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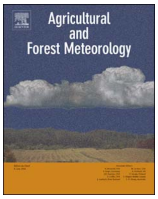

An evaluation of a methodology for seasonal soil water forecasting for Australian dry land cropping systems

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ABSTRACT

Soil water is a critical resource in many rain-fed agricultural systems. Climate variability represents a significant risk in these systems, which has been addressed in the past through seasonal weather outlooks. This study undertakes a pilot assessment of the potential to extend seasonal weather outlooks to plant available soil water (PASW). We analyse 20 sites in the southeast Australian wheat belt using seasonal weather outlooks from the Predictive Ocean-Atmosphere Model for Australia (POAMA; (the operational seasonal model of the Australian Bureau of Meteorology), which were downscaled and used in conjunction with the Agricultural Production Simulator (APSIM). Hindcast rainfall, potential evapotranspiration (*PET*) and PASW outlooks were produced on a monthly basis for 33 years at a point scale. The outlooks were assessed using a range of ensemble verification tools. The results showed hit rates that outperformed climatology for rainfall and *PET* in the short-term (0–2 months), and for PASW with longer lead times (2–5 months). Continuous rank probability skill scores (CRPSS) were generally statistically worse than climatology for rainfall and *PET* and statistically better than climatology for PASW over 1–3 months. The influence of initial soil water is seasonally dependent, with longer dependence in low evapotranspiration periods. Improved weather model downscaling approaches would transition to climatology and could improve both weather and PASW outlooks. PASW outlooks were strongly reliant on initial conditions, indicating the importance of understanding current soil water status, which needs to be interpreted in a seasonal context as its influence varies over the year. Expanded operational soil water monitoring would be important if PASW outlooks are to become routine.

1. Introduction

Water is the key limiting factor for productivity of natural and agricultural ecosystems in many places (Nemani et al., 2003). Soil water constitutes only about 0.005% of global water resources; however, it is not only an important part of the terrestrial hydrological cycle but also a key control variable in numerous landscape processes and feedback loops within climate systems (Seneviratne et al., 2010). In this paper, we concentrate on soil water in the root zone.

A soil's ability to retain water is an important hydrological property as it strongly influences the availability of water to plants over dry periods. This in turn influences a variety of biophysical processes important in both the water cycle and in the primary productivity of plants (Western et al., 2002). Root zone soil water is the primary water resource for dry land agriculture; the largest form of agriculture in the world. Over 80% (1.5billion ha) of the global cultivated land area is under rain-fed farming and it contributes about 60% of world's crop production (FAO, 2015; Sharma, 2011). In Australia nearly 75% of agricultural enterprises are rain-fed systems that represent about 99.5% of the total farmland (Australian Bureau of Statistics, 2015).

Dry Land agricultural systems are inherently risky enterprises, particularly in Australia, due to uncertainties associated with climate variability i.e. highly variable rainfall, recurrent dry spells and droughts. A number of critical management decisions in dry land cropping such as sowing and fertiliser application rely on rainfall and/or soil water status, hence the level of soil water storage is a key piece of information that could help farmers make more informed decisions on the management of rain-fed cropping systems. Further adding to the complexity, under changing climate crop production potential and cropping inputs are likely to be subject to greater instability and uncertainty due to increased seasonal variability.

Short-term to seasonal prediction of soil water availability based on

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climate outlooks has the potential to help optimize production and maintain profitability from dryland agricultural systems. Relevant decisions include logistics such as scheduling of planting, tactical crop management in terms of fertilizer and pesticide use, decisions about crop type, crop sequence, crop rotation, and land use and adaptation of current systems (Meinke and Stone, 2005).

The need to make decisions based on limited and uncertain information means that farmers face two challenges. First, decisions such as crop type, planting time, sowing densities or rate of nitrogen fertilisation have to be made prior to the growing season and in the face of climatic uncertainty. Secondly, devising a strategy balancing the cost of using suboptimal inputs and the cost of failing to capitalise on favourable seasons by leaving a field fallow to increase soil water storage (Hayman, 2011). Management of these risks could be informed by providing two types of information to farmers for decision making to reduce climate related risk. The first is the presentation of historical data that allows farmers to extend their knowledge base due to testing of different crop related scenarios. The second is forecasts of the coming season that can be presented in either a probabilistic or a categorical manner (Hansen, 2002; Hayman et al., 2007; Meinke and Stone, 2005). While there are many important factors in addition to climate variability that farmers consider in their decision-making, agricultural decisions at a range of temporal and spatial scales can benefit from targeted climate forecasts.

There are known climatic phenomena that contribute to rainfall variability in Australia and are relevant to farmers' decision making (Meinke and Stone, 2005). These include the Madden-Julian Oscillation (MJO) (Meinke and Stone, 2005), El Nino-Southern Oscillation ENSO (Hansen, 2002; Meinke and Stone, 2005), the Quasi-Biennial Oscillation (QBO), the Antarctica Circumpolar Wave (ACW) and the Interdecadal Pacific Oscillation (IPO) (Meinke and Stone, 2005). Conventional seasonal climate forecasts (SCFs) are statistical in nature and forecast information is most completely characterized by a probability density function (Tippett et al., 2007). These forecasts were based on teleconnections to the above phenomena, particularly ENSO. With recent advances in computing technology, physics-based SCFs have become more accurate, relevant and offer great potential to mitigate risks and take advantage of expected favourable climatic conditions, particularly for climate dependent enterprises such dry land agriculture (Paull, 2002). SCFs have become an important aspect of decision making for farmers since the 1980s as they offer potential for improving management and planning of crop production (Hansen, 2002; Hayman et al., 2007; Nelson et al., 2002).

The SCFs of the Australian Bureau of Meteorology are currently based on the Predictive Ocean Atmosphere Model for Australia (POAMA), which is comprised of a coupled ocean-atmosphere model, a data assimilation system and a strategy for generating forecast ensembles. In Australia, the Bureau of Meteorology provides seasonal outlook forecasts for streamflow and climatic variables including SOI, rainfall and temperature, which are considered to be important for farmers in their decision making (Bureau of Meteorology, 2014). However, seasonal soil water availability has been a key missing piece of information that could assist dry land farmers to make better decisions well in advance, minimising the potential risks and associated financial penalties.

A number of agencies in North America and Europe (The Soil Climate Analysis Network (SCAN); National Water and Climate Center, USDA; European Environment Agency; Natural Resources Canada) provide current status of soil water as low resolution map products. In the meantime, the US National Weather Service has developed forecasting tools, which are able to predict soil water for the next fortnight, upcoming month and for seasons up to 12 months in advance. The 14 day soil water forecast is based on the National Weather Service Global Forecast System (GFS) global model (Environmental Modeling Center, 2003), while monthly and seasonal forecasting tools are based on the Constructed Analog on Soil Moisture in the top 1.6m of the soil profile (van den Dool et al., 2003). The GFS model runs at a resolution of 0.5° x 0.5° for 16 day forecast lead times, but with decreasing spatial and temporal resolution over time and the volumetric soil water content is limited to a layer of 10cm from the surface.

More recently, Dirmeyer, (2013) assessed NOAA's Coupled Forecast System v2 (CFS v2) forecasts of precipitation and soil water outlooks for four soil layers (0–10, 10–40, 40–100 and 100–200 cm). Using a rank probability skill score for tercile forecasts, they found rapidly declining skill in precipitation and regionally dependent declines in layer 2 soil moisture forecasts that show some skill up to five months. These assessments were at the model grid scale. Spennemann et al. (2017) also consider CFS v2 soil water forecasts for the top 1m of the soil profile, concentrating on south-east South America. They find limited skill in precipitation prediction and some skill (assessed by anomaly correlation coefficient) against Global Land Data Assimilation Scheme soil water estimates (top 1m) for the first month in summer and up to 3 months in winter.

The above tools are more applicable at regional to global scales. The other key deficiency of these tools in agricultural decision making is that they do not effectively account for crop water dynamics; soil water is estimated with a monthly scale soil water balance approach (van den Dool et al., 2003). The Centre for Ocean-Land-Atmosphere Studies of George Mason University routinely produce 8-day soil water forecast maps for 11 regions around the world based on the Community Climate System Model version 4 (CCSM4) (Gent et al., 2011; Oleson et al., 2010). Again, the spatial resolution of the embedded land and atmospheric models ($1.25^\circ \times 0.94^\circ$) limit the applicability of the predictions at local scales.

While weather dynamics have an important impact on soil water dynamics, those dynamics are modulated by the soil. Water retention characteristics of soils vary significantly across the landscape and also down the soil depth profile (Geroy et al., 2011). Further, soil water storage is also affected by various other factors including land and soil management, type of vegetation and growth patterns (phenology) and management (BIO Intelligence Service, 2014; Haruna and Nkongolo, 2013). To make soil water outlooks more relevant and meaningful for agricultural production systems, these key aspects should be integral components of the forecasting processes.

To further our understanding of the potential of dynamical soil water outlooks, this paper assesses the skill of soil water outlooks made using a combination of the APSIM crop model and POAMA seasonal outlooks, which are downscaled to individual weather stations. For this initial approach we selected the Agricultural Production Systems Simulator (APSIM), because it is the most widely used and well parameterized cropping systems model in Australia and elsewhere, and it is well calibrated for large numbers of sites across various agro-ecological regions of Australia (Holzworth et al., 2014). Here we develop a workflow for generating site scale estimates of current soil water conditions and seasonal soil water outlooks. These outlooks are assessed for predictive skill utilising a 33 year hindcast period using modelled soil water based on historical weather observations.

2. Methodology

2.1. Study area

This study covered a range of representative sites in the South-East Australian wheat belt (Fig. 1). The sites correspond to weather stations run by the Bureau of Meteorology, Australia (Table 1). Soil properties at these sites were selected to represent the dominant cropping soil in the area. This was done by combining the online soil map and profile information from the Victorian Soil and Land Survey of 'Victorian Resources Online' (http://vro.depi.vic.gov.au/dpi/vro/soilsurv.nsf/HTML/Index) and NSW soil and land information data from "eSPADE" (http://www.environment.nsw.gov.au/eSpadeWebApp/) with APSIM's soil database "Apsoil" (https://www.apsim.info/