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Crop responses to compacted soil: capture and efficiency in the use of water and radiation

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Abstract

We combined field and modelling experiments to investigate crop-level responses to soil compaction. Our working hypotheses are that the effect of soil compaction on crop growth is (i) primarily mediated by reduction in capture of water and photosynthetically active radiation (PAR), and (ii) secondarily affected by reduced transpiration efficiency (biomass per unit transpiration) and radiation-use efficiency (biomass per unit intercepted PAR).

Three field experiments were carried out in the Mediterranean-type Mallee region of south Australia where the landscape alternates sand dunes (hills) and swales (flats) of sandy loam soil. All three experiments compared wheat crops grown in compacted (control) soils, and soils in which compaction was alleviated with deep tillage (ripped); additional sources of variation include season and soil type as related to topography.

All soil and crop responses to ripping were more marked in sand hills than in sandy loam flats. Penetration resistance of undisturbed soil had a peak ~2 MPa at 0.1–0.2 m depth in sandy loam flats and ~3 MPa at 0.2–0.3 m depth in sand hills. Ripping dramatically reduced soil penetration resistance between 0.10 and 0.3–0.4 m. Control crops yielded between 1.2 and 2.9 t ha^{-1} and yield improvement attributable to alleviation of soil compaction ranged from nil to 43%; yield response to ripping remained for at least two cropping seasons.

Increased transpiration and PAR interception fully accounted for the increase in crop growth associated with alleviation of soil compaction; ripping did not affect transpiration efficiency or radiation-use efficiency. The proportion of evapotranspiration accounted for by soil evaporation (E:ET) declined from 0.58 in controls to 0.36–0.45 in ripped sand hills.

A limited modelling study showed that water availability, as characterised with the lower limit of plant available water, could partially account for the effect of soil compaction and deep tillage on crop growth and evapotranspiration. Long-term simulations indicated important changes in the fate of water in response to ripping in sandy soils, including a moderate increase

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in evapotranspiration, a substantial reduction in E:ET, and important reductions in the frequency and rate of drainage beyond the crop root zone.

Keywords: Radiation-use efficiency; Transpiration efficiency; Soil penetration resistance; Dryland agriculture; Grain protein; Water budget; Modelling; Drainage; Soil evaporation; Wheat

1. Introduction

Soil compaction can occur naturally by settling of soil or may be induced by tillage, machinery traffic, trampling by animals and fire (Kozlowski, 1999). Compaction affects key soil properties (porosity, bulk density, mechanical impedance, hydraulic conductivity, plant available water), has the potential to dramatically alter plant morphology and physiology (Bingham, 2001; Passioura, 2002), and to reduce crop growth and yield. Reductions in grain yield attributable to high soil mechanical impedance have been reported for several crops in a wide range of soils from sands to heavy clays (Barber and Diaz, 1992; Arvidsson and Håkansson, 1996; Ishaq et al., 2001a; Radford et al., 2001a; Tennant and Hall, 2001; Dauda and Samari, 2002; Hamza and Anderson, 2002, 2003; Montavalli et al., 2003).

Bingham (2001) and Passioura (2002) reviewed the physiological responses of plants grown in soils with biological and physical constraints, including high mechanical impedance. Reduction in shoot growth of plants growing in compacted soils has been linked to reduced stomatal conductance, and reduced rates of cell division, cell expansion and leaf appearance. Initially, these responses are mediated by inhibitory root-to-shoot signals of diverse nature; Trewavas (2003) highlighted the extraordinary complexity of signalling between plant cells, tissues and organs. Reduced availability of soil resources contribute further to reduced shoot growth.

There are therefore two major perspectives in research of plant responses to soil mechanical impedance. Agronomic studies focus on yield responses, and generally do not account for the dynamics of the processes involved. Physiological studies often deal with response variables, e.g. stomatal conductance, whose integration at the crop level is not straightforward. Here we combined field and modelling experiments to investigate crop-level responses to soil compaction against the framework of resource capture and resource-use efficiency (Passioura, 1977; Monteith, 1994).

2. Methods

2.1. Hypotheses

Resource capture is proportional to the area, activity and longevity of canopies and root systems. As expansion of plant tissues is more sensitive to soil-related stresses than physiological activity (e.g. gas exchange) per unit area (Hsiao et al., 1976; Scott et al., 1994; Sadras and Milroy, 1996), our working hypotheses are that the effect of soil compaction on crop growth is (i) primarily mediated by reduction in capture of water and photosynthetically active radiation (PAR) (pathway 2 in Fig. 1), and (ii) secondarily related to reduced transpiration efficiency and radiation-use efficiency (pathway 3). While a range of root signals play a likely role in the initial response of shoots to soil compaction (pathway 1) the strong loop mediated by availability of resources (pathway 2) is expected to override these initial effects.

A hypothetical causal sequence accounting for reduced RUE involves reductions in root growth, nitrogen uptake, leaf nitrogen concentration, and RUE. Depending on the relative changes in RUE and canopy conductance, reductions in RUE could lead to reductions in TE (Caviglia and Sadras, 2001). The allometry of leaf nitrogen could be maintained, however, with no changes in leaf nitrogen concentration and RUE due to soil compaction. Water-use efficiency defined as biomass or grain yield per unit evapotranspiration (ET) could be reduced as a consequence of reduced canopy cover leading to increase in the evaporation component of ET (Cooper et al., 1987). Unbalanced uptake of nutrients, e.g. less