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A comparison of three empirical models for assessing cropping options in a data-sparse environment, with reference to Laos and Cambodia

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Camilla Vote, Oeurng Chantha, Sok Ty, Chanseng Phongpacith, Thavone Inthavong, Seng Vang, Philip Eberbach and John Hornbuckle

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Cover: Empirical models can be used to assess the yield potential of high-value, market-oriented crops—such as watermelons seen here in Sukhuma district, southern Laos—as an alternative to rice production. (Photo: Camilla Vote)

Foreword

Cambodia and Lao PDR are two of the most impoverished nations in South East Asia, with high rates of poverty, food insecurity and poor nutrition, particularly amongst small landholders. The climate is one of the main challenges that farmers face. Crops, mostly rice, are primarily grown during the wet season, while the lack of water during the dry season limits options, except where irrigation infrastructure exists.

There is potential to increase farm productivity by better exploitation of the dry season. It may be possible to increase farm incomes significantly by growing high-value short-duration crops, such as mungbean, soybean, peanut and watermelon, through improving water and nutrient management where irrigation exists, and better use of residual soil water remaining after the wet season.

ACIAR project SMCN/2012/071, 'Improving water and nutrient management to enable double cropping in the rice growing lowlands of Lao PDR and Cambodia', aims to address this. The project began in 2014, and the team identified the need for a modelling framework to assist the project meet its larger goals about the needs and suitability of various candidate dry season crops. Though there are several models available with a range of strengths and weaknesses, a thorough analytical comparative assessment of the major models was not available, and this assessment was therefore undertaken by the project team. This technical report presents this comparison, which will be useful to other research groups developing dry season cropping options in rice-based systems, to increase the efficiency of research for development in this area and its applications.

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Summary

In many less developed countries, there is a need to improve productivity and profitability of agricultural systems to improve rural livelihoods, particularly in areas where monocultural production has dominated the historical land use. Generally, there are a number of physical, chemical and biological soil constraints in these systems that prevent the successful production of alternative crops, often compounded by limited access to water. Rather than conduct time-consuming and expensive field trials, modelling techniques can provide a relatively inexpensive, first assessment of yield potential of cropping options under different water/nutrient regimes which can be used to inform and refine further research. However, in less developed regions, crop modelling activities are often constrained by limited institutional and technical capacity and inadequate or incomplete input datasets. In this case, complex models that require significant technical capacity and comprehensive datasets may be inappropriate, and less complex models with relatively simple input requirements may be better suited. This report discusses three relatively simple modelling options that can be applied within a data-sparse environment, and presents them within the context of Laos and Cambodia. The capabilities and limitations of each model are comprehensively reviewed to provide the reader with an understanding of the options to reliably simulate crop processes that may be useful, for example, to influence farmer practice, decision making, and to improve and optimise resource use.

Introduction

The Lower Mekong River Basin (LMRB) encompasses parts of Thailand, Laos, Vietnam and Cambodia and is home to 67 million people (Mainuddin et al. 2013). About 70% of these people are subsistence farmers, growing mostly wet season (WS) rice supplemented by fish, plants and animals gathered from nearby water bodies and forests (Kamoto and Juntopas 2011). Laos and Cambodia have 85% and 86% of their land area within the LMRB, respectively; while Thailand and Vietnam have 36% and 20%, respectively. The majority of the populations of Laos and Cambodia live within the basin boundaries (97% and 90%, respectively), and only 60% of people in the basin have access to safe water (Franken 2012). Additionally, as least developed countries, Laos and Cambodia have some of the highest rates of poverty, food insecurity and malnourishment in South East Asia, particularly in rural areas (World Bank 2013).

With a tropical monsoonal climate, the historical agricultural activity in Laos and Cambodia is predominately WS rice production in the rain-fed lowlands, which occupy 70–80% of the total rice cultivated area in those countries (Ly et al. 2013; Mitchell et al. 2014). As a 'pathway out of poverty' (World Bank 2007), agricultural diversification is recognised as a way to improve the productivity and profitability of these lowland systems, and this has become a priority for both Lao and Cambodian governments (Sarom 2007; Bunna et al. 2011; Mitchell et al. 2014). As well as improving WS rice varieties to withstand increasing incidence of drought and boost yield, there are opportunities to increase productivity and profitability of lowland rice production areas through the cultivation of dry season (DS) crops, including rice. This may be possible where water is available for irrigation or where, following the end of WS rains, residual soil moisture is sufficient to grow high-value, short duration crops.

In addition to limited water availability, previous studies in the region have identified a number of physical, chemical and biological soil constraints that may restrict DS crop production, particularly in the lowlands. For instance, the clay content of common topsoils of the rain-fed lowlands in Laos and Cambodia is low; therefore the water holding and nutrient retention capacity of these coarsely textured, sandy soils is also low (Seng et al. 2005; Inthavong et al. 2012; Mitchell et al. 2013). Additionally, soils can become moderately to strongly acidic under aerobic conditions, inhibiting plant growth through low cation exchange capacity (CEC), aluminium (Al) toxicity and/or high phosphorus (P) fixation during the DS (Haefele et al. 2014). Furthermore, traditional puddling methods and tillage operations for WS rice production result in a high bulk density soil layer, or 'hardpan', approximately 5 cm thick that lies beneath the soil surface at a depth of approximately 20 cm. This reduces water loss through percolation, decreasing drought stress and preserving rice yield (Vial et al. 2013); however, the hardpan negatively affects the potential for DS crop rotation as it restricts root growth and access to water and nutrient sources in deeper soil layers (Mitchell et al. 2013). Regular tillage also leads to increased decomposition of soil organic matter through mineralisation, rates of which are high in the warm climatic conditions experienced in Laos and Cambodia, further degrading physical, chemical and biological properties of the soil (Johansen et al. 2012).

In addition to DS rice, there are other high-value, market-oriented crops (e.g. maize, mungbean, soybean, peanuts, watermelons and vegetables) that could potentially result in increased cash income for the smallholder provided the required production inputs (e.g. water, fertiliser and soil ameliorants) and their costs are managed adequately (Mitchell et al. 2013). This can be achieved in part through

simulation modelling. For example, modelling of crop physiological processes can be used to predict the growth, development and crop yield based on a number of input parameters, such as genetic features of a specific cultivar, environmental variables (soil and climate) and management practices (Raes et al. 2009; Steduto et al. 2009a). Although modelling outputs provide a quantative representation of real-world processes, the accuracy is highly dependent on the complexity of the model and the quality of input data. Notwithstanding, crop models are a useful tool for a variety of applications. For instance, for extensive and, thus, potentially expensive field experiments, crop simulation can be used to pre-evaluate treatments thereby refining the research focus and decreasing the cost of field trials. It can also be used as a management tool to optimise farming system operations, including crop selection, sowing dates, irrigation and fertiliser applications. At a regional or national level, crop modelling can also be used to inform planning and policy (Steduto et al. 2009a).

There are many models designed to simulate water and nutrient dynamics of cropping systems, 18 of which have been comprehensively reviewed by Kersebaum et al. (2007). Technical expertise and input requirements vary greatly, depending on the sophistication of the model. In less developed regions, such as Laos and Cambodia, institutional, technical and financial capacity are limited and datasets are non-existent or fragmented at best. Under these circumstances, complex models with large input requirements may not provide reliable outputs, and models with the following features may be more appropriate:

- relatively simple to use with minimal input data and training requirements;
- data are readily available or easy to obtain; and
- reasonable inferences can be drawn from the model simulations.

Empirical models that provide a more simplified mathematical model of crop physiological processes and that require fewer parameters provide a more useful analytical tool for farmers, water managers, policy makers and other end-users in less developed regions where data are limited (Dourado-Neto et al. 1998; Steduto et al. 2009a). For example, if the aim of a research project is to identify and subsequently alleviate water and soil constraints to increase non-rice DS crop production in Laos and Cambodia, models based on these principles should be considered. The Food and Agriculture Organization of the United Nations (FAO) has developed two empirical models, CropWat and AquaCrop, which could potentially fulfil these needs based on primary design function, input requirements and availability and ease of use. A third empirical model, the soil water balance model (SWBM), developed locally by the National Agriculture and Forestry Research Institute of Laos (NAFRI), University of Queensland (UQ) and the International Rice Research Institute (IRRI), might be another option. A comprehensive review of these models is provided below, and a quick reference table can be found in Appendix 1.

CropWat

General applications

CropWat is a decision support system developed by the Land and Water Division of FAO, and designed for practical use by agronomists, agro-meteorologists and irrigation engineers (Antoine 1998; Bernardi 2004). It is an empirical process-based crop model that is used to calculate crop water and irrigation requirements from crop and climate data. It can also be used to estimate crop performance under both rain-fed and irrigated conditions based on calculations of the daily soil water balance. At the field scale, it can be used to evaluate farmer irrigation practice; at the larger scale, it can be used to establish water supply schedules for different cropping patterns within an irrigation scheme, and can include a maximum of 20 different cultivars, including paddy and upland rice (FAO Water Development and Management Unit 2013; FAO 2014).

Theory and concepts

The algorithms of the CropWat model are based on the calculations described in FAO Irrigation and Drainage Papers No. 33 'Yield response to water' (Doorenbos et al. 1979) and No. 56 'Crop evapotranspiration − Guidelines for computing crop water requirements' (Allen et al. 1988). CropWat is comprised of eight modules: five input modules and three calculation modules. Climate, rain and crop data input modules are required to provide estimates of daily reference evapotranspiration (ET_0), crop evapotranspiration (ET_c) and subsequent calculations of crop water and irrigation requirements. Observed values of ET_0 can be directly input in to the model, or it can be calculated using daily, monthly or decadal time series climate data via the Penman−Monteith equation described in detail by Allen et al. (1988). ET_c is then calculated from ET_0, crop coefficients (K_c) and a water stress coefficient (K_s) used to describe the effect of soil water deficit conditions on ET_c given by the equation:

$$ET_c = ET_0 \times K_c \times K_s \quad (1)$$

where $K_s = 1$ under optimal conditions (i.e. no water stress) and $K_s < 1$ for soil limiting conditions (FAO 2009); methods to calculate K_s can be found in Allen et al. (1988). Estimations of effective rainfall (P_{eff}) used to determine crop water and irrigation requirements are calculated within the rain module based on one of four methods: fixed percentage, dependable rainfall (FAO/AGLW method), empirical formula, or the USDA Soil Conservation Service (USDA SCS) method. Brief descriptions of these methods and calculations are given in Appendix 2. Seasonal or decadal crop water and irrigation requirements are then calculated as the difference between ET_c and effective rainfall (P_{eff}) given by:

$$CWR = ET_c - P_{eff} \quad (2)$$

P_{eff} is also used to account for deep percolation and surface run-off which cannot be calculated within the model.

Soil and cropping pattern input modules are required to determine irrigation scheduling and scheme supply which are based on calculations of daily soil water balance. To determine the soil water balance, total rainfall (P), rather than P_{eff}, is used as water lost through run-off and deep percolation is estimated according to root zone soil moisture content and maximum infiltration rate. Within the irrigation scheduling module, there are options that allow the user to stipulate irrigation timing and irrigation application, and these are detailed in Appendix 2. The scheduling module also caters for an assessment of crop performance in response to full, supplementary or deficit irrigation by using yield response factors (K_y) derived from crop water

functions defined in Doorenbos et al. (1979) and given by the equation:

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = K_y \left(\frac{ET_x - ET_a}{ET_x}\right) \quad (3)$$

where Y_x and Y_a represent maximum and actual yield; and ET_x and ET_a are the maximum and actual evapotranspiration. Standard values for crop parameters (including K_c, critical depletion fraction (p) and rooting depth) and K_y values have been incorporated into the model but can be modified to match local conditions. Irrigation efficiency can also be defined within the scheme supply module to account for water losses from the field or the system because of failing infrastructure, poor land levelling, etc. A default value of 70% is recommended for a well-maintained gravity-fed system (FAO 2009). There are additional options within CropWat that are designed specifically for the irrigation of rice crops; for further information see FAO (2009). The net scheme irrigation requirement is determined on a monthly basis and considers previously calculated irrigation requirements of all crops in the command area over the growing season (Figure 1). Note that the net irrigation requirement does not account for any losses within the system, which would then be the gross irrigation requirement.

Advantages

Compared to other crop models that are data intensive and require substantial calibration for local conditions (e.g. CropSyst or WOFOST; see Todorovic et al. 2009), CropWat requires minimal input data. It is capable of predicting crop water and irrigation requirements for many different agro-ecological zones and climates due to its interoperability with the CLIMWAT 2.0 database, which was developed specifically to provide basic monthly observations of climate data from 3,200 meteorological stations located in 144 different countries (Smith 1992). Additionally, the algorithms upon which the model is based have been widely used to estimate yield response to water at all spatial scales (field, farm, scheme, regional and national) by engineers and economists who require the information to plan, design and manage irrigation and/or water trading schemes. For the water manager, CropWat is a practical, useful tool that provides a rapid approximation of yield reductions when water is limited, particularly within a farm/scheme where many different crops are grown (e.g. herbaceous crops, viticulture and horticulture) (Steduto et al. 2012). By default, the model is also able to provide estimates of actual evapotranspiration (ET_a) from the soil water balance based on average monthly rainfall and ET_0 through the application of the irrigation schedule function for

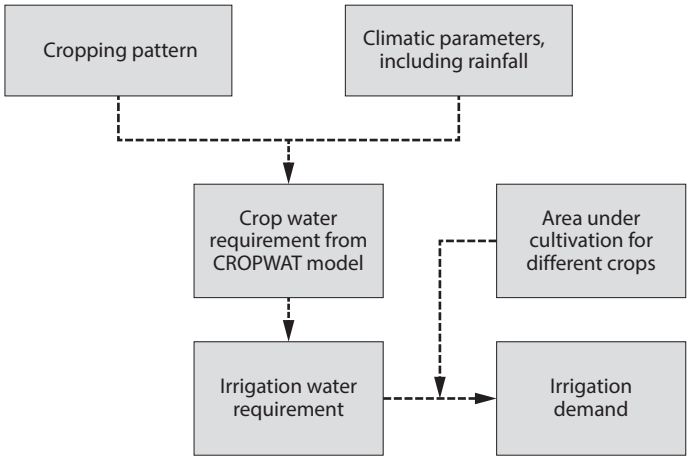

Figure 1. Irrigation demand estimation module within CropWat (Mohan and Ramsundram 2014).

rain-fed conditions, i.e. no irrigation. Researchers have also used CropWat or previous versions to investigate the potential impacts of climate change on crop yield based on decreased rainfall and water availability (e.g. Doria et al. 2006; Nkomozepi and Chung 2012). Other features of CropWat include standard crop (Doorenbos et al. 1979; Allen et al. 1988) and soil data which have been incorporated into the model, but these datasets should only be used where local data are unavailable (FAO Water Development and Management Unit 2013). The CropWat model can also be integrated with other data products and software programs to improve estimations of ET_c and, thus, crop water requirements, and to visualise model outputs. For example, Stancalie et al. (2010) incorporated daily ET_c estimations derived from surface energy balance algorithms using NOAA–AVHRR satellite data as an alternative to the classic Penman−Monteith method of ET_c calculation within the model. Generalised spatial distribution of crop and irrigation water requirements within a rain-fed or irrigated agricultural system can also be visualised within a GIS environment through simple interpolation of point-based estimates, as shown by Al-Najar (2011) and Feng et al. (2007).

Limitations

Research has shown that K_y values can vary greatly both temporally and spatially between crops, crop varieties and within single cultivars based on microclimates, soil environments and nutrient availability (e.g. Popova et al. 2006; Lovelli et al. 2007; Singh et al. 2010). Therefore, the simplified approach of providing one empirically derived value of K_y over a defined period limits accuracy of estimates, thereby increasing uncertainty in model outputs. Hence, CropWat is best used for general design, planning and operation of irrigation systems and to provide a rapid assessment of crop performance under water-limiting conditions; or to identify water allocation priorities at a regional or national level as environmental conditions are homogenised over space and time (Doorenbos et al. 1979). Hess (2010) highlighted other shortfalls of CropWat, including the inability to carry soil moisture over calendar years due to the fact that simulations are programmed to run for discrete, individual years despite the facility to use daily values of rainfall and ET_0. In addition, when calculating effective rainfall, the USDA SCS method is often used as the default method because it does not require local calibration and is a simple calculation. However, because this empirical relationship was developed within a semi-arid environment with well-drained soils, application should be limited to similar bioclimatic regions and/or months where ET_0 is high, otherwise estimates of P_{eff} may be underestimated, as shown by Mohan et al. (1996) who compared several methods to estimate effective rainfall within lowland rice production systems in tropical monsoon climates. Other constraints of the model include its incapacity to simulate the effects of rising atmospheric carbon dioxide (CO_2) concentrations on crop water use (UNFCCC 2014).

Applications of CropWat in Lao PDR and Cambodia

Whilst CropWat has been applied to assess crop water and irrigation requirements for a wide variety of crops, soil types and climatic conditions (Tran et al. 2012), a review of the literature reveals very few published studies in the context of Laos. The only study found related crop yield response of WS rice to supplementary irrigation application in Savannakhet Province (Toda et al. 2005). In Cambodia, CropWat has been more widely used to investigate the water, food and energy trade-offs in the development of multi-purpose reservoirs used for irrigation and hydropower production along the Mekong River (e.g. Räsänen et al. 2013, 2014). Researchers at the Institute of Technology of Cambodia have also investigated the use of CropWat to assess rice water requirements and to compare the modelled results with observed water fluxes (i.e. ET_c) measured using traditional water balance approaches, including the Bowen ratio method which is based on flux-gradient theory. The preliminary results from these studies have shown good agreement between observed and simulated values of seasonal rice water requirements in Cambodia. Based on these results, CropWat could provide a useful alternative to traditional methods of rice water and irrigation requirement estimation. In irrigation areas with adequate meteorological data, CropWat could further assist in the planning of seasonal irrigation scheduling and supply.

AquaCrop

General applications

AquaCrop is an empirical process-based, dynamic crop-growth model developed to simulate biomass and yield response of herbaceous crops (i.e. field and vegetable crops) to water under varying management and environmental conditions. It was developed by the Land and Water Division of FAO as a practical tool for users such as farmers, agronomists, engineers, water managers, economists and policy makers. The model is also a valuable tool for conceptualisation and analysis for research scientists (Steduto et al. 2008, 2012; Hsiao et al. 2009). It can be used to model the soil−crop−atmosphere continuum at many spatio-temporal scales; hence, there are many different applications of the model. For instance, at the field/farm scale, AquaCrop could be used by the farmer/water manager to develop a seasonal irrigation schedule (full, supplementary or deficit) for a specific crop or crop components. It can also be used: to optimise irrigation practices by comparing simulated model outputs with actual field data; to determine an irrigation program that ensures that soil water content within the crop root zone is fully depleted at the time of harvest, i.e. the best use of stored soil water; to assess the impact of soil properties (e.g. soil fertility) and management practices on yield; and to determine the optimal planting date based on probability analysis of historical rainfall and ET_0 data. At the larger scale, AquaCrop can be used to assess the effect of weather and climate on crop production and water use. For instance, the impact of rainfall variability on crop yields in rain-fed areas can be predicted using historical climate data. In conjunction with a geographic information system (GIS), model outputs can also be used to map the yield potential of a rain-fed agricultural system or region. Additionally, possible implications of a changing climate (e.g. increasing air temperatures and atmospheric CO_2 concentrations) on future crop production and water use can be simulated using the AquaCrop model. Furthermore, the outputs resulting from the aforementioned simulations could be incorporated into integrated water allocation and economic models to assist in water governance at the regional or basin level (Steduto et al. 2012).

Theory and concepts

Yield response to water presented by Doorenbos et al. (1979) was based on empirical functions of field, vegetable and tree crops. Since then, scientific knowledge of soil−crop−atmospheric processes has improved greatly. Coupled with the need to improve water productivity, which has escalated through decreasing water availability, a revision of the work of Doorenbos et al. (1979) was undertaken involving global consultation with researchers, experts and practitioners. Through this, AquaCrop evolved as a simulation model for herbaceous crops only (including forage, grain, fruit, oil, root and tuber crops), retaining the water-driven growth engine of Doorenbos et al. (1979) but improving the accuracy of outputs by partitioning ET_c into non-productive soil evaporation (E) and productive crop transpiration (T_r); and final yield (Y) into biomass (B) and harvest index (HI) (Steduto et al. 2008, 2009a, b; Hsiao et al. 2009). To partition yield, biomass production is directly estimated from ET_c through the introduction of a water productivity (WP) parameter as presented by Steduto et al. (2008; 2009b; 2012). It is given by the equation:

$$B = WP \times \Sigma T_r \quad (4)$$

where B is the cumulative biomass production (kg/m^2), $\sum T_r$ is the total crop transpiration over a specified time period for biomass production (mm or m^3/unit surface) and WP is the water productivity coefficient (kg of biomass/m^2, kg of biomass/mm or kg of biomass/m^3 of water transpired). Note that WP has been found to be approximately constant based

on the highly linear relationship between biomass production and water consumption of a given plant species (Steduto et al. 2007; 2012). Yield is then calculated as:

$$Y = HI \times B \quad (5)$$

In addition to these two core functions, four components have been incorporated into the model: a soil component to estimate the soil water balance; a crop component to model development, growth and yield processes; a climate component to establish the thermal regime, evaporative demand, rainfall and CO_2 concentrations; and a management component which explicitly considers the effect of management options on the soil water balance including the effects of fertiliser, water conservation methods (e.g. mulching, soil bunds) and forage cuttings on plant growth (Steduto et al. 2008, 2009a). The functional relationships between the model components are illustrated in Figure 2.

The climate component requires daily input values of minimum/maximum air temperature or growing degree days (GDD), rainfall and ET_0. Similar to CropWat, daily observations of ET_0 can be entered directly into the model or they can be calculated via the Penman−Monteith method. Alternatively, where daily data are insufficient, decadal or monthly averages of ET_0 and other meteorological variables can be provided and downscaled to a daily time step by using methods described by Gommes (1983). AquaCrop also requires mean annual concentrations of atmospheric CO_2. Default values derived from the Mauna Loa Observatory in Hawaii (1902–present) have been included in the model, although site-specific and forecast datasets from climate models can be

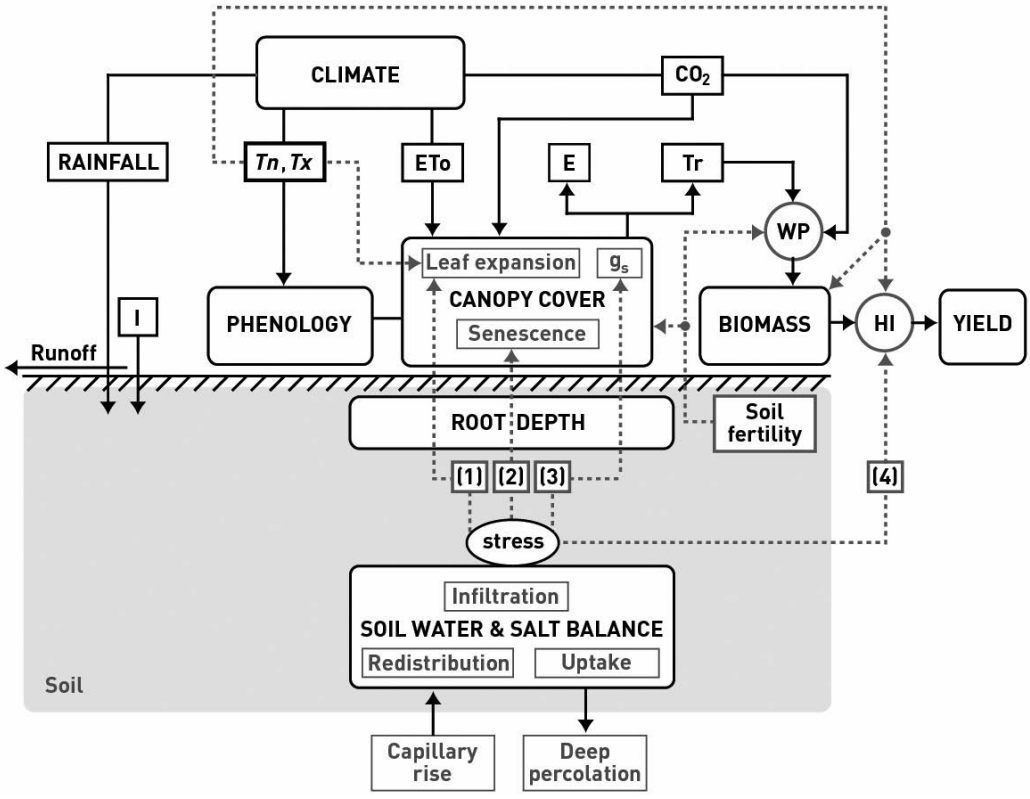

Figure 2. Functional relationships between AquaCrop model components (Steduto et al. 2008).

used to improve model accuracy and assess potential impacts of rising CO_2 concentrations, respectively (Steduto et al. 2009b, 2012).

The soil component allows the user to define up to five horizons of variable textural composition and depth within the soil profile. For each of the differentiated soil layers that encompass the root zone, it is necessary to define field capacity (Θ_{FC}), volumetric water content at saturation (Θ_{sat}), permanent wilting point (Θ_{PWP}), drainage coefficient (τ) and hydraulic conductivity at saturation (K_{sat}; note that K_{sat} is different to K_s which is the previously defined soil water stress coefficient). If site-specific or local data are unavailable, indicative values of the hydraulic parameters can be estimated via pedotransfer functions based on the USDA triangle soil textural class included in the model (Steduto et al. 2008, 2009a, 2012; Raes et al. 2009). Note that these functions rely on textural classification only and do not account for soil aggregation. Therefore, these estimates provide an approximation of hydraulic characteristics and users should modify the input based on known values. Additional specifications within the soil component are: soil water content in each soil layer at the beginning of a simulation, if not at field capacity; and the depth of a hard pan within the root zone that limits downward fluxes, which is mostly the case in the agricultural lowlands of Laos and Cambodia (Steduto et al. 2012). The main function of the AquaCrop soil component is to compute a daily soil water balance that provides estimates of water fluxes in and out of the root zone and changes in soil water content within the root zone boundaries. The processes included in the soil water balance include infiltration, run-off, deep percolation, drainage within the root zone, plant uptake, evaporation, transpiration and capillary rise (Steduto et al. 2009a, b, 2012). In addition, AquaCrop simulates a salt balance of salts that enter the soil profile by either capillary rise from shallow saline groundwater or irrigation water and salts that are flushed from the profile by excessive rainfall or irrigation applications. This function considers both the vertical and horizontal diffusion within the soil matrix based on salt concentration gradients (Raes et al. 2012; Steduto et al. 2012).

The crop component consists of five major elements and corresponding dynamic responses, namely phenology, canopy cover, rooting depth, biomass production and harvestable yield (Steduto et al. 2009a). The canopy plays a significant role within AquaCrop as it determines the amount of water transpired through plant development (i.e. canopy expansion, rooting depth, stomatal conductance and senescence) and consequent biomass production as a function of WP (Steduto et al. 2008, 2009a, b). To simulate the effect of water stress on crop productivity at different phenological stages, AquaCrop defines four stress effects: on leaf growth, stomatal conductance, senescence and *HI*. For all but *HI*, water stress is represented by K_s. The response of *HI* to water stress is more complex and involves more than one component; for more information see Raes et al. (2009) and Steduto et al. (2009a). Air temperature stress can also be assessed within the model by simulating dynamic crop growth and development which is usually described in either thermal time (*GDD*, °C day) or calendar time. In AquaCrop, *GDD* is the default clock, but there is the option to use calendar time if *GDD* is unavailable. *GDD* is computed following McMaster and Wilhelm (1997) and is given by the equation:

$$GDD = \left(\frac{T_{\max} - T_{\min}}{2}\right) - T_{\text{base}} \tag{6}$$

where *GDD* is the number of temperature degrees that determines proportional growth and development, T_{max} is the daily maximum air temperature, T_{min} is the daily minimum air temperature and T_{base} is the temperature below which crop development ceases (Steduto et al. 2008). AquaCrop considers an upper air temperature threshold (T_{upper}) as well; more detailed information regarding methods of *GDD* calculation within AquaCrop is presented by Raes et al. (2012).

As mentioned, biomass production is estimated as a function of ET_c and the *WP* parameter. *WP* is normalised for atmospheric evaporative demand and climate conditions (represented by *WP**) as defined by ET_0 and atmospheric CO_2 concentrations, and is given by the equation:

$$WP^* = \left[\frac{B}{\sum\left(\frac{T_r}{ET_0}\right)}\right]_{[CO_2]} \tag{7}$$

where $[CO_2]$ outside the bracket indicates that the normalisation is for a given year and its specific mean annual CO_2 concentration (Steduto et al. 2009a). *WP* has proved to be almost constant for a given crop not limited by mineral nutrients, except in extreme cases of water and salinity stress. As *WP* is sensitive to

nutrient deficiencies, particularly nitrogen, the model allows the user to define soil fertility stress within the management component, which is discussed further below (Steduto et al. 2009a, 2012).

The management component is designed to include information specific to field or water management. Whilst AquaCrop is not designed to calculate nutrient balances nor simulate nutrient cycles, the impact of soil fertility on crop production can be reproduced through the field management option by stipulating one of three scenarios: non-limiting, medium or poor fertility, with increasing reductions in *WP*, canopy cover and other associated coefficients (for more information, see Steduto et al. 2008, 2009a, b; Zhang et al. 2011). Other field management options that are able to be simulated include previously mentioned water conservation methods of mulching (organic or synthetic) to reduce soil evaporation, and soil bunds, soil ridging or contouring to control surface run-off and infiltration. The timing of forage cuttings can also be specified here. In the water management option, the user can define rain-fed or irrigated conditions and water application methods including sprinkler, surface and drip (either surface or below-ground). The routines to assess the effect of water management strategies in AquaCrop are based on the same algorithms included in CropWat (Raes et al. 2009).

Advantages

A distinctive feature of AquaCrop is that it expresses foliage development as canopy cover (CC) rather than the more widely used leaf area index (LAI). This greatly simplifies the simulation by reducing the overall canopy expansion to a growth function that directly accounts for the effects of planting density by using CC values that can be easily estimated by the human eye or generated from satellite data (Steduto et al. 2009a, b). Furthermore, *WP* is normalised for evaporative demand as defined by ET_0 and atmospheric CO_2 concentrations. It is also relatively insensitive to variation in soil nutrient status (Yuan et al. 2013) which enables the quantative assessment of water-limited productivity between different agro-ecological zones, crops and seasons, including predicted climate change scenarios (Steduto et al. 2007, 2008, 2009a). In AquaCrop, *WP* is calculated by using ET_0 rather than more traditional methods using vapour pressure deficit (VPD) as it has been shown to account for advective transfer of energy where the use of VPD does not. In addition, for crops with yields high in protein and fat content that require more energy per unit of dry matter produced after flowering and during the grain/fruit filling stage, AquaCrop will simulate decreasing *WP* values to compensate for yield composition (Steduto et al. 2012). Moreover, AquaCrop provides an environment to appraise water-related yield response functions that could further assist in crop ideotype design (Fernández et al. 2013; FAO 2014).

Like CropWat, the number of input parameters and data required to run AquaCrop compared to other crop models is small and they are easily measured or readily available. However, AquaCrop is an evolution of CropWat that features better reproduction of the crop environment through more advanced crop routines. To target a broad range of users with varying modelling competence the graphical user interface (GUI) is designed in a series of 'layers' with underlying components that are able to be manipulated, depending on the experience of the user. Input data are stored in management files that can be directly accessed through the GUI, and consequences of changes to input parameters can be easily visualised through the generation of multiple graphs and schematic displays (Steduto et al. 2009a).

Despite its simplicity, studies have shown that the performance of AquaCrop compares well to other, more complex models (Steduto et al. 2011), which is attributed to the incorporation of fundamental physiological and agronomic processes of crop production and its responses to water within the model. Thus, AquaCrop provides an accurate, simple and robust alternative to model crop response to water supply that can predict attainable yield; and considers irrigation and field strategies, soil type, sowing dates etc. for rain-fed and irrigated agriculture (Raes et al. 2009; Steduto et al. 2009b). AquaCrop also offers an additional plug-in program that incorporates all calculation procedures included in the standard program, which facilitates multiple simulations pre-defined in the GUI, the results of which are saved as project files (Raes et al. 2012).

Limitations

In contrast to CropWat, ET_0 cannot be calculated within the model via the Penman−Monteith method; instead, observed values of ET_0 are required as an input parameter. In the absence of measured data, ET_0 can be estimated using climatic data as described by Allen et al. (1988); or it can be generated through

the use of an ET_0 calculator, which is a companion software package also developed by FAO Land and Water Division (Raes 2012). At the time of writing the authors are aware that an updated version of AquaCrop (v 5.0) is under development which will include instructions to estimate ET_0 (Touch Veasna, personal communication, 2015). Another sub-routine that could potentially increase the uncertainty of model outputs relates to the estimation of effective rainfall. For example, when daily observations are available, P_{eff} can be calculated by subtracting run-off from P. However, when there is only 10-day or monthly data available, P_{eff} is determined by setting P_{eff} as a fixed percentage of P; or by the USDA SCS method, which has been shown to underestimate P_{eff} in tropical monsoonal climates similar to those of Laos and Cambodia. Furthermore, whilst AquaCrop has demonstrated comparative performance against more sophisticated models, Steduto et al. (2011) highlight the importance of local refinements to improve model reliability, especially in areas that have been under-represented in FAO calibrations of the model or experience severe water stress.

As mentioned, multiple simulations can be performed using an additional plug-in program. However, the project files need to be predefined using the standard AquaCrop GUI which can be time consuming if a large number of simulations are required (Raes et al. 2012). Simultaneous visualisation of multiple simulations to assess spatio-temporal impacts of various environmental/management treatments across larger spatial scales is also not possible within the standard AquaCrop program. To this end, FAO has developed two tools, AquaData and AquaGIS, to substantially decrease the time required to create a large number of input files by automating file generation containing basic data specific to the experimental conditions; and to automatically execute AquaCrop project files over space and time to analyse, interpret and visualise simulated results (Lorite et al. 2013).

Applications of AquaCrop in Lao PDR and Cambodia

Mainuddin et al. (2010) used AquaCrop to assess the impact of future basin development and climate change scenarios on agricultural productivity (specifically rain-fed rice, DS irrigated rice and maize), water productivity and food security in the Lower Mekong River Basin (LMRB). Based on annual rainfall and ET_0, 14 agro-climatic zones were delineated across the LMRB and included sites in Laos, Thailand, Vietnam and Cambodia. Future productivity was assessed using AquaCrop validated with climate data for the period 1996–2000 which were obtained from the global surface at 30 min arc resolution, from the Climate Research Unit at the University of East Anglia (see http://www.cru.uea.ac.uk/data/) and from global surface summary of daily data from the National Climatic Data Centre of the National Oceanic and Atmospheric Administration (see http://www.ncdc.noaa.gov/cdo-web/datasets). Localised meteorological data were obtained from the International Water Management Institute database, where available (Mainuddin and Kirby 2009b). The results showed that rice yield will generally increase in the northern parts of the LMRB including Laos and Thailand, attributed mostly to increased rainfall and atmospheric CO_2 concentrations. In the lower regions of the LMRB (Cambodia and Vietnam), where yield was adversely affected, the model showed that yields could potentially be increased by shifting planting dates. Simulations of productivity were further enhanced by improving soil fertility and applying supplementary irrigation. Other models considered for this study included APSIM (Keating et al. 2003), DSSAT (Jones et al. 2003), ORYZA2000 (Bouman et al. 2001), INFOCROP (Aggarwal et al. 2006), CERES-Maize (Jones et al. 1986) and CropSyst (Stockle et al. 2003). However, these models were considered too complex for the majority of the targeted users, i.e. researchers, extension officers, water/farm managers and economists. Furthermore, the number of parameters and variables required to run these models is far greater than those required for AquaCrop and they are not always readily available (Mainuddin et al. 2010; Steduto et al. 2011), especially in data-sparse regions such as Laos and Cambodia. Impacts of basin development and climate change on agricultural and water productivity using AquaCrop in the LMRB are further explored in Mainuddin and Kirby (2009a) and Mainuddin et al. (2011, 2012, 2013).

The USAID Mekong ARCC Climate Change Impact and Adaptation Study also explored projected shifts in hydroclimatology in the LMRB to 2050 and consequent impacts on agriculture and other important livelihood sectors (including fisheries and livestock). In this study, eight hotspots representative of the agro-ecosystems found in the LMRB that are expected to experience the greatest increase in relative air temperatures, rainfall or sea level rise

were identified as being particularly vulnerable to the impacts of climate change. In Laos, the Khammouan and Champasak provinces were recognised as hotspots; in Cambodia, the hotspots were found to be the Mondulkiri and Kampong Thom provinces. A vulnerability assessment of crop production (yield, t/ha) in the hotspot areas was conducted using AquaCrop. Only rain-fed rice and maize were included in the analysis to reduce computing time, and because of their economic importance for subsistence agriculture in the LMRB. Projected increases in rainfall during the wet season were found to have a negative impact on rice yields in the lowlands of Champasak, and maize yield projections showed general decreases across the LMRB.

NAFRI soil water balance model

General applications

As described by Inthavong et al. (2011, 2012), this soil water balance model (SWBM) was originally developed to project the length of the growing period (LGP) for rain-fed lowland rice in southern Laos based on the level of water stress as determined by rainfall and the empirical relationship between soil clay content and deep percolation of standing water. It can also be used to estimate yield reductions caused by soil nutrient and water stress. Furthermore, the model can be used to identify short periods of drought that may occur during critical phenological periods at which time irrigation may be necessary. Estimates of stored soil water can also be used to identify periods at the end of the WS where there are opportunities to use residual soil moisture to grow short duration, non-rice DS crops; and to determine deficit irrigation schedules to increase irrigation water use efficiency.

Theory and concepts

The SWBM is designed to determine the water stored in the soil profile, and thus LGP, by calculating weekly ET_c, percolation, standing water level (WL), volumetric soil moisture content at saturation, field capacity and wilting point, and is described in detail by Inthavong et al. (2011). As previously discussed, traditional puddling methods and land preparations for WS rice production lead to the development of a hardpan, therefore the soil profile within the model has been divided into two layers: the surface soil layer (0–20 cm) which is regarded as the effective root zone; and the subsoil layer (20–100 cm). The amount of stored water in the surface layer also considers the standing water level and is given by the equation:

$$W_{\mathrm{surface(t)}} = W_{\mathrm{surface(t-1)}} + P_{\mathrm{(t)}} - ET_{\mathrm{C(t)}} - D_{\mathrm{topsoil(t)}} - RO_{\mathrm{(t)}} \quad (8)$$

where $W_{surface}$ is the amount of stored water (mm), P is rainfall, $D_{topsoil}$ is the downward water loss from the topsoil (mm), RO is surface run-off and t is time given as day or week. Stored water in the subsoil is calculated by the equation:

$$W_{\mathrm{subsoil(t)}} = W_{\mathrm{subsoil(t-1)}} + D_{\mathrm{topsoil(t)}} - D_{\mathrm{subsoil(t)}} \quad (9)$$

where $W_{subsoil}$ is the amount of water stored in the subsoil (mm), and $D_{subsoil}$ is the downward water loss from the subsoil (mm). The total amount of water stored in the soil profile is then calculated by adding these two components together, given simply by:

$$W_{\mathrm{total(t)}} = W_{\mathrm{surface(t)}} + W_{\mathrm{subsoil(t)}} \quad (10)$$

ET_c is calculated by multiplying ET_0 (determined using the Penman−Monteith equation) with a crop coefficient and a water stress coefficient presented previously in equation (2).

Downward vertical movement of water (D) through both the topsoil and subsoil was estimated using an empirical relationship derived from studies in northeast Thailand, Laos and Cambodia of soil clay content and downward water movement, and is given by the equation:

$$D_{\mathrm{top/subsoil}} = \frac{18.7}{C} - 0.16 \quad (11)$$

where C is the clay content of the soil expressed as a percentage (%).

Surface run-off (RO) is only calculated when the amount of water in the surface layer (which includes the saturated topsoil profile and standing water level) exceeds bund height (h). The maximum amount of water available in the surface layer is given by the equation:

$$W_{\mathrm{max}} = S_{\mathrm{w\_sat}} + h \quad (12)$$

If

$$W_{\max} \geq W_{\text{surface(t}-1)} + P_{(\text{t})} - ET_{\text{C(t)}} - D_{\text{topsoil(t)}} \quad (13)$$

then $RO_{(\text{t})} = 0$. However, if

$$W_{\max} \leq W_{\text{surface(t}-1)} + P_{(\text{t})} - ET_{\text{C(t)}} - D_{\text{topsoil(t)}} \quad (14)$$

then $RO_{(\text{t})} > 0$ and is calculated as follows:

$$RO_{(\text{t})} = W_{\max} - \left(W_{\text{surface(t}-1)} + P_{(\text{t})} - ET_{\text{C(t)}} - D_{\text{topsoil(t)}}\right) \quad (15)$$

Estimates of standing water levels are calculated based on one of three conditions: below the soil surface ($WL < 0$), above the soil surface ($0 < WL < W_{\max}$); and above the soil surface at the maximum level ($WL = h$).

Characteristics of the topsoil and subsoil (volumetric soil moisture content at saturation, field capacity and wilting point) are determined based on statistical correlations described by Saxton and Rawls (2006). From these values, the start of the growing period (SGP), the end of the growing period (EGP) and thus the LGP can be identified. For instance, the SGP is defined as the time when the soil water content within the surface layer is greater than field capacity for three consecutive weeks; and the EGP is defined as the time when the soil water content within the surface layer falls below wilting point.

Advantages

Inputs for the NAFRI SWBM are minimal, requiring daily or weekly records of rainfall, sunshine hours, maximum/minimum wind speed, relative humidity and maximum/minimum temperature and information related to soil properties (texture, depth and mineral nutrients N, P and K). An additional advantage of the model is that it provides point-based information which can be scaled up to the district/provincial scale using GIS interpolation techniques.

Limitations

The toposequence of the rice-growing lowlands is characterised by lower, middle and upper positions and whilst this model has satisfactorily predicted soil water conditions in rice fields in the middle, it fails to perform well in the lower and upper reaches of the toposequence. This can be attributed to the inability of the model to estimate lateral water movement in the landscape which is highly dynamic and variable through space and time (Inthavong et al. 2004, 2011). Furthermore, this model was originally developed by Inthavong et al. (2001) to identify agro-ecological zones and provide land suitability maps in Laos with the aim of increasing agricultural production. Although the model has since been calibrated with soil, climate and yield data obtained from extensive field studies of lowland rice production in Savannakhet Province (Inthavong et al. 2011), soil and climate data for the remaining 16 provinces of Laos are restricted to FAO soil classification maps (FAO 1988) and interpolated climate surfaces derived from often incomplete, long-term meteorological records collected at 32 locations across the country. Therefore, for the model to be more widely applicable across the region, it is recommended that extensive field campaigns designed to characterise the soils, climate, productivity and the effect of crop management practices on lowland rice production in other parts of the LMRB (e.g. southern Laos and Cambodia) be conducted to calibrate the model. Moreover, this model was developed primarily to assess field water availability for lowland rice production only; its ability to reliably assess field storage, LGP and yield estimates of alternative crops (including long bean, cassava, cotton, maize, potato, sweet potato and soybean) are yet to be reported.

Applications of NAFRI SWBM in Lao PDR and Cambodia

As it was developed by the National Agriculture and Forestry Institute of Laos in conjunction with UQ and IRRI, studies that have reported using this model are limited to Laos only; these have been discussed in the previous text.

Summary and conclusions

The main purpose of this report was to compare three freely available crop models (CropWat, AquaCrop and NAFRI SWBM) that can be used to identify water and soil constraints to the adoption of non-rice DS crops in data-sparse environments where institutional/technical capacity is limited. The three models were investigated to explore potential production capacity for a range of DS cropping alternatives. All three models require minimal input data compared to more complex process-based models. Generally, if the input data are not readily available in a compatible form they are easy to measure. Additionally, CropWat, AquaCrop and the NAFRI SWBM have similar functions and can be used to predict water availability and crop response to current and future agro-climatic conditions. However, in this respect, the AquaCrop model is considered superior in that it can account for rising atmospheric concentrations of CO_2 as well as increasing surface temperatures; the CropWat and NAFRI models can account only for increasing temperatures. Another advantage of the AquaCrop model is that, unlike the CropWat and NAFRI models, it normalises water productivity for atmospheric evaporative demand and CO_2 concentrations and is relatively insensitive to variation in soil nutrient status; this enables the quantitative assessment of water-limited productivity between different agro-ecological zones, crops and seasons.

As an evolution of CropWat, AquaCrop reproduces the crop environment more accurately through more advanced crop routines including the partitioning of ET_c into non-productive soil evaporation and productive crop transpiration; and final yield into biomass and harvest index. AquaCrop also allows the user to better define the soil profile by incorporating up to five horizons of variable textural composition and depth within the root zone, whereas the CropWat and NAFRI models allow the user to specify only one (i.e. maximum rooting depth) or two layers (i.e. topsoil and subsoil), respectively. An additional feature unique to AquaCrop is that it simulates a balance of salts entering or leaving the root zone and considers both the vertical and horizontal diffusion within the soil matrix based on salt concentration gradients. AquaCrop also offers an additional plug-in program that incorporates all calculation procedures included in the standard program, which facilitates multiple concurrent simulations, substantially decreasing time requirements.

Finally, CropWat and AquaCrop are relatively easy to manipulate through a GUI and have been widely adopted within the global scientific and other user communities. Outside of Laos, the NAFRI SWBM is less well known and, at the time of publication, the interface was not immediately intuitive and required greater familiarisation, which could limit its useful application.

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Appendix 1. Comparison of model capabilities and constraints

Model	AquaCrop
Developer	FAO Land and Water Division
Primary design function	To simulate biomass and yield response of herbaceous crops to varying water availability; empirical process-based crop model
Applications	Assessment of water-limited, attainable crop yield at specified geo-location Comparison of predicted yield vs. actual yield at different spatial scales (i.e. field, farm, region) to identify yield gap and constraints limiting production; extrapolation at larger scales is achieved through GIS applications Assessment of long-term rain-fed crop production Development of irrigation schedules for maximum production; this includes operational and seasonal strategies Scheduling deficit and supplemental irrigation Evaluation of the impact of fixed delivery irrigation schedules on attainable yields Simulation of crop sequences Analysis of crop water; requirements/irrigation schedules for future climate change scenarios (inc. elevated temperatures and $[CO_2]$) Optimisation of water use where availability is limited based on economic, equitability and sustainability criteria Evaluation of the impact of low fertility and water−fertility interactions on yield Assessment of water productivity at different spatial scales Assist in further crop ideotype design Support decision making regarding water allocation and other water policy tools
Input parameters and variables	Meteorological data: T_a, ET_0, rainfall, compatible with CLIMWAT 2.0 Soil texture data: sand, clay, loam expressed as % Crop parameters: initial, final and rate of change in % canopy cover; initial, final and rate of change in % rooting depth; biomass WP; HI; typical management conditions, e.g. irrigation dates and volumes, sowing and harvest dates, mulching ET_c
Outputs	Various indicators including yield and water deficit
Limitations	Does not account for the effects of pests and diseases; ET_0 cannot be calculated within the model
Additional features and comments	AquaCrop plug-in that facilitates multiple model runs pre-defined in the GUI; results are saved as output files Evolution of CropWat that features better reproduction of crop environment through more advanced crop routines Training not required; degree of difficulty is rated low Runs on daily calendar or thermal (GDD) time steps Distinguishing features: WP normalised for climatic conditions (i.e. ET_0 and atmospheric $[CO_2]$); use of ground canopy cover instead of LAI Based on FAO Irrigation and Drainage Paper No. 33 'Yield response to water' $[CO_2]$ derived from Mauna Loa Observatory in Hawaii Does not compute nutrient balances or simulate nutrient cycles; instead parameterises for fertility levels (poor to optimal) Can run simulation in daily or seasonal time steps

Model	CropWat
Developer	FAO Land and Water Division
Primary design function	To calculate crop water/irrigation requirements; empirical process-based crop model
Applications	Development of irrigation schedules for different management practices based on daily soil water balance calculations Calculate irrigation scheme water supply for varying crop patterns (up to 20 crops) Evaluate farmer irrigation practices Estimate crop performance for rain-fed and irrigated conditions
Input parameters and variables	Soil: inc. initial available water, initial soil moisture depletion, max. infiltration rate, max. rooting depth, total available water (TAW), critical depletion for puddle cracking, drainable porosity, field capacity, wilting point, readily available water (RAW) Climate (whilst compatible with data from CLIMWAT, data from nearest meteorological station should be used): temp, RH (%) or VPD (kPa), wind speed, sunshine, rainfall Crop (rice and non-rice): planting/transplanting date, crop coefficient (K_c), stages, rooting depth, puddling depth, critical depletion fraction (p), yield response factor (K_y), max. crop height
Outputs	Climatic data and ET_0 Daily soil water balance Crop water/scheme irrigation requirements
Limitations	Does not have the capacity to simulate the direct effects of rising atmospheric [CO_2] on crop water use
Additional features and comments	Standard crop and soil data have been incorporated into the model but should only be used as a starting point where local data are unavailable Daily, monthly and decadal input of climate data to calculate ET_0 Calculation of crop water requirements and irrigation scheduling for paddy and upland rice Interactive adjustable irrigation schedules Graphical representation of input data, crop water requirements and schedules Easy import and export of data and graphics via clipboard or ASCII files Based on FAO Irrigation and Drainage Paper No. 33 'Yield response to water' and No. 56 'Crop evapotranspiration − guidelines for computing crop water requirements' Simplicity of model and minimal input parameters may lead to large uncertainties in outputs

Model	NAFRI SWBM
Developer	Suan Pheng Kam,Thavone Inthavong and Chu Thai Hoanh at IRRI, 2000
Primary design function	To estimate stored field water, for defining the length of growing period (LGP) and water stress development during growth for rain-fed lowland rice crops
Applications	Estimate the soil water level for the growing period in the wet season Evaluate possible yield reductions caused by soil and plant water deficits
Input parameters and variables	Daily or weekly meteorological data (inc. RH, wind speed, max/min temp) Digital elevation model (DEM), land use and soil maps
Outputs	Estimation of length of growing season and potential stress development Gridded maps of interpolated soil moisture status
Limitations	There is overestimation/underestimation of water availability at different toposequence positions Cannot account for lateral flow within the root zone
Additional features and comments	–

Appendix 2. Effective rainfall and irrigation options for non-rice crops in CropWat

Table 1. Methods to calculate effective rainfall (adapted from Dastane 1978; Smith 1992; FAO 2009).

Method	Description	Calculation
Fixed percentage	P_{eff} is estimated as a fixed percentage of rainfall (P) to account for surface run-off and drainage	P_{eff} = fixed percentage × P
Dependable rainfall	This is based on empirical formulae derived from studies conducted in arid and sub-humid climates. It is the combined effect of dependable rainfall (80% probability of exceedance) and estimated losses due to run-off and deep percolation. For more information, see Smith (1992)	Monthly P data (P_{mth}) $P_{eff} = 0.6 \times P - 10$ for $P_{mth} \leq 70$ mm $P_{eff} = 0.8 \times P - 24$ for $P_{mth} > 70$ mm Decadal P data (P_{dec}) $P_{eff} = 0.6 \times P_{dec} - (10$ for $P_{dec} \leq (70/3)$ mm $P_{eff} = 0.8 \times P_{dec} - (24/3$ for $P_{dec} > (70/3)$ mm
Empirical formula	This is similar to dependable rainfall except that parameters can be adjusted to match regression analysis of local climate data: a, b, c, d and z are correlation coefficients	Monthly P data (P_{mth}) $P_{eff} = a \times P - b$ for $P_{mth} \leq z$ mm $P_{eff} = c \times P - d$ for $P_{mth} > z$ mm Decadal P data (P_{dec}) $P_{eff} = a \times P_{dec} - (b$ for $P_{dec} \leq (z/3)$ mm $P_{eff} = c \times P_{dec} - (d/3$ for $P_{dec} > (z/3)$ mm
USDA Soil Conservation Service (USDA SCS)	This is based on empirical relationships derived from the analysis of long-term climate and soil data observed at 22 experimental sites representative of different climatic and soil conditions throughout the USA	Monthly P data (P_{mth}) $P_{eff} = P_{mth} \times (125 - 0.2 \times P_{mth})/125 \leq 250$ mm $P_{eff} = 125 + 0.1 \times P_{mth}$ for $P_{mth} > 250$ mm Decadal P data (P_{dec}) $P_{eff} = P_{dec} \times (125 - 0.6 \times P_{mth})/125 \leq (250/3)$ mm $P_{eff} = (125/3) + 0.1 \times P_{mth}$ for $P_{mth} > (250/3)$ mm

Table 2. Irrigation timing options for non-rice crops (FAO 2009).

Irrigation timing	Description
User defined intervals	This allows the user to set defined intervals of irrigation events, specified as 'days after planting'. This option can be used to evaluate current irrigation practices and simulate alternative irrigation schedules. It can also be used to refine the programming of irrigation schedules that are developed in other options within the model.
Critical depletion	This is the classic method used to determine irrigation schedules that ensures minimal use of irrigation water applied at irregular intervals. It is based on the application of water only when the readily available water (RAW) is totally depleted; as such, it relies on having flexible irrigation infrastructure.
Above or below critical depletion	Similar to critical depletion except that the user can stipulate a percentage of RAW at which to irrigate. For values set below 100%, water will be applied before critical depletion; for values set above 100%, water will be applied after critical depletion and the crop will experience a certain level of water stress.
Fixed intervals per stage	This allows the user to set a defined interval between irrigation applications per growth stage which are broadly classified as initial stage, development stage, mid-season and late season. This option is particularly useful in an irrigation system that has a rotational distribution of water.
Fixed depletion	This option will determine irrigation events based on a fixed value of soil moisture depletion (mm). This is particularly useful in determining an irrigation schedule at the field level.
At predetermined reduction in ET_c per stage	This option schedules irrigation applications based on an accepted level of reduced ET_c and is most useful when there is a known water shortage and deficit irrigation methods are required.
Predetermined reduction in yield	This option will schedule irrigation events based on an acceptable level in yield reduction. This method is also useful when deficit irrigation methods are required.
No irrigation	This allows the user to assess crop production within a rain-fed environment.

Table 3. Irrigation application options for non-rice crops (FAO 2009).

Irrigation application	Description
User defined application depth (mm)	This allows the user to define different application depths for each irrigation event.
Fixed application depth (mm)	This option will base irrigation water delivery to wet the soil to a fixed depth after every irrigation event.
Refill soil to field capacity	This option will calculate irrigation water volumes based on the amount required to refill the soil to field capacity. As depletion in the root zones varies over the course of the growing season, irrigation volumes may also vary substantially.
Refill soil above or below field capacity	This is similar to the previous option except that the user can stipulate a percentage of refill. For values set below 100%, water applications will not be adequate to refill the soil to field capacity; for values set above 100%, water applications will exceed field capacity of the soil and result in water losses through deep percolation which is very useful in situations where leaching is required.

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