1 Introduction

There are few easily identifiable or accessible sources where the results of international irrigation research have been brought together and interpreted in coherent and useful ways for individual crops. This is in part due to the diversity of sources, and also to the difficulty of reconciling the results of research conducted in contrasting situations, often with insufficient supporting information, to allow the results to be extrapolated to new situations with confidence (Carr, 2000a).

A scientific understanding of the role that water plays in the growth and development of crops is essential, but this knowledge needs to be interpreted and presented as practical advice in a language that can assist planners, irrigation engineers, irrigation agronomists and producers to allocate and use water, whether rainfall or irrigation, effectively and profitably. Communication between the professions attempting to improve irrigation water management for the benefit of the commercial producer and the wider community can always be improved. Field experiments must be designed and managed to quantify with precision the (marketable) yield responses of crops to water. Adequate supporting measurements need to be taken to enable the results to be interpreted and applied with confidence to other locations, or at other times, where the climate, weather and/or soils may be different. Site specific, single discipline, empirical studies should normally be avoided. *But, to minimise duplication of effort, existing information on the water relations and irrigation need of individual crops first needs to be collated and interpreted in practically useful ways*. This is especially true for plantation crops having international commercial importance (Carr, 2000a).

What is plantation agriculture?

Plantation agriculture can be broadly distinguished from other farming systems in the following ways (Tiffen and Mortimore, 1990; Stephens *et al*., 1998):

- Plantations involve the cultivation of one crop or perhaps two crops from a restricted range.
- In the tropics and subtropics, these include tree crops such as cocoa, coconut, coffee (Figure 1.1.), oil palm, rubber and tea and perennial field crops such as bananas, sugar cane and sisal.

Figure 1.1 Irrigated coffee estate – Kilimanjaro Region, northern Tanzania (MKVC). (See also colour plate.)

- These are mainly crops that require prompt initial processing (added value) and for which there is an export market (source of foreign exchange).
- This involves a high fixed capital investment cost: for example, for planting material, and processing facilities and infrastructure, including roads and housing.
- Work on plantations often continues throughout the year, requiring a large permanent labour force and associated social facilities.
- The size of a plantation can vary from <100 ha to several thousand hectares.
- Plantations require specialised management teams to run an industrial-scale business, and to be responsible for quality control at all stages in the production process.
- Plantation agriculture is very vulnerable to fluctuations in global commodity prices: there is always a risk of overproduction and there are usually limited opportunities for a rapid change in the product or processes.
- Plantations are dependent on access to the results of good-quality research if they are to remain profitable. Specialised plantation crop research institutes, often funded by the industry, exist in many countries.

Increasingly, so-called plantation crops are grown by smallholders on a much smaller scale, either for local consumption or for export when they may be linked, for example, to a central estate and/or a processing facility through an

Figure 1.2 A mosaic of smallholder crops (tea, bananas) –Tukuyu, southern Tanzania (MKVC).

outgrower-scheme or a cooperative (Figure 1.2). In these cases an individual cropped area may be less than 0.3 ha.

Well-managed estates offer some advantages as a production system due to economies of scale when combined with adequate capitalisation (Figure 1.3). If management is poor the estate loses much of its economic advantage over smallholder production. Organisational structures range from autocratic bureaucracy on some large estates through to loose democratic alliances of smallholders. Although the early plantations in America and elsewhere were often oppressive, a modern plantation is a progressive commercial enterprise competing for labour and capital with other industries in an open market (Stephens *et al*., 1998).

The business objectives of a plantation are to maximise profit in the short and long term, to optimise the use of resources (e.g. land/climate, people, capital) and to ensure long-term sustainability (wealth creation, employment, environment).

Research

Until the 1960s, agricultural research in the tropics was focused on plantation crops grown for export, at the expense of food crops research. Specialist research institutes were established focusing on individual crops (e.g. tea research institutes, coffee research foundations, rubber research institutes). Many of these still exist. They were often funded, at least in part, by a cess (levy) paid by the producer. This meant that the scientists were closely integrated with the industry they were serving, which developed as a result from a strong science base. Research focused

Figure 1.3 A well-managed irrigated tea estate surrounded by indigenous forest – Mufindi, Tanzania (MKVC). (See also colour plate.)

on plantation crops today is largely outside the international research networks (CGIAR[1]) and continues to be funded by producers, national governments and willing donors (those who appreciate that successful plantation crops can make a major contribution to poverty alleviation). Many of these specialist crop research institutes remain small, and physically (and often intellectually) isolated. The challenge to the researcher with limited resources is how best to reconcile the competing, sometimes conflicting, demands of the progressive estate and the resource-poor smallholder (Figure 1.4). This applies particularly to research on crop water relations and irrigation where much could be gained by an international coordinated approach on topics of generic interest. The same need applies to public concerns about the environmental impact of plantation agriculture in the tropics. With a focus on soil erosion, soil fertility decline, pollution, biodiversity and carbon sequestration, research on this subject has been reviewed by Hartemink (2005).

Purpose

Average yields of all plantation crops, even the best commercial yields, are still far below the potential yields. Water is just one of many limiting factors, but in some locations it is the major one. One purpose of this book is to collate all the published information on the water relations of the important plantation crops

Figure 1.4 A tea irrigation experiment – Ngwazi Tea Research Station, Mufindi, Tanzania (MKVC).

in order to quantify where possible the yield losses due to water stress or, where appropriate, the likely benefits from irrigation or other approaches to drought mitigation as an aid to planning. Another purpose is to provide an entry point for researchers on these topics wishing to build on what is already known rather than duplication of effort. A third purpose is to compare and contrast different plantation crops since, because of the structure of the plantation industry and its research support, there is often little cross-fertilisation of knowledge between crops. A fourth purpose is to make a contribution to the need, frequently stated, to use water efficiently in the face of increasing competition for a scarce resource. The uncertainties associated with climate change make this even more of an imperative. Finally the book is intended to be a source of reference for students wishing to know more about tropical agriculture and its continuing challenges.

Content

Each chapter is devoted to a single crop and follows a similar format. Following an introduction, the centre of origin of the crop is described, together with the current centres of production and production trends. There then follows a description of the key crop development stages, including root growth, with an emphasis on how water availability influences each stage. A detailed review of research on fundamental plant water relations, crop water requirements and water productivity then follows. Where appropriate, irrigation systems suitable for the crop are

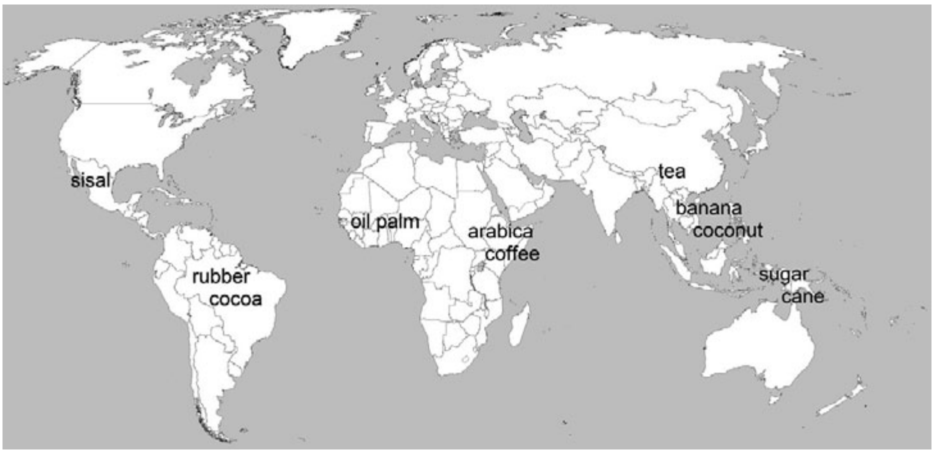

Figure 1.5 World map showing centres of origin of plantation crops.

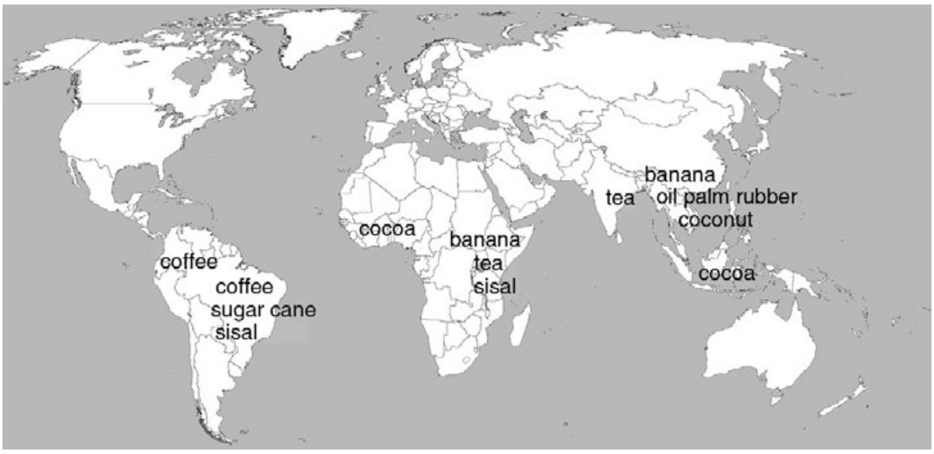

Figure 1.6 World map showing principal regions of plantation crop production.

then considered, together with irrigation scheduling methods. Not all crops have been researched to the same level of detail. As background, the key generic issues and terminology are now summarised here using the same headings.

Centres of origin and production

Understanding the conditions under which a species originated and evolved is central to understanding the climatic and soil conditions under which it is likely to perform well and/or the likely limiting factors in areas where it is being cultivated, which may be thousands of kilometres away from its region of origin (Figures 1.5 and 1.6). Several of the crops considered here evolved in rainforests under shade, for example cocoa, coffee and tea. Does this mean that they need shade when grown commercially? If a crop originated where there is a regular dry season, does it mean it is drought tolerant? What attributes contribute to its capacity to withstand dry conditions?

The transfer of crops across the world is a continuing process driven by economic and social forces. For example, rubber is now being grown in drier regions of South-east Asia as competition from oil palm for land, and urbanisation, displace it from its traditional areas of production. Tea is now being grown as an irrigated crop in dry areas of eastern Africa as public pressure makes it mandatory to protect the rainforest, the previous site of first choice for tea plantations. The threat of climate change will increase the need for managers to be as well informed as possible on plant water requirements when making decisions about where best to plant long-term perennial crops.

Crop development stages

Among the plantation crops being considered in this book, there is tremendous variety in the so-called useful product, which ranges from young shoots (tea), through fruits (banana), seeds (coffee, cocoa) to sucrose (sugar cane), oil (coconut, oil palm), fibre (sisal) and latex (rubber). Some crops have a diverse range of products such as the coconut, the so-called tree of life, in which nearly the whole tree contributes something to livelihoods although the primary product is copra (for oil).

The yield of any crop (Y) can be considered in terms of the efficiency of successive stages in the conversion of solar energy (S) to the economic or useful product (Monteith, 1972). Thus:

$$Y = S \times f \times e \times HI$$

where S is the total solar energy received at the surface of the crop, f is the fraction of the energy intercepted by the leaf canopy, e is the conversion ratio (or efficiency) of solar radiation to dry matter, and HI is the ratio of energy in the economic product to the total energy fixed by the crop (or in non-oil-bearing crops the dry matter ratio is often used instead of energy). Typical annual incident solar radiation totals range from around 55 TJ ha^{-1} in the high-rainfall tea-growing areas in Bangladesh and Assam to 63 TJ ha^{-1} in oil-palm-growing areas of Malaysia to 70 TJ ha^{-1} in parts of East Africa which have clear skies during long dry seasons (Stephens *et al.*, 1998).

The leaf area required to intercept a given proportion of solar radiation depends largely on the canopy geometry. Crops with erect leaves held in clumps (e.g. palms) require a larger leaf area index (L) to intercept a given proportion of radiation than those with horizontal, uniformly spaced leaves (e.g. tea). The aim with most crops is to seek to achieve full crop cover as soon as possible after planting in order to intercept as much radiation as possible during the lifetime of the crop. The duration of the immature phase varies between crops from, for example, three to four years for tea to seven to eight years for coconuts (talls). Growing trees under shade obviously reduces the proportion of light intercepted by the crop canopy. The conversion ratio is expressed in units of g (dry matter) MJ^{-1} (intercepted radiation) and values range from 0.2 g MJ^{-1} for tea to 0.8 g MJ^{-1} for oil palm. For comparison the corresponding figure for a temperate cereal crop is 1.4 g MJ^{-1}. Excessively high leaf temperatures and/or dry air (low humidity or large saturation deficit), soil water stress and nutrient stress can all reduce the photosynthetic efficiency. Losses of dry matter as a result of respiration by a large standing biomass (e.g. the trunks of a palm) in a warm climate are another reason for apparent low conversion efficiencies.

The aim of plant breeders and others is to maximise the amount of dry matter (or energy) in the plant that is allocated to the useful product. This is known as the harvest index and varies considerably between species. For example, Corley (1983) listed the harvest indices (above-ground dry matter) recorded for a selection of a well-managed plantation crops as 0.42 for oil palm to 0.20 for cocoa.

Using this analytical approach it is possible to calculate the potential yield of a crop and, by comparing this with the actual yield, seek to identify possible reasons for a yield deficit. Corley (1983, 1985) did such an analysis for a selection of plantation crops. Water stress can influence each of the growth processes described above, including crop establishment, leaf expansion (light interception), photosynthesis (conversion efficiency), flower formation, pollination, fruit development, and the harvest index, while root growth, depth and distribution affect the amount of water easily available to the crop.

Plant water relations

Water deficits in plants develop as a consequence of water loss from the leaves as the *stomata* open to allow the ingress of carbon dioxide from the atmosphere for *photosynthesis* and the egress of water vapour (*transpiration*). This is referred to as a *gaseous exchange* process (water vapour for carbon dioxide). Stomata are found on either the adaxial (upper) surface of the leaf or the abaxial (lower) surface or both. The water lost by *transpiration* from the leaf mesophyl cells is replaced by water drawn from the soil into the roots, and then up the stems and through the leaves along the *xylem vessels*. Water moves along a gradient of *water potential* from a relatively wet soil (high potential) to a relatively dry air (low potential). The energy driving this process comes primarily from solar radiation, which is providing the latent heat needed to evaporate water (*transpiration*). The energy status of the water is described in terms of its *water potential*, which in the plant has two principal components: the *osmotic potential* (due to the presence of salts in solution) and the *pressure potential* (or *turgor pressure*). In the soil the principal component is the *matric potential* (a result of the *capillary forces* in the soil pores, and the *attraction* of water molecules to soil particles) and, if there are salts in solution, the *osmotic potential*.

A *pressure bomb* is commonly used to measure the *leaf water status* (*leaf water potential* and its components), while a *tensiometer* measures the *matric potential* in the soil. A *porometer* (there are several types) measures the *stomatal conductance* (a measure of the degree of stomatal opening). *Infrared gas analysers* are used to measure *photosynthesis* and *instantaneous transpiration* rates (Monteith *et al*., 1981; Squire *et al*., 1981).

Crop water requirements

Actual crop water use (*ET*) can be measured (by means of water balance, sap flow, micrometeorology) or estimated (by calculation) in a number of ways. The *water balance approach* involves measuring the change in water content (volumetric) of the soil profile (ΔW) over a period of time after allowing for rainfall (P), run-off (R) and deep drainage (D), and finding ET by difference:

$$ET = P - R - D \pm \Delta W$$

This can be done at different scales – from a whole catchment, when comparing changes in land use from, for example, rainforest to tea or oil palm, or from an individual tree grown in a large container (known as a lysimeter). Changes in soil water content can be measured *gravimetrically* or with a *neutron probe* or a *capacitance probe*.

Evapotranspiration (*ET*) has two components: *transpiration* (T) and *evaporation* (E) from the soil (and crop) surface. Both processes occur simultaneously, and there is no easy way of distinguishing between the two. When the crop is small, water is predominantly lost by evaporation from the soil surface (while it remains wet), but once the crop canopy covers the ground T becomes the main process (Allen *et al*., 1998).

The *sap flow method* (of which there are several variations) involves measuring the rate of flow of water up the stem using a heat pulse. It is a direct measure of T. It is well suited to tree crops and has been tried, for example, on tea, coconut and rubber.

Micrometeorological methods, namely the Bowen Ratio and eddy-flux methods, involve measuring the flux of water vapour above a crop (*ET*) using an array of sensors. These methods have been used with, for example, oil palm and sugar cane.

In most practical situations, *potential crop evapotranspiration* (ET_c) is estimated using a formula such as the Penman equation or the Penman–Monteith equation, both of which require standard weather data, or a well-sited evaporation pan such as the USWB Class A pan (E_{pan}). These give estimates of evaporation from a standard crop surface, usually taken to be short grass or alfalfa, well supplied with water, now known as *reference crop evapotranspiration* (ET_0) (Allen *et al*., 1998).

To convert this to potential water use by a specific crop (ET_c) a crop factor (K_c) is needed. This varies with the stage of development of the crop.

$$ET_c = K_c \times ET_0$$

A pan factor (K_p), its value depending on the siting of the pan, is needed to convert E_{pan} to ET_0, thus:

$$ET_0 = K_p \times E_{pan}$$

Unfortunately few researchers define precisely the methods they have used to calculate crop water use (there are several versions of the Penman equation). This can sometimes lead to confusion. The guidelines provided by Allen *et al*. (1998) are intended to help to standardise the approaches used internationally.

Water productivity

There are several ways in which water productivity can be defined and again it is necessary to be very precise in order to compare like with like. The term *transpiration efficiency* is used to describe dry matter production per unit of transpiration. Alternatively, *water-use efficiency* describes dry matter production per unit of water lost by *evaporation* (from the soil and crop surface) and by *transpiration*. For commercial purposes, it is often easier to compare the water-use efficiency on the basis of the *commercial yield* per unit of *evapotranspiration* (evaporation plus transpiration) or per unit of rainfall and/or irrigation. It is important to be able to differentiate between these descriptors when making comparisons; they are rarely defined precisely. *Water productivity* is a generic term covering all these terms (Turner, 1986; Carr and Stephens, 1992).

As an example, for a tea crop yielding 5000 kg ha^{-1} y^{-1} in an area where the annual evapotranspiration (*ET*) is 1250 mm, of which transpiration is 1050 mm, the *water-use efficiency – ET* (for yield) – is 4 kg ha^{-1} mm^{-1} (5000/1250), and the *transpiration efficiency* is 4.8 kg ha^{-1} mm^{-1} (5000/1050). If the total annual rainfall is 1700 mm, the *water-use efficiency for rain* is 2.9 kg ha^{-1} mm^{-1} (5000/1700). If 300 mm of supplementary irrigation increases yields by 1500 kg ha^{-1}, the incremental *yield response to irrigation* is 5 kg ha^{-1} mm^{-1} (1500/300). Water productivity values like these are a valuable way of evaluating the effectiveness of various agronomic or drought-mitigation practices, or for assessing in crop yield and financial terms the worthwhileness of irrigation. They can also act as a benchmark against which to judge good practice (Carr and Stephens, 1992).

Another way of specifying the yield response to water is that proposed by Doorenbos and Kassam (1979), using the following relationship:

$$(1 - Y_a/Y_m) = K_y(1 - ET_a/ET_m)$$

where Y_a is the actual harvested yield, Y_m is the maximum harvested yield, ET_a is the actual evapotranspiration, and ET_m is the maximum evapotranspiration. K_y is