A simple versatile model of crop yield response to water deficit

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Abstract

Farmers need to know when to irrigate, how much water to put on, and the yield penalty if the crop is not irrigated. To develop answers to these questions we use a simple model developed 30 years ago that relates crop yield to maximum potential soil moisture deficit (MPSMD). MPSMD is calculated from potential evapotranspiration, rainfall and irrigation data. To calibrate the model for different crops, we use a rainshelter that covers the experiment automatically when it rains. Crops grown in the rainshelter have included wheat, oats, sweet corn, carrots, peas and white clover for seed production. Six to twelve irrigation treatments, based on timing or intensity of drought, were set up in each of the experimental crops. Total or economic yield of all the crops tested, with the exception of white clover seed, decreased linearly as the MPSMD increased, regardless of the timing of drought. The slope of the regression line between yield and MPSMD is the yield loss with increasing deficit. In some crops, very small deficits caused problems through excessive vegetative growth. The information from these experiments has enabled clear irrigation scheduling information to be given to growers. It has also been included in computerized decision support systems being developed for arable and vegetable farmers in New Zealand.

Media summary

We use a simple model and a greenhouse on wheels to help farmers use irrigation water wisely.

Keywords

Rainshelter, irrigation, water deficit, crops, yield, drought stress.

Introduction

Despite New Zealand's green image, many parts of the country lie in the rain shadow east of the Southern Alps and can suffer drought at any time of the year. Daily PET values often exceed 6mm/day over summer. This is double the mean summer rainfall, which has a coefficient of variation of 42% (Ryan 1987). Irrigation is the major user of water resources in parts of New Zealand, and increasingly farmers there have to justify their use of water to regulatory authorities and the public.

A quantitative knowledge of the response of crops to drought stress is important for the management of both irrigated and dryland crops. Farmers who have irrigation can use the known responses to decide when to start irrigation, how much water to apply and when, and when irrigation will have no further value. Farmers without irrigation can use the knowledge as a guide to potential production, and hence adjust management strategies accordingly.

Yield response to drought stress can be quantified by using the maximum potential soil moisture deficit (MPSMD or D_{pmax}) experienced during the growth of the crop as the measure of stress. This concept was developed by Penman (1971) and refined by French & Legg (1979). Potential soil moisture deficit (PSMD or D_p) is readily calculated from potential evapotranspiration, rainfall and irrigation data, and has practical meaning in that the deficit can be equated with irrigation applications (or lack of them). Responses to the potential deficit are given in terms of reductions in yield below the much more stable fully irrigated yield. The model produces two meaningful numbers: a critical deficit beyond which yield is reduced, and a reduction in yield per unit of potential deficit when the critical deficit is exceeded.

The model needs to be calibrated for individual crops, as they differ in their susceptibility to drought. Calibration using conventional field trials can be difficult in humid and sub-humid environments, because untimely rainfall can negate the effects of the imposed irrigation treatments, resulting in costly repetition of experiments over a number of seasons. To avoid this problem, we have used a mobile automatic rainshelter to exclude rainfall from experimental plots, which are otherwise exposed to normal weather. This has allowed us to reliably impose a range of drought treatments, which have included timing and duration of drought periods, and irrigation amounts and frequencies.

Methods

The rainshelter at Lincoln, Canterbury, New Zealand, is a mobile 55 m x 12 m greenhouse that automatically covers the experimental crop during rainfall, but is otherwise positioned some 50 m away (Figure 1). Therefore, except when it is raining, the crop experiences a near normal field environment. The area between the rails is divided into four, and one of these 54 x 12 m sites is used each year. Each site is divided into 24 3.6 m x 5 m plots. Two strips c. 10 m wide immediately adjacent to the rainshelter can also be planted in crop to minimise edge effects. The soil is a deep (>1.6 m) Templeton sandy loam (*Udic Ustochrept*, USDA Soil Taxonomy) (New Zealand Soil Bureau 1968) with an available water holding capacity of c. 190 mm/m of depth.

Figure 1. Aerial view of the rainshelter at the Crop & Food Research Farm at Lincoln, New Zealand.

The crops we have grown in the rainshelter include wheat, barley, and maize (Jamieson et al. 1995), peas (Martin and Jamieson 1996), sweet corn (Stone et al. 2001a,b), oats (Martin et al 2001), white clover for seed production (Martin et al. 2003) and carrots (Reid and Gillespie, unpublished). Six to twelve irrigation treatments, based on timing or intensity of drought, were set up for each of the experimental crops. Irrigation applications were determined from actual water use as measured by Time Domain Reflectometry and neutron probe soil moisture measurements. The PSMD was calculated for each treatment by adding the maximum weekly Penman evapotranspiration from the fully irrigated control treatment to the irrigation deficit (the difference between the amount of water applied to the treatment and to the fully irrigated control). The deficit was adjusted for different ground cover using the modified Penman model of Ritchie (1971).

Results

Total, grain, root or tuber yield of all the crops tested, with the exception of white clover seed, generally decreased linearly as the MPSMD experienced during crop growth increased (Figure 2). The slope of the regression line between yield and MPSMD is the yield loss with increasing deficit. This varies from 8 kg/ha/mm for peas (Martin and Jamieson 1996) up to 25 kg/ha/mm for barley (Jamieson et al. 1995). A critical deficit, below which there is no loss in yield with changing deficit, was able to be determined analytically for wheat (Jamieson et al. 1995), but not for any of the other crops.

This linear reduction in yield with increasing deficit occurred regardless of the timing of drought. Consequently economic yield in most crops was related to the intensity and not the timing of drought. How the stress influences the structure of yield can vary with timing of stress, as grain size and harvest index in some crops were reduced by late drought (Jamieson et al 1995, Martin and Jamieson 1996). In oats, frequent irrigation led to excessive stem growth, which caused the crop to lodge, reducing grain yield at small moisture deficits (Martin et al. 2001).

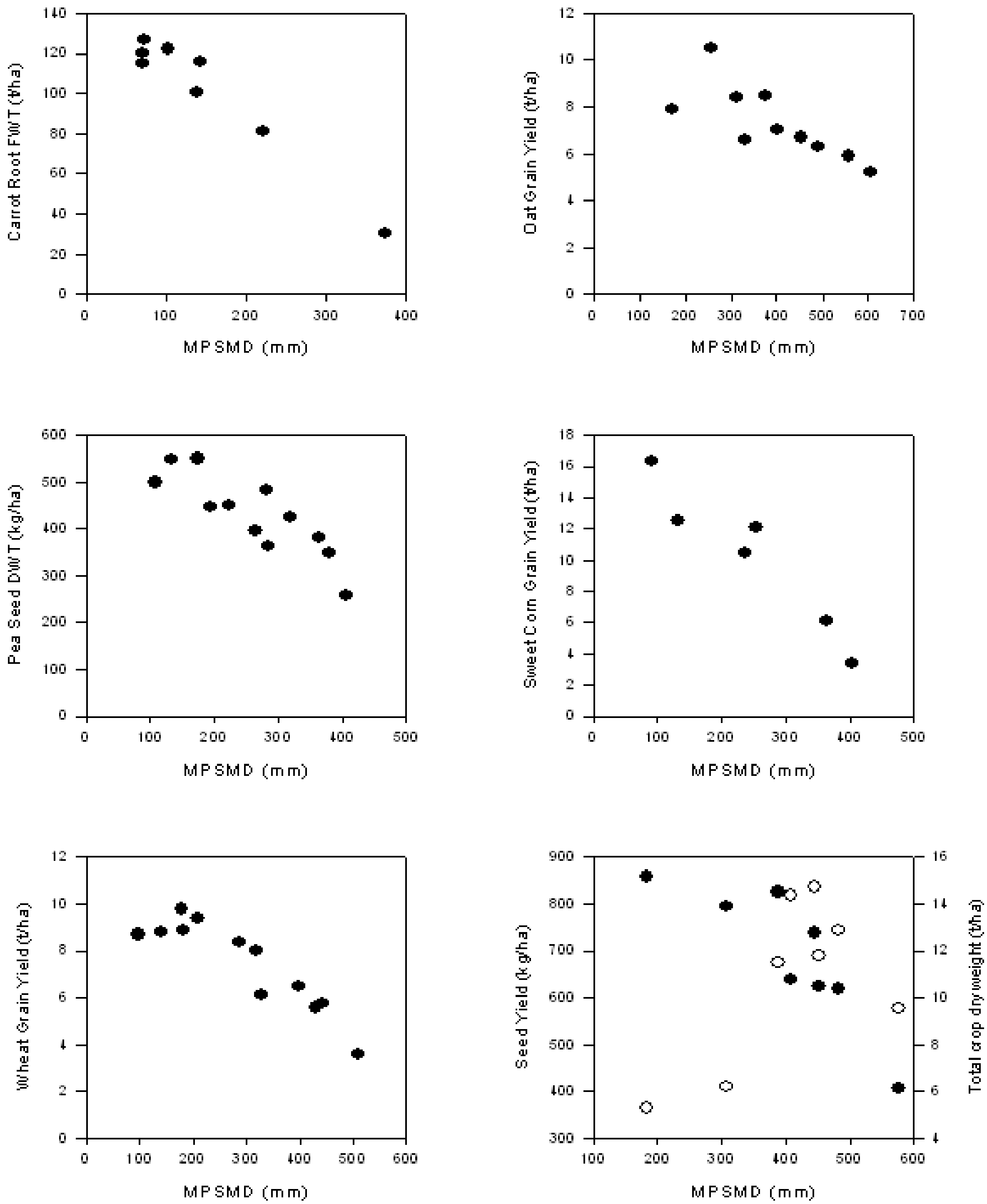

Figure 2. Effect of maximum potential soil moisture deficit (MPSMD) on yield of carrot roots, oat grain (Martin et al. 2001), pea seed (Martin & Jamieson 1996), sweet corn fresh grain yield (Stone et al. 2001), wheat grain yield (Jamieson et al. 1995) and white clover total biomass (●) and seed (○) yield (Martin et al. 2003).

White clover differed from the other crops examined in that, while total crop dry weight decreased with increasing deficit (as for the other crops) seed yield was highest in treatments that provided some stress during flowering, preventing leaves from growing high enough to shade the flowers (Martin et al. 2003). This means that growth stage has to be factored into the model for white clover seed crops.

The combination of the rainshelter and the MPSMD approach is not only useful for predicting final yield. It has been successfully used to determine the effects of drought stress on radiation use efficiency and to model canopy development (Stone et al. 2001b).

The relationship between crop yield and MPSMD is also affected by the water holding capacity (WHC) of the soil; the lower the WHC, the lower the yield at a given MPSMD. However, we have successfully extrapolated the results from the rainshelter experiments to other soil types by adjusting the model for:

- Rooting depth, which varies from about 0.8 m for peas to about 2 m for maize.
- Depth of soil to gravel, and we have found that the available water holding capacity of most New Zealand cropping soils is 165 mm/m of depth, and that of the underlying gravel is 55 mm/m.
- Depth of soil to a pan, which impedes rooting.

Conclusion

The information from these experiments has enabled clear irrigation scheduling information to be given to farmers. It has also been included in computerised decision support systems developed for wheat, pea, maize, potato and carrot growers in New Zealand, which enable farmers to see the effects of altering their irrigation practices (e.g. Jamieson et al. 2001). The information has also been used to develop farm water demand scenarios for irrigation planning.

Acknowledgments

Numerous other technical staff assisted in these experiments. The experiments were funded mainly by the New Zealand Foundation for Research, Science and Technology, with supplementary funding from the Foundation for Arable Research, VegFed, Alex McDonald Merchants, United Wheatgrowers, and Heinz Wattie’s Australasia.

References

French BK and Legg BJ (1979). Rothamsted Irrigation. Journal of Agricultural Science 92, 15-37.

Jamieson PD, Martin RJ and Francis GS (1995). Drought influences on grain yield of barley, wheat and maize. New Zealand Journal of Crop and Horticultural Science 23, 55-66.

Jamieson, PD, Reid JB, Halse SJ, Tregurtha CS and Martin RJ (2001). Nutrition and water effects on grain production in wheat – a combined model approach. Agronomy New Zealand 31, 45-52.

Martin RJ and Jamieson PD (1996). The effect of timing and intensity of drought on the growth and yield of field peas. New Zealand Journal of Crop and Horticultural Science 24, 167-174.

Martin RJ, Jamieson PD, Gillespie RN and Maley S (2001). Effect of timing and intensity of drought on the yield of Oats (Avena sativa L.). Proceedings 10th Australian Agronomy Conference, Hobart. www.regional.org.au/au/asa/2001/b/martin.htm

Martin RJ, Gillespie RN, Maley S and Robson MB. (2003). Effect of timing and intensity of drought on the yield of white clover (Trifolium repens L.). Proceedings 11th Australian Agronomy Society, Geelong. www.regional.org.au/au/asa/2003/c/14/martin.htm

New Zealand Soil Bureau (1968). General survey of the soils of the South Island. New Zealand. NZ Soil Bureau Bulletin 27, 404 p.

Penman HL (1971). Irrigation at Woburn VII. Report Rothamsted Experimental Station for 1970, Part 2, 147-170.

Ritchie JT (1972). Model for predicting evaporation from a row crop during incomplete cover. Water Resources Research 8, 1204-1213.

Ryan AP (1987). The climate and weather of Canterbury. New Zealand Meteorological Service Miscellaneous Publication 115 (17). 66p.

Stone PJ, Wilson DR and Gillespie RN (2001a). Water deficit effects on sweet corn. I. Water use, radiation use efficiency, and yield. Australian Journal of Agricultural Research 52, 103-113.

Stone PJ, Wilson DR and Gillespie RN (2001b). Water deficit effects on sweet corn. II. Canopy development. Australian Journal of Agricultural Research 52, 115-126.