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Rainfall-related opportunities, risks and constraints to rainfed cropping in the Central Dry Zone of Myanmar as defined by soil water balance modelling

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ABSTRACT

The Central Dry Zone in Myanmar is a major production area of rainfed pulses and sesame, grown in double-crop systems or intercropped with pigeon pea. Yields are generally low and variable. Water balance modelling in the Magway Region was used to identify opportunities for improvement. Annual rainfall from 1951 to 2016 was 754 mm (CV = 0.22), with 668 mm (CV = 0.26) in the growing season of 180 days (CV = 0.15). Variable rainfall and low soil water holding capacity lead to wide inter- and intra-annual fluctuation between water deficit and excess, with nutrient leaching expected from substantial deep percolation (61 mm yr^{-1}). Despite variable rainfall, monsoon crops of 80–90 days duration had relatively stable ET (CV = 0.09) suggesting reliable potential yields, estimated to average 2.9 t ha^{-1} for groundnut. Reliable yields should also be achievable when this crop is intercropped with long duration (180 days) pigeon pea, a system that ensures income from the intercrop whilst having the capacity to adapt to variable post-monsoon conditions. The challenge with monsoon crops and pigeon pea is to effectively provide soluble nutrients (N, S) in a leaching environment, and P when surface soil is frequently dry. The post-monsoon crop in a double-crop system is risky, with variable ET (CV = 0.37) and yield potential. An option here is to vary inputs according to the potential, which is high with early sowing on a wet soil profile. Rainfall has declined since the 1950's, notably in June-July, but with no discernible effect on planting date or growing season length. There are now fewer but larger rainfall events, with implications for hydrology, agronomy and soil conservation.

1. Introduction

The Central Dry Zone (CDZ) of Myanmar covers c. 80,000 km^2 between mountain ranges to the north, east and west and the Ayeyarwady Delta to the south. It encompasses parts of the Magway, Sagaing and Mandalay Regions and holds 25% of the country's population, most of who rely on agriculture for their livelihoods. Food insecurity and endemic poverty are critical constraints to development (Vaughan and Levine, 2015). An estimated 75% of cropping is in rainfed upland systems, equivalent to c. 4 M ha of crop. Annual rainfall for over 85% of the CDZ is in the range of 500–900 mm concentrated into a 4–6 month monsoonal wet season (McCartney et al., 2013), which should favour reliable crop production although yields are generally low and variable (MoAI, 2014; FAOSTAT, 2017). Results from participatory rural appraisal suggest that groundnut (*Arachis hypogaea*) yields vary between around 0.6 t ha^{-1} in "poor years" and 1.4 t ha^{-1} in "normal" years, with occasional fields yielding up to 3.0 t ha^{-1} in the best years, whilst pigeon pea (*Cajanus cajan*) yields are about half this (Birchall et al., 2017; Guppy et al., 2017).

Inter-annual variation in both rainfall and the dates for onset and recession of the monsoon is high (McCartney et al., 2013). This potentially makes for a challenging cropping environment, especially as most soils in the CDZ are sandy with low organic matter (Guppy et al., 2017) and have little capacity to retain water and nutrients. The situation is further complicated by possible effects of climate change (Anon, 2012; IWMI, 2015).

A summary of three studies by the International Water Management Institute concluded that managing water variability is the key to improving crop yields and livelihoods in the CDZ (IWMI, 2015). However, despite large surface water resources, relatively few farmers have access to water for irrigation because of poor infrastructure. The prospects for a sustainable increase in groundwater extraction also appear to be limited, with recharge of around 50 mm yr^{-1} or $<$ 10% of rainfall (Pavelic et al., 2015). It is likely, therefore, that improved livelihoods in the immediate future will depend largely on using rainfall more effectively.

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Underpinning any improvement in cropping system performance will be a sound understanding of the opportunities provided by rainfall and the rainfall-related risks. It is not sufficient to know that rainfall is variable, or that the dates for the onset and recession of the monsoon vary, because plants respond to soil water which provides a buffer against rainfall variability. Soil water balance modelling has proven to be a useful tool for improving insight into risks and opportunities for rainfed cropping, particularly where there are insufficient data to apply more process-driven crop simulation models (Cornish et al., 2015a, 2015b).

This paper reports the adaptation of a soil water balance model (Cornish et al., 2015a) and its application to the analysis of cropping systems on coarse-textured soils of the southern CDZ, where major crops are the pulses pigeon pea and green gram (*Vigna radiata*), the oilseed legume groundnut, and the oilseed non-legume sesame (*Sesamum indicum*). In most years, short duration (80 to 90 day) monsoon and post-monsoon crops are grown in a double-cropping system, in many instances intercropped with long duration (180 day) pigeon pea. The aims of this study were to identify rainfall-related risks and opportunities, evaluate change in these over time, and propose management strategies for more effective water use.

2. Methods

The intention was to characterise rainfall-related risks and opportunities rather than predict crop yields. This avoided the need to parameterise and validate several crop models, which would have been impracticable as the study region has little history of the research required for model parameterisation (e.g. Fensterseifer et al., 2017). The study focused on the Magway township area of the Magway Region (20° 9′ 26.47″N; 94° 56′ 13.92″E), which was considered to represent rainfed agriculture of the southern half of the CDZ. It was one of several locations for collaborative Myanmar-Australia field research during 2012–2017, and extensive participatory on-farm research in 2016 and 2017.

2.1. Model overview

The model was adapted from a daily water balance model used in rice-based systems in India (Cornish et al., 2015a), by removing surface ponding and including a soil surface layer (0–15 cm) to simulate water in the cultivated and fertilised surface. The two-layer model is described briefly below and in more detail in Cornish et al. (2015a). It is a point model, so outputs of deep drainage and runoff cannot be directly scaled up to the watershed. It assumes that lateral inflows are balanced by outflows and there is no upward flux from a shallow water table. At the heart of the model, evapotranspiration (ET) is estimated as a function of potential evapotranspiration (Eo) and soil water (Allen et al., 1998).

The daily water balance was computed for a rainfed system of wet season crops and grazed weeds in the subsequent fallow. The soil water balance was:

$$\mathrm{PAW}_{\mathrm{day}\,2} = \mathrm{PAW}_{\mathrm{day}\,1} + \mathrm{R} - (\mathrm{ET} + \mathrm{RO} + \mathrm{DP}) \tag{1}$$

Where PAW is the plant-available water (mm) in a soil profile, held between an upper limit (UL) determined by soil properties and a crop-specific lower limit (CLL) or "wilting point"; R is daily rainfall (mm); ET is evapotranspiration (mm); RO is runoff (mm) and DP is deep percolation (mm) beyond the root-zone.

Model inputs are daily rainfall and potential evaporation (Eo). Outputs are daily PAW, ET, RO and DP. ET is taken first from the 0–15 cm layer and then from the layer below.

For modelling purposes, soil profiles are often characterised by their maximum PAW, referred to as the plant available water capacity (PAWC) at the drained upper limit (DUL) or "field capacity" (Verburg et al., 2015). The present model was parameterised for PAWC at both the DUL ($\mathrm{PAWC}_{\mathrm{DUL}}$) and at saturation, which is the upper limit (UL) defined by total porosity ($\mathrm{PAWC}_{\mathrm{UL}}$). Water held between the drained upper limit and saturation is available to plants, although only transiently because of drainage. In the model, soils retain water up to saturation and simultaneously lose water by ET and DP until the soil profile reaches the DUL, at which point water is lost only by ET until reaching the CLL. The model assumes that CLL is the same for all crop species except for differences due to rooting depth.

Daily ET is estimated as a function of Eo, but scaled to account for the effect of soil water content on ET. The model assumes ET = Eo when PAW ≥ 0.33 (DUL-CLL) and ET = 0.5 Eo when PAW < 0.33 (DUL-CLL) (after Allen et al., 1998). This approach to estimating daily ET ignores inter-specific differences in crop factor (Kc), but estimates of seasonal ET reflect any differences related to crop duration. ET is integral to the water balance, and also to agronomy as it relates to yield (French and Schultz, 1984a). Modelled ET represents the potential; actual ET may be less than this, depending on agronomy and crop duration.

2.2. Model parameterisation

The model was parameterised for three scenarios typical of the southern CDZ. The first represented a double-crop system, a sequence of two short duration crops (80–90 days) grown during and immediately following the wet season. The crops are mainly sesame and groundnut, but may include other pulses. The other scenarios involved longer duration, deeper rooted crops of pigeon pea with increased potentially available water. Pigeon pea duration varies, but in Magway is generally c. 180 days. It is grown in wide rows (2.4–3.0 m) and intercropped with short duration crops, usually groundnut or sesame.

The first scenario was parameterised using data from experiments at the Magway Department of Agricultural Research (DAR) research facility (Thu, 2015; Birchall, unpublished). These provided values for CLL and DUL to 100 cm depth based on the average of five treatments representing combinations of crop type and cropping system. Estimates were checked against published values for soils with similar texture (Kramer, 1983). The estimated plant-available water between the CLL and DUL (i.e. $\mathrm{PAWC}_{\mathrm{DUL}}$) was 100 mm. $\mathrm{PAWC}_{\mathrm{UL}}$ was estimated to be 210 mm based on total porosity derived from particle density and published values of bulk density for fine sand (surface) to sandy loam (sub-surface) soils, after allowing for entrapped air (see https://www.apsim.info/portals/0/apsoil/soilmatters/pdf/Mod4.pdf). The pigeon pea scenarios were arbitrarily assigned $\mathrm{PAWC}_{\mathrm{DUL}}$ values of 150 and 200 mm with $\mathrm{PAWC}_{\mathrm{UL}}$ of 270 and 330 mm. The three scenarios are referred to as $\mathrm{PAWC}_{\mathrm{DUL}}$ 100, 150 and 200 mm.

The model requires parameterisation for the maximum rate of deep percolation (DP). As DP is difficult to measure, we used the average of 10 mm d^{-1} for sandy and sandy loam profiles reported by Bethune et al. (2008). Water movement from layer 1 to layer 2 was not limited.

Runoff was estimated using the curve number (CN) approach, with a CN of 60 which is for cultivated land in good condition in Hydrologic Soil Group A (Chow et al., 1988). This CN was based on the sandy texture, absence of surface crusting, and generally low slope of cropped land in the southern CDZ. With a CN of 60, runoff occurs only when event rainfall exceeds 50 mm. The first step in calculating the daily water balance was to partition any rainfall into runoff and infiltration. The final step after accounting for ET and DP was to add any infiltration in excess of profile saturation to runoff.

2.3. Rainfall and evaporation data

The APHRODITE daily rainfall data (Yatagai et al., 2012) were used for 1951–2002 and DAR Magway data for 2011 and 2013–16. APHRODITE is gauge-based, gridded data with spatial resolution of 0.25° × 0.25°. Data represent the area within a grid cell not a single gauge. APHRODITE data were used for water resource assessment in