas at high temperatures the stomata on the leaves can close so as to limit gaseous exchange, water loss, and consequently active growth. As shown in Figure 3, these bell-shaped responses to temperature are likely to be distorted by extension on the cool side and truncation on the warm side. Cool temperate climatic plants typically have lower minimum, maximum and optimal temperatures for growth than warm-season C_3 crops and tropical C_4 crops (Figure 3). Temperature is important in controlling phenological changes in development from germination and seedling emergence, through vegetative growth to floral initiation and reproductive growth. Of course variation in temperature tolerance is evident both within populations of single plants and between genotypes. Temperature within a plant, particularly at the growing points, may differ from prevailing air temperatures for a number of reasons, including plant structure and density, distance from the soil surface, and shade. Temperature also has a major influence on the rate of evaporative loss from soils and leaf surfaces as discussed in the following section.

Radiation frosts are common in many temperate environments due to high radiative loss on cloudless, calm nights. Intracellular freezing ensues at around -7ºC, tissue death resulting from the combined effects of membrane injury, cytoplasm dehydration and protein denaturation. Frost hardiness of plant cells involves cell size, wall thickness, osmotic pressure of cell sap and membrane properties, all of which can either delay the onset or diminish adverse consequences of ice formation. Plant organs that are rapidly growing rapidly are sensitive to frosts.

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Biographical Sketches

Dr David White has been Director of ASIT Consulting since 1997. Before then he was Senior Principal Research Scientist (Agricultural Production & Natural Resources) in the Bureau of Resource (now Rural) Sciences in Canberra. He graduated M.Agr.Sc. at Lincoln College, New Zealand, before working at the Ruakura Agricultural Research Centre. Moving to Australia in 1967, he obtained a Grad.Dip.Elec.Comp. from the Bendigo Institute of Technology and a Ph.D. from the University of New South Wales (and CSIRO Plant Industry). He spent 21 years in the Victorian Department of Agriculture, initially undertaking field research and extension in northern Victoria and later leading the development, testing and application of simulation models for analyzing agricultural systems at Werribee. His primary focus has always been improving the productivity, sustainability and financial viability of farming systems. During his eight years in BRS his main role was coordinating the scientific input into the development and implementation of the National Drought Policy, including leading a national research program aimed at improving the monitoring, assessment and declaration of exceptional droughts. He is a Fellow of the Australian Institute of Science & Technology, and in 1999 was awarded the Biennial Medal (General Systems) of the Modelling and Simulation Society of Australia and New Zealand. He has published more than 200 scientific and related publications covering topics as diverse as the management of grazing livestock, crop-livestock integration, coping with climate variability, adapting to climate change, and improving water use efficiency on irrigated farms.

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