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REGULAR ARTICLE

Yield and environmental benefits of ameliorating subsoil constraints under variable rainfall in a Mediterranean environment

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Abstract Subsoil constraints to root growth exacerbate frequent water and nutrient limitations to crop yields in Mediterranean-type environments. Amelioration of subsoil constraints can relieve these limitations by opening root-access to subsoil water and nutrients. However, decisions in subsoil amelioration are hampered by seasonally variable yield responses in these environments. We used the APSIM model to analyse the impact of subsoil constraints on yield and yield variability. The simulated yield data were used to calculate the financial benefits of subsoil amelioration across several scenarios. There was a strong yield-dependence on accessible soil water governed by root depth. Root depth development was limited to a minimum of either the effect of subsoil constraints or the weather-dependent depth of the soil wetting front. Insufficient rainfall in dry years or in a drier region often resulted in shallow soil wetting fronts and correspondingly shallow roots even in the absence of subsoil compaction. In these situations, there is little response to subsoil amelioration. Positive yield responses and positive financial returns to subsoil amelioration are therefore greater in good rainfall years and are more likely in a wetter region. A yield response to amelioration is also greater in coarser textured sand than finer textured sandy loam in an average rainfall season because the same amount of rainfall results in a deeper wetting front in sand than in sandy loam. Hence, roots in a sand are required to grow deeper compared to a sandy loam to access the same amount of water and therefore benefited more from subsoil amelioration in an average rainfall year. In wet years, sands leach more nitrate than sandy loam, which decreases yields and the response to subsoil amelioration in sands is more than in the sandy loam. Environmental threats occur along with yield loss when roots cannot access subsoil water. These include increased nitrate leaching and deep drainage due to unused water remaining in the soil profile. By allowing roots to access deep soil water, ameliorating subsoil is expected to yield financial gains in average to good rainfall seasons and decrease the environmental risk of drainage and leaching loss. The financial gains are expected to offset potential financial losses in dry and dry finish seasons especially in coarser textured soils and wetter environment.

Keywords APSIM · Soil compaction · Drainage · Nitrate leaching · Plant available soil water storage capacity · Root depth · Spatial variability · Temporal variability · Financial

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Introduction

Rooting depth-affected by any subsoil constraints can be a limit to grain yields when the stock of water and nutrients is not sufficient in this soil volume. A yield-limiting effect may not be noticed if water and nutrient supply are sufficient in the initial rooting depth. Working with subsoil compaction for example, Taylor and Barr (1991) suggest that even if root development is altered, above-ground growth may be normal if the growing season conditions are such that the plant is able to obtain sufficient water and nutrients. Observations, such as inverse relationship between response to deep tillage and seasonal rainfall (Barber and Diaz 1992) support the proposition that shallow roots have less adverse impacts on yields when supply of water and/or nutrients are increased. Alleviating any subsoil constraint to increase potential rooting depth can therefore have a positive or no effect on grain yields (Henderson 1986; Jarvis 1982, 1986; Tang et al. 2003). It can depress grain yields in some years by promoting early crop growth and increased water demand not matched by water supply later in the season. This is a common problem in Mediterranean-type environments prone to terminal water stress (Delroy and Bowden 1986; Wong et al. 2000). Negative crop response to deep tillage is commonly observed in Western Australia (WA; Jarvis 1982, 1986).

The frequency of low, zero or negative responses to subsoil amelioration is a major concern for growers. The temporal and spatial occurrence of water limitation to crop yield is season and soil type dependent (Wong and Asseng 2006). Therefore, the yield depressing effect of subsoil constraints due to restricted root access to subsoil water and nutrients is also expected to be dependent on season and soil-type. This temporal and spatial dependence of the effect of subsoil constraints on yield is reported regularly in field experiments (Barber and Diaz 1992; Clark et al. 2003; Jarvis 1982, 1986; Sadras et al. 2005; Swan et al. 1987; Taylor and Barr 1991; Timlin et al. 1998). The dynamic interaction between spatial and temporal variability leads to difficulties in interpreting the results of field experiments. Jarvis (1982) suggested the need for more fieldwork to determine where responses occur, why they occur and whether responses are dependent on seasonal conditions. Such fieldwork needs to be long term to represent the range of inter-seasonal variability encountered in a Mediterranean-type environment as well as wide ranging to cover the variation in soil types and fertiliser management scenarios. These requirements would make extensive fieldwork too inefficient and costly to be viable. A viable alternative is to use a reliable model such as APSIM to simulate the effect of soil properties, seasonal conditions and fertiliser management on crop yields and extrapolate the results of targeted field experiments spatially and temporally (e.g. Wong and Asseng 2006).

Subsoil constraints such as compaction, sodicity and acidity result in decreased rates of root elongation (Clark et al. 2003; Schmidt et al. 1994; Tang et al. 2003). Whilst this work is on crop and environmental response to subsoil amelioration in general, we used subsoil compaction and varying soil depth to illustrate the implications of shallower roots and the principles governing response to subsoil amelioration. Decreased rate of root elongation in compacted soils is due to increased root growth (σ) pressure required to displace soil during root growth (Clark et al. 2003). The rate of root growth decreases as σ increases until a maximum value is reached when roots cease to elongate. This maximum σ ranges from 0.4 to 0.5 MPa for wheat, barley and lupin (Clark et al. 2003). Inverse curvilinear relationships were obtained between root growth of barley, cotton and peanut and soil strength under laboratory conditions (Russell and Goss 1974; Taylor and Barr 1991). Although, root counts in the field are dependent on the time the counts were made, seasonal and soil conditions, a similar curvilinear relationship was obtained between root counts in spring and soil strength measured in early summer in field grown cotton (Busscher and Bauer 2003). Crop models that take account of increased mechanical subsoil impedance should therefore consider its effect on root growth and the capture of water and nutrients. APSIM simulates subsoil compaction (and acidity and shallow soils) by using a root hospitality (Rh) factor to adjust the rate of root depth extension according to the severity of the subsoil constraint (Asseng et al. 1998). Recent work by Sadras et al. (2005) in a Mediterranean-type environment suggests that there is no need to change the crop's radiation-use efficiency or transpiration efficiency as a result of changing subsoil mechanical impedance.

A paradox in Australia is insufficient water limiting crop yields yet too much water causing deep drainage, rise in saline water table and widespread salinity (Pracilio et al. 2003). Subsoil constraints result in unused water in the soil profile. In addition to potential yield losses, environmental risk is increased due to deep drainage and nitrate leaching

(Delroy and Bowden 1986; Pracilio et al. 2003; Wong et al. 2006). A number of options exist to treat subsoil constraints and achieve financial and environmental benefits. For example, acidity can be treated by liming (Whitten et al. 2000) and non-liming methods (Snars et al. 2004; Wong and Swift 2003; Wong et al. 2004) and compaction by deep tillage (this involves using a set of tines consisting of a shallow (10 cm) leading tine and three progressively deeper tines down to 40 cm) combined with structural stabilization of the soil with gypsum and organic matter (Hamza and Anderson 2005; Yamaguchi et al. 2004). The ensuing investment risk due to uncertain crop response undermines the formulation of financially sound grower recommendations to alleviate these constraints.

The aims of this work were (1) to simulate the sensitivity of wheat yields to a range of soil depths and levels of subsoil compactions on two commonly occurring soil types under different weather conditions for a low and a medium rainfall location in Mediterranean Australia, (2) to assess the seasonal risk and financial benefits of ameliorating subsoil compaction and (3) its effect on unused water, deep drainage and nitrate leaching.

Materials and methods

The crop model used here was APSIM Nwheat version 1.55 s (Asseng et al. 2004; Keating et al. 2003). It simulates daily root and shoot growth and subsequent grain yields based on information on daily weather, soil property data and nitrogen (N) management. The model has been successfully tested against data from field experiments in Mediterranean Australia and elsewhere covering a wide range of soil types and seasonal conditions (e.g. Asseng et al. 2000; Asseng and Van Herwaarden 2003). In particular, it successfully simulated wheat yields under different rates of fertiliser N in soils affected by both subsoil compaction and acidity (Asseng et al. 1998; Tang et al. 2003). APSIM deals with static soil constraints such as compaction and acidity which are assumed to be constant across a season. In the model, the rate of root elongation to depth and root length density development in soil layers is modified in response to soil constraints by applying a root hospitality factor in specific soil layers (Asseng et al. 1998; Tang et al. 2003). The root hospitality factor (Rh) scales down potential root growth rates according to the severity of the subsoil constraint.

The root elongation rates in APSIM include separate control for root depth extension and root proliferation within each soil layer. The potential rate of root depth extension (2.2 mm (°C d)$^{-1}$) is reduced by the minimum of either a crop water stress factor, a factor reflecting the water content in the deepest rooted layer or the root hospitality (Rh) factor for the layer (Asseng et al. 1998). Increases or decreases in mechanical impedance do not usually occur uniformly with depth. Here, we use the layer specific Rh values to represent the constraint to root growth due to mechanical impedance (Table 1). The Rh of the control soil (0.4) reflects the rate of unimpeded root elongation obtained for wheat grown on sandy soils free of subsoil constraints in WA (Asseng et al. 1998). This potential root elongation rate is multiplied by Rh to give the constrained root elongation rate. Using this approach, APSIM was able to simulate root growth of wheat at four contrasting locations in WA with measured root depths ranging from 0.05 to 1.3 m. The root mean square deviation (RMSD) of the root depth simulations was 0.13 m across the four sites (Asseng et al. 1998). For comparison, the corresponding RMSD of simulated wheat yields was 0.4 t/ha with measured yields ranging from 1.0 to 4.0 t/ha. Roots within a layer interval e.g. 12 cm are assumed to have access to water in the whole layer (10–20 cm) but only in proportion to how deep it penetrated that layer i.e. 20% in the case of 2 cm penetration of the 10–20 cm layer.

Simulation experiments

Simulations were carried out for two locations in the northern sandplain of the WA wheatbelt for a commonly occurring sandy soil and a sandy loam to allow an understanding of the response of the system to seasonal rainfall, nitrogen fertiliser application, soil depth, increased subsoil mechanical impedance (compaction) and the alleviation of this impedance (e.g. by deep cultivation). The volumetric soil water content at field capacity (drained upper limit) was assumed to be 10% for the deep sandy soil and 15% for the deep sandy loam, and the potential crop lower limit was set to 5% for both soils. These values were used to allow us to simulate the effect of doubling the potential plant available soil water content (PAWC) of each soil layer from 5% for sand to 10% for sandy loam.

Table 1 Root hospitality factors (Rh) used for the simulation treatments

Depth	Layer	Treatment																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0–5	1	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
5–10	2	0.005	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
10–20	3	0.00	0.0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
20–30	4	0.00	0.0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.2	0.1	0.01
30–40	5	0.00	0.0	0.0	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.2	0.1	0.01
40–50	6	0.00	0.0	0.0	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
50–60	7	0.00	0.0	0.0	0.0	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
60–70	8	0.00	0.0	0.0	0.0	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
70–90	9	0.00	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
90–110	10	0.00	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
110–130	11	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
130–150	12	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
150–170	13	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
170–190	14	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
190–210	15	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
210–230	16	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40
230–250	17	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4	0.3	0.2	0.1	0.01	0.4	0.4	0.40

Although these two soils were artificially constructed to enhance the clarity of the soil effects, they represent two common WA soils (Asseng et al. 1998) but without the constraints. The soil constraints were then applied in a systematic way as treatments onto these soil types. APSIM was run using long-term daily weather records (1954–2003) for a low rainfall location (Buntine, 29.99°S, 116.57°E) and a medium rainfall location (Mingenew, 29.19°S, 115.44°E). These locations have a Mediterranean-type climate with wet winters and hot, dry summers. The average annual rainfall for Buntine is 333 mm, of which 238 mm falls in May to October (growing) season. Mingenew is nearer to the coast and wetter with an average annual rainfall of 396 mm, of which 315 mm falls in May to October. There is a 30% probability in Buntine and 25% probability in Mingenew of receiving 120 mm summer rain. This would result in an average of approximately 30 mm stored water in the soil profile. In the simulation, wheat (cv. Spear) was initially sown with 0 to 210 kg N/ha. This was given in 30 kg N/ha increments. Rates of fertiliser up to 90 kg N/ha were applied as a single dose at sowing. Higher rates were applied as two splits at sowing and at 4 weeks after sowing. These simulations were used to identify the rate of fertiliser nitrogen at which crop yields were most responsive to subsoil amelioration (Asseng et al. 1998). Further simulations were carried out with the rate of nitrogen (60 kg N/ha) commonly used by growers in the region. Simulations were reset each year on 24 April to a dry soil profile (at crop lower limit) or to a ‘wet’ soil profile (with 30 mm of plant available soil water distributed below 30 cm depth by filling successive soil layers to their drained upper limits until 30 mm of water is stored). Root depth and grain yields were simulated for each site for a range of seasonal rainfall (0–33.3% driest, 33.3–66.6% average and 66.6–100% wettest years) and subsoil Rh scenarios (Table 1).

Subsoil constraint treatments

Several magnitudes and vertical distributions of soil strength down the soil profile were simulated by varying the Rh values to represent a range of soil depth and subsoil compaction scenarios typical of those encountered in the field. Treatment numbers 1 to 9 (Table 1) represent increasing soil depths over an impenetrable layer (Rh=0) such as of compacted gravel or rock. Treatment 11 is a control with uniformly good Rh throughout the potential rooting depth of 250 cm. Rooting depth to 300 cm has been reported for some deep loamy sands in WA (Hamblin and Tennant 1987). Treatment numbers 12 to 15 represent soils with the entire profile becoming increasingly more hostile to root growth. Treatments

16 to 18 represent typical subsoil compaction profiles (Jarvis 1982; Schmidt et al. 1994) that develop as a result of cultivation.

Loamy sand with subsoil penetration resistance of 2–4 MPa measured immediately after autumn sowing in the region of our study decreased the subsequent rate of root growth of wheat in the field by a third to a fifth compared with the deep cultivated control (Schmidt et al. 1994). Measurements on another loamy sand with subsoil penetrometer resistance 3-4 MPa showed a similar impact, decreasing the rate of root growth of wheat by about a third (Atwell 1990). This subsoil compaction scenario is represented in the medium compaction treatment 17 where Rh is decreased from 0.4 to 0.1. Root growth response of field-grown wheat to subsoil compaction varies greatly in the 1-4 MPa range. Plotting relative root density against penetration resistance however shows a well defined lower boundary (Martino and Shaykewich 1994). Points above this boundary are suggested to represent situations where roots grew in spite of high soil compaction for example by growing through channels and cracks or localised soil paths with lower penetrometer resistance. Root growth along this lower boundary stopped at a soil strength of 2 MPa irrespective of soil type. Treatment 18 represents this scenario where wheat is grown on a soil with minimal channels, cracks and localised paths for root growth.

Measuring crop yields on deep and shallow soils

The response of wheat yield to soil depth was assessed in a field at Buntine. Yield was monitored on a field with a non-uniform depth of sandy soil for the period 1996 to 2002. Soil depth ranged from 10 to >200 cm over a compacted laterite gravel layer (penetrometer resistance, >5 MPa). Roots would not be expected to grow through the compacted subsoil gravel layers because of their high penetration resistance (Clark et al. 2003). The field was planted to wheat in 1996, 1999 and 2002 and given 60 kg N/ha at sowing. A yield monitor (AgLeader) logged yield data at intervals of 3 s. The point data were kriged to a 5 m grid with the software Vesper (Minasny et al. 1999). For each of three soil depths (5–15, 25–35 and >200 cm), six locations were selected at random. These locations were identified on the kriged yield maps to determine yield values for each of the soil depth intervals.

Economic analysis

This analysis focused on soil-type, weather and location-dependent wheat yield response to amelioration of subsoil compaction by deep cultivation. Grain yields for treatments 16 (mild compaction), 17 (medium compaction), 18 (severe compaction with hardpan at 20–40 cm) and 11 (control) were simulated for 50 years at both Buntine and Mingenew for initially dry soil profiles. Simulated yields were sorted according to dry, average and wet season terciles. The analysis compared sand with a sandy loam to evaluate seasonal risks between these soil types. The gross margins for wheat in compaction treatments 16–18 were calculated using a recent price of wheat (Australian Wheat Board 2004) and average input costs of Australian $127/ha plus $1/kg N applied (Department of Agriculture and Food, Western Australia Gross Margins Guide 2003). Deep cultivation of the compacted subsoils (treatment 16–18) to 40 cm and chemical stabilisation of the loosened soil with gypsum to convert it to an uncompacted profile (treatment 11) would cost $150/ha (M. Hamza, personal communication, 2005). This cost includes the need to use a set of tines consisting of a shallow (10 cm) leading tine and three progressively deeper tines to cultivate the soil down to 40 cm (Hamza et al. 2005). To maintain the uncompacted profile, repeated deep cultivation and stabilisation at a cost of $150 was assumed every 3 years (Jarvis 1991; Sadras et al. 2005). It was further assumed that the effect of deep cultivation on root growth and yield remained stable throughout the 3-year period between repeated deep cultivations. This represents a best case scenario as resettling of soil after deep cultivation is likely to occur during the intervening time.

Results

The adverse effect of subsoil compaction on simulated average wheat yields at both the low (Buntine) and medium-rainfall (Mingenew) locations decreased with increasing amounts of fertiliser N applied. Nitrogen fertiliser applied at the rate of 90 kg N/ha at Buntine and at 150 kg N/ha at Mingenew overcame the effect of medium compaction on average yield (Fig. 1). This decrease in yield response to deep cultivation with nitrogen application is in accord with measurements and simulations in Mediterranean Australia where wheat response to deep tillage decreased from ~0.75 t/ha at 25 kg N/ha to a non-significant response at 100 kg N/ha (Delroy and Bowden 1986; Asseng et al. 1998). At the fertiliser rate (60 kg N/ha) commonly used by growers in Buntine and Mingenew, subsoil constraints described in Table 1 affected simulated average root depth of wheat grown on a sandy soil and sandy loam at low (Buntine) and medium-rainfall (Mingenew) locations (Fig. 2). Soil type and local average rainfall had little effect on root depth for soils with 5–70 cm depth (treatments 1 to 5) or if a hard pan was encountered in the 20- to 40-cm layer (treatment 18). In these treatments, characterised by very low Rh values <0.01, the depths of subsoil constraints regulated root depths. Treatment 15 had low Rh values (0.01) throughout the soil profile resulting in the shallowest simulated root depth that varied little with soil type and location. In other treatments, roots grew deeper in sandy soil and at the wetter (Mingenew) location compared to the sandy loam and drier location (Buntine) due to deeper wetting fronts in dry seasons. The same amount of rainfall was distributed deeper in the sand than the sandy loam which holds more water per unit depth. The largest effect of soil type and location on root growth occurred when the soil profile had high Rh values (treatments 10 and 11).

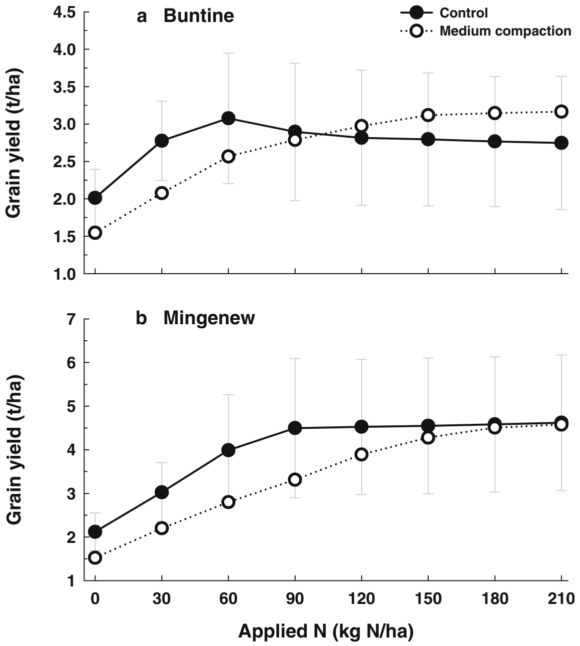


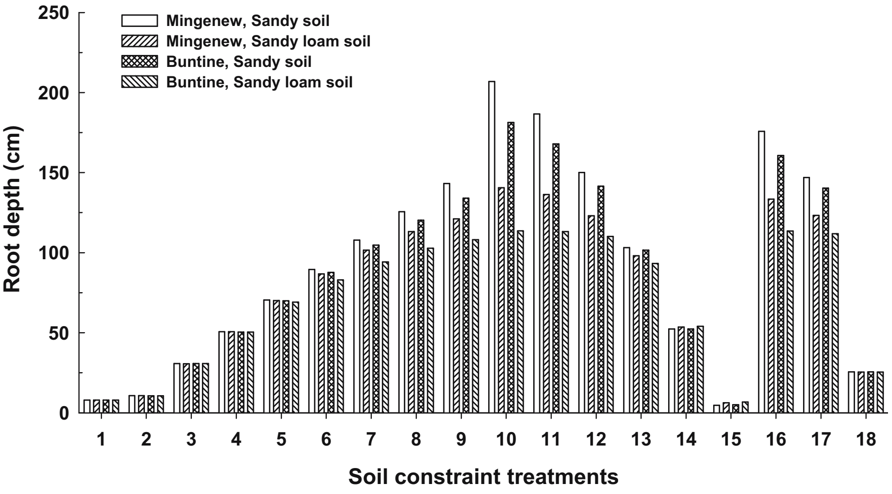
Fig. 1 Simulated average wheat yield response to nitrogen fertiliser application on a sandy soil at **a** a low-rainfall location (Buntine, 335 mm) and **b** a medium-rainfall location (Mingenew, 395 mm) for an initially dry soil. Control and medium compactions refer to treatments 11 and 17 (Table 1)

Restrictions in root depths decreased long-term average simulated wheat yields in both sand and sandy loam at Buntine and Mingenew (Fig. 3). In these simulations, the first 10-cm root depth had the largest impact on yields and further but smaller yield increments occurred with increases from 10 to 200 cm root depth. Mapping measured yields and soil depth at Buntine confirmed that 3-year average (over two wet and a dry year) yields of 1.06 t/ha could be achieved on only 5–15 cm deep sandy soils when 60 kg N/ha was applied (Table 2). Corresponding measured average yields increased to 1.28 t/ha at soil depths of 25–35 cm and to 1.91 t/ha at soil depth >200 cm. Simulated deeper root depths in sand than sandy loam was not necessarily translated into grain yields which reached a maximum average of 4 t/ha in both soils at the medium rainfall and a maximum average of 3 t/ha at the low-rainfall location.

The effect of seasonal rainfall on long-term average simulated root depth in an unconstrained sand and sandy loam (treatment 11) is shown in Fig. 4 for Buntine. The same results were obtained for Mingenew as the two sites only differ in seasonal rainfall (data not shown). Even in an unconstrained soil profile, root depth was limited by the amount of rainfall and hence the depth of the wetting front. The long-term average May to October rainfalls in Buntine (238 mm) and Mingenew (315 mm) are only sufficient to allow root growth down to an average maximum of 1.5 and 2.0 m respectively in the sandy loam (with 10% volumetric water content) given an initially dry soil profile. A root depth of 1.5 m represents a PAWC of 150 mm and a root depth of 2.0 m represents a PAWC of 200 mm in this simulated soil.

The effect of seasonal rainfall in the period 1954–2003 and of different intensities of subsoil compactions on annual wheat yields on initially dry sand is shown in Fig. 5 for Buntine. Large variations in simulated wheat yields for each subsoil compaction treatment and seasonal rainfall values occurred as a result of differences in the distribution of rainfall across each season. The severe compaction depicted in treatment 18 resulted in the lowest yields in most years compared with the less compacted soils. Annual yields on such a soil depend strongly on the distribution of rainfall across the season and this varied widely from

Fig. 2 Simulated average root depth of wheat with 60 kg N/ha fertiliser grown on an initially dry sand and sandy loam for a low rainfall location (Buntine, 335 mm) and a medium-rainfall location (Mingenew, 395 mm). See Table 1 for the soil constraint treatments used



year to year giving rise to a poor correlation coefficient (r^2=0.13) between grain yield and May to October rainfall. This correlation coefficient increased (r^2=0.37) in the deep cultivated control where greater plant available soil water storage capacities could buffer in-season rainfall variability better. In very dry years (May to October rainfall of 100–150 mm), yields were <2 t/ha across all treatments. Treatment effect depicted as difference in grain yields between the control and the compacted treatments increased with increasing amounts of seasonal rainfall until maximum yields of an average of around 5 t/ha were obtained in the deep cultivated control at 250–300 mm seasonal rainfall. The strong seasonal dependence of the yield benefits of ameliorating compaction is shown for wheat given 60 kg N/ha for the actual seasonal rainfalls received in 1996 to 2003 in Buntine (Fig. 6). Simulated grain yields in the deep cultivated control plots exceeded yields in other subsoil compaction treatments in 1996, 1998, 1999 and 2003. Seasonal rainfalls in these years exceeded 250 mm and allowed harvest indices of 0.3 to 0.4 to be achieved in the control plots. In years with seasonal rainfall of 113–203 mm, the medium compaction treatment out-yielded all other treatments. The medium compaction treatment produced less biomass than the control and this allowed it to maintain harvest indices 0.3 to 0.4. The control produced more biomass and correspondingly larger water requirements that were not met in years with terminal drought. This resulted in lower harvest indices of 0.15 to 0.2 and lower yields than the medium compaction treatment. Ameliorating a medium compacted soil would be financially unfavourable in these specific years. Differences in treatment yields were greatest in good rainfall years, and it is in those years that the maximum benefits of ameliorating subsoil compaction are obtained.

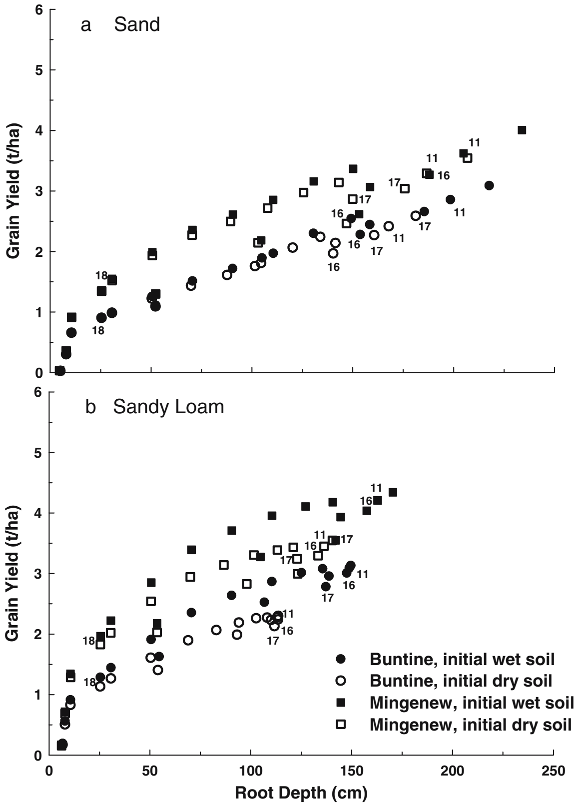


Fig. 3 Simulated average wheat yield response to root depth in **a** sand and **b** sandy loam for initially dry and wet soil conditions, with 60 kg N/ha fertiliser for a low rainfall location (Buntine, 335 mm) and a medium-rainfall location (Mingenew, 395 mm). *Numbers* indicate selected treatments (see Table 1)

Table 2 Measured average wheat yields for various soil depths in a field at a low rainfall location (Buntine)

Year	Measured May–October rain (mm)	Season tercile for Buntine	Wheat yields on 15 cm soil access (t/ha)	Wheat yields on 35 cm soil access (t/ha)	Wheat yields on >200 cm soil access (t/ha)
1996	284	Wet	1.61	1.80	2.84
1999	386	Wet	1.05	1.43	2.34
2002	114	Dry	0.53	0.60	0.55

Subsoil compaction limits the root's ability to tap into soil water at depth and results in unused soil water at harvest (Table 3). The amount of unused soil water at harvest increased with increasing severity of subsoil compaction and with increasing May–October rainfall. It was also greater at the wetter location (Mingenew) than the drier location (Buntine). At both locations, sand had more unused water than sandy loam in medium to dry years. Sand leached more nitrate (Wong et al. 2006) resulting in less biomass and water use and more unused water than sandy loam.

The financial risk of subsoil amelioration by deep cultivation to transform the compacted soil profiles to the non-compacted control was greatest in a dry environment (Table 4). In dry years at the drier location (Buntine), when both the sandy soil and sandy loam had initially dry soil profiles, subsoil amelioration returned losses across all treatments (Table 4). At the wetter location (Mingenew), these losses were only recorded following amelioration of mild and medium compaction. In this scenario, the low average gross margin of AUD 15 /ha×year obtained on an initially dry sandy loam often translated into losses because of large yield variability associated with variable in-season rainfall distribution (Fig. 5). Except for the case of amelioration of a mild compaction in a sandy loam, the Mingenew site returned positive financial benefits to subsoil amelioration for all other treatments in average to wet years. In these years at Buntine, sandy soils again gave more reliable returns on investment than sandy loam.

In an average rainfall season, sand responded better than sandy loam and gave better financial returns to deep cultivation by allowing deeper root growth

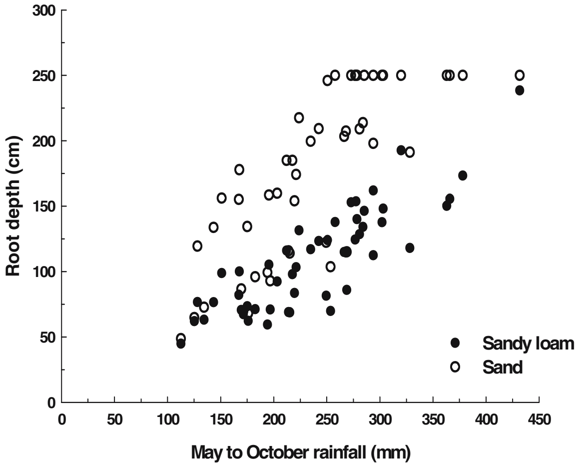


Fig. 4 Simulated annual (1954–2003) root depth response to seasonal (May to October) rainfall in an initially dry sand and sandy loam with no subsoil compaction (treatment 11, Table 1) at a low-rainfall location (Buntine, 335 mm)

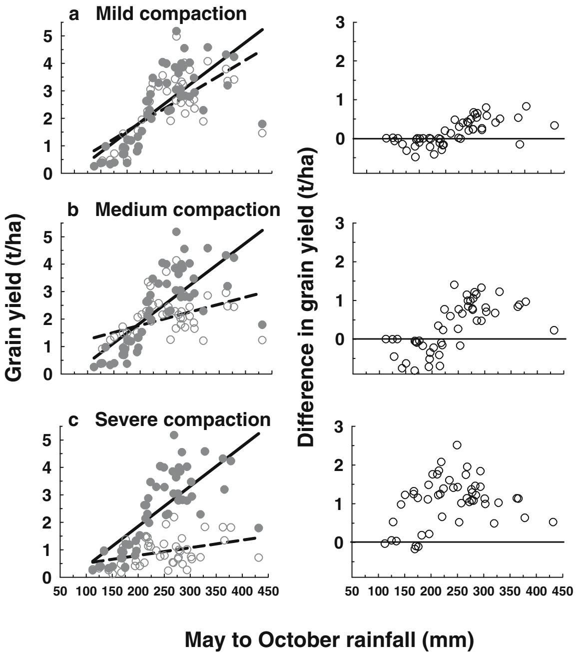
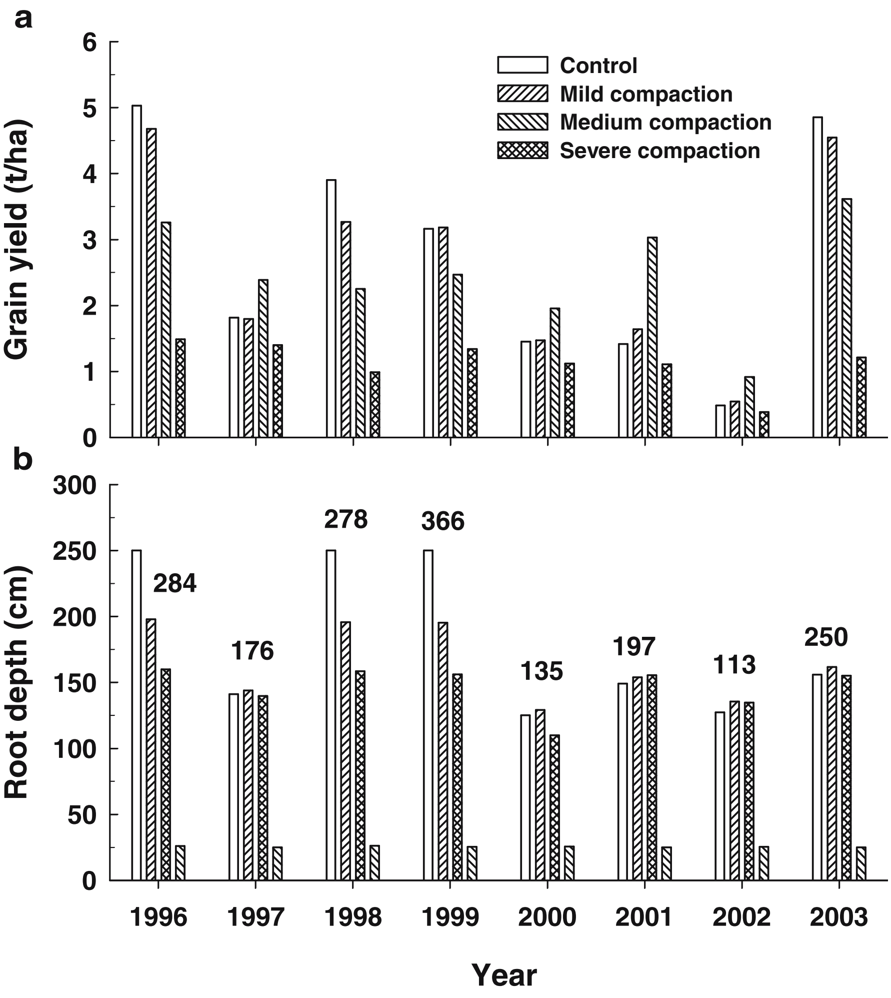


Fig. 5 Regressions (*left*) of simulated wheat yields with 60 kg N/ha fertiliser on seasonal (May to October) rainfall (1954–2003) for an initially dry sand at a low-rainfall (Buntine, 335 mm) location. Control (*filled circle*), mild (**a**), medium (**b**) and severe (**c**) subsoil compactions (*open circle*) referring to treatments 11, 16, 17 and 18 respectively (Table 1). The difference in grain yields between control minus compaction treatments (*right*) is given for comparison

Fig. 6 Simulated **a** annual wheat yields and **b** maximum root depth for control (treatment 11), mild (treatment 16), medium (treatment 17) and severe (treatment 18) subsoil compaction, with 60 kg N/ha fertiliser and an initially wet sandy soil. *Numbers* in **b** indicate seasonal (May to October) rainfall at the low-rainfall location (Buntine, 335 mm)



(Table 4, Fig. 4). In wet years at Mingenew, sandy loam generally outperformed the sand because less nitrate was leached (see below). Viewed over an average of three season types that are assumed to occur over a 3-year period over which the amelioration is expected to remain effective (and assumed constant), both the Buntine and Mingenew sites benefited financially from ameliorating severe subsoil compaction (treatment 11) in both sandy soil and sandy loam. Ameliorating a medium compacted soil in this scenario also results in financial benefits except in the sandy loam at Buntine where a loss is expected. In contrast, ameliorating a mildly compacted soil in this scenario resulted in losses at both locations and in both soils. The average financial benefits over the three season types were greater in sand than sandy loam at both Buntine and Mingenew.

Ameliorating severely compacted subsoil with a hard pan described in Table 4 (treatment 18) to the control conditions (treatment 11) decreased simulated deep drainage and nitrate leaching. In an average rainfall season, deep drainage in sand decreased on average by 44% to 23 mm at Buntine and by 42% to 46 mm at Mingenew. Drainage only occurred in wet years in sandy loam and subsoil amelioration decreased it on average by 25% to 3 mm at Buntine and by 43% to 12 mm at Mingenew. The corresponding rate of nitrate leaching in an average rainfall season, decreased in sand on average by 55% at Buntine to 5 kg N/(ha year) and by 52% at Mingenew to 14 kg N/(ha year). Sandy loam only leached nitrate in wet years and subsoil amelioration decreased leaching by 50% to 1 kg N/(ha year) at Buntine and by 44% to 5 kg N/(ha year) at Mingenew.

Table 3 Simulated average unused soil water in 0–210 cm after wheat harvest for a sand and a sandy loam with initial dry soil conditions at a low (Buntine) and medium-rainfall (Mingenew) location with 60 kg N/ha applied at sowing

Location	Season Type (based on terciles)	Seasonal Terciles (% occurrence)	May–October Rainfall range (mm)	Unused water after harvest (mm)			
				Control[a]	Mild[b] compaction	Medium[c] compaction	Severe[d] compaction
Sand							
Buntine	Dry	100.0–66.6	113–203	6	10	19	52
	Average	66.6–33.3	212–269	20	28	50	89
	Wet	33.3–0.0	273–432	29	39	63	92
Mingenew	Dry	100.0–66.6	172–260	11	17	34	75
	Average	66.6–33.3	266–345	30	41	67	96
	Wet	33.3–0.0	349–520	60	72	88	99
Sandy loam							
Buntine	Dry	100.0–66.6	113–203	3	4	8	28
	Average	66.6–33.3	212–269	8	9	17	67
	Wet	33.3–0.0	273–432	18	22	47	111
Mingenew	Dry	100.0–66.6	172–260	6	6	10	38
	Average	66.6–33.3	266–345	18	21	43	104
	Wet	33.3–0.0	349–520	70	82	120	163

[a] Treatment 11 (control, no compaction, Table 1)

[b] Treatment 16 (mild compaction at 20–40 cm depth, Table 1)

[c] Treatment 17 (medium compaction at 20–40 cm depth, refer to Table 1)

[d] Treatment 18 (severe compaction at 20–40 cm depth, Table 1)

Discussion

Seasonal and spatial expression of subsoil constraints

The simulation experiments indicated the situations where profits from subsoil amelioration in a Mediterranean-type environment are more likely. In dry years, there is less response to subsoil amelioration. For example, measured wheat response to deep cultivation on a sandy clay loam in this environment was 8% above the untreated control plots in the year of cultivation (1997) when the site received 186 mm growing season rainfall. This response increased to 25% in the wetter year of 1999 when the site received 236 mm season rainfall. These results were similar on loamy sand where the response was larger in the wetter year (Hamza and Anderson 2003). This increased response to deep cultivation in wetter years is in accord with other measurements in the region. For example, following deep cultivation, measured wheat yields on a loamy sand with medium subsoil compaction increased from 1.8 to 2.2 t/ha with 212 mm seasonal rainfall in 1990 and from 2.7 to 3.6 t/ha with 251 mm rainfall (Schmidt et al. 1994). A financially profitable response to subsoil amelioration can be obtained in some dry years if the crop can access stored water from rainfalls before the May to October growing season. Deep cultivating traffic-induced compaction allows growers to make the most of average to high rainfall seasons. In these seasons, roots growing faster in ameliorated subsoils are better able to keep pace with leaching nutrients such as nitrate and allow more to be taken up earlier during the critical tillering phase (Delroy and Bowden 1986).

Deeper wetting fronts in sand than loamy sand partly explain the results of earlier field experiments and grower experience which indicate that coarser textured soils often respond better to deep cultivation than finer textured soils (Jarvis 1982, 1986, 1991). In wet years however, sands have the disadvantage of leaching more nitrate resulting in lower yields and lower response to deep cultivation than sandy loam. Large differences in water holding capacities occur across fields as a result of variations in soil type (Wong and Asseng 2006). This would result in a spatially variable response to subsoil amelioration

Table 4 Simulated average gross margin benefits for three season types of ameliorating compaction in a sandy soil and a sandy loam with initial dry soil profiles at a low (Buntine) and medium-rainfall (Mingenew) location with 60 kg N/ha applied at sowing

Location	Season type	May–October rainfall range (mm)	Gross margin ($/ha year)[a]				Benefits from deep cultivation ($/ha year)[b]		
			No[c] compaction (Control)	Mild[d] compaction	Medium[e] compaction	Severe[f] compaction	Mild compaction	Medium compaction	Severe compaction
Sandy soil									
Buntine	Dry	113–203	−79	−2	67	−66	−77	−146	−13
	Average	212–269	349	378	286	20	−28	63	329
	Wet	273–432	370	337	181	0	33	189	370
Mingenew	Dry	172–260	256	318	274	30	−62	−18	226
	Average	266–345	476	462	306	94	14	170	382
	Wet	349–520	345	316	179	54	29	165	290
Sandy loam soil									
Buntine	Dry	113–203	−152	−100	−81	−101	−52	−72	−51
	Average	212–269	171	228	263	79	−57	−93	91
	Wet	273–432	542	569	446	110	−27	96	432
Mingenew	Dry	172–260	93	146	184	77	−53	−91	15
	Average	266–345	516	553	496	218	−37	20	298
	Wet	349–520	557	542	377	150	15	180	407

[a] Gross margin calculations include input costs of $127/ha plus nitrogen costs of $1/kg N applied.

[b] Costs for deep cultivating to 40 cm of $150/ha, spread over 3 years

[c] Treatment 11 (control, no compaction; refer to Table 1). This assumes a cost of $150/ha incurred to achieve the control condition (see f below).

[d] Treatment 16 (mild compaction at 20–40 cm depth; refer to Table 1)

[e] Treatment 17 (medium compaction at 20–40 cm depth; refer to Table 1)

[f] Treatment 18 (severe compaction at 20–40 cm depth; refer to Table 1)

across the field. On a larger spatial scale, responses to subsoil amelioration are more likely in high than in low rainfall locations due to deep wetting fronts.

Unused soil water and increases in crop lower limits

Measured water contents of compaction-affected soil profiles at the end of the growing season are usually larger than those of the corresponding deep-cultivated soils (Delroy and Bowden 1986). The inability of crops to use this water, especially late in the season from spring onwards when the water balance is negative is a main reason for yield loss in affected soils. In addition to the loss of yields due to unused water, potential loss of this unused water to deep drainage may contribute to the rise of saline water tables which is currently a major problem affecting the wheatbelt of Mediterranean Australia (Pracilio et al. 2003; Sadras et al. 2005). However, in non-saline soils, unused soil water at crop maturity can help to locate and map areas affected by subsoil constraints across fields by electromagnetic (EM38) sensing of water in the soil profile soon after harvest (O'Leary et al. 2003). This map is useful to avoid the high cost of deep cultivating across areas of the field that do not need amelioration.

Benefits and risks of managing subsoil constraints

Grain yield responses to deep cultivation in an average rainfall year are greater in wetter locations and in coarser textured soil types in a Mediterranean-type environment. In the sandy soils, the losses in dry and dry-finish years due to investing in deep cultivating medium to severe subsoil compaction are expected to be offset by the gains in average and wet years if a constant deep cultivation effect is assumed over a 3-year period. Deep cultivating a loam is more risky as losses can be expected when a medium compacted soil is ameliorated at drier locations. The use of gypsum, organic matter and of control traffic minimise re-compaction and can extend the benefits of deep cultivation (Hamza and Anderson 2005; Yamaguchi et al. 2004). But only the use of gypsum has been justified financially in some soils (Hamza and Anderson 2005). Deep cultivation of mildly compacted soils may result in negative grain yield responses especially with low seasonal rainfall. It is therefore important to measure the severity of subsoil compaction with a penetrometer during crop growth (when roots are expected to be growing through the subsoil layer) and checking the results with bulk density measurements and soil profile description to avoid the high cost of deep cultivating these soils before they are due. The process of deep cultivation may itself involve some risks such as poor seed germination and crop establishment in freshly loosened soil. The use of a shallow leading tine minimises this effect by decreasing clod size and improving soil tilth to provide a better seed bed (Hamza et al. 2005). If the subsoil has multiple constraints such as acidity and sodicity, then deep-cultivation on its own is unlikely to be beneficial and should be avoided until these constraints can be resolved. Possible options include injection of lime into the subsoil to neutralise acidity and application of gypsum or organic matter to stabilise sodic soils (Hamza and Anderson 2005; Yamaguchi et al. 2004). Deep cultivation is also not practicable in some situations such as in shallow soils overlying rocks and gravel. In this case soil depth and rainfall control the yield potential of the site and management may consist of adjusting nutrient inputs to match the yield potential (Wong et al. 2001).

Simulating multiple subsoil constraints

The consequence of decreased root growth in compacted subsoils is decreased access to subsoil water resulting in apparently higher crop lower limits (inaccessible soil water) in deeper soil layers. This increase in apparent crop lower limits is commonly observed in subsoil constraints (O'Leary et al. 2003; Sadras et al. 2005). Increased values of apparent crop lower limits without altering root depth development have therefore been used in other studies to simulate subsoil compaction with APSIM (Sadras et al. 2005). The alternative approach used in our study was to alter the root hospitality factor (Rh) to represent the effect of multiple subsoil constraints on root growth. This results in variable soil water extraction as a consequence of root depth development, which is a more realistic outcome. The Rh value can represent root elongation constraints such as static soil diseases, soil acidification or soil compaction (Asseng et al. 1998; Tang et al. 2003). In some seasons, a root growth constraint due to dry soil conditions below the wetting front was as effective as a severe subsoil compaction in restricting root growth and yields.

Conclusions

Crop response to subsoil amelioration in the Mediterranean environment will vary from year to year and from place to place due to subsoil constraints – weather–soil type–fertiliser management interactions. Adequate amounts of nitrogen fertilisers must be applied to avoid the risk of nitrogen deficiency amplifying the adverse effect of subsoil constraint on grain yields. This can be done by using various fertiliser recommendations systems currently available. Fields at a wetter location are more likely to benefit from subsoil amelioration than those at a drier location in this environment. Those with predominantly coarser textured soils will respond better to subsoil amelioration than those with predominantly finer textured soils. These findings provide a basis to prioritise farmers' fields for treatment. More response to subsoil amelioration is expected in wetter than drier years. While it is not possible to pick good rainfall years in advance, a medium-term (several years) perspective should be taken when investing in subsoil amelioration. The effect of amelioration should last over the medium-term and over this period, we would expect losses in dry and dry finish years to be offset by gains in more favourable rainfall years especially on coarser textured soils and at wetter locations. The use of a crop model such as APSIM eases decision on subsoil amelioration by providing insights into why alleviating subsoil constraints can have a positive, a negative or no effect on grain yields. Yield simulations with soil and weather data enable assessment of likely financial and environmental benefits and risk of subsoil amelioration for specific scenarios likely to be encountered on-farm. The benefit analysis is based on the assumption that the main effect of subsoil constraints and their amelioration is on root growth. Other effects such as changes in nutrient mineralisation rates and the possibility of transferring hostile subsoils such as dispersive sodic and boron toxic subsoils to the top during subsoil amelioration are not considered. While this study was carried out with wheat grown in a Mediterranean environment, the approach could be easily adapted to other crops and locations.

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