



WEST MIDLANDS
GROUP

The impact of gravel on crop management – a desktop study

Project funded by COGGO



COGGO

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Executive Summary

Gravel soils (soils with > 20% gravel in the topsoil) make up about 3 million hectares of the 18 million hectares of alienated land in the agricultural areas of south western WA. They are ubiquitous, and occur at high frequency in the increasingly cropped, high rainfall zone of WA. They are all lateritic but fall into two natural classes according to location. Those to the west in the forest country are dominated by iron and aluminum oxides while those in the wheatbelt to the east contain a lot more silica.

Why study the gravel content of soils?

If a soil depth contains 50% inert gravel then:-

- The supply of nutrients in a given depth would be halved
- Half the rate of fertiliser would give the same concentration.
- Lime rates could be halved to raise pH by one unit.
- Acidification rates would double for the same acid input.
- At a given organic carbon (OC) %, carbon sequestration would be halved.
- The soil would store half as much water for crops to get through dry periods.
- 5mm of rainfall would effectively be 10mm and allow germination on the gravelly soil.
- Water would drain more readily to twice the depth and leach more chemicals
- There would be half the buffering (e.g. Phosphorous Buffering Index (PBI) and Cation Exchange Capacity (CEC)) to hold nutrients

All of these points can impact on input decision making and/or management choices.

The question arises as to whether we can assume gravel is inert or whether it interacts with and adsorbs/absorbs agricultural chemicals and water?

The study was carried out in three sections:-

1. **Gravel and agricultural inputs.** Is the gravel content of soils taken into account in the most appropriate way for recommendation systems on the use of agricultural inputs?
2. **Gravel and soil water.** How does the gravel content of soils impact on soil water relations and through that, what are the implications for agricultural management practices?
3. **Gravel and root exploration.** Does the gravel content of soils affect root growth dynamics and soil exploration and does this interact with nutrient and water uptake by crops?

Findings

1. Gravel and agricultural inputs

An email survey of growers, agronomists, researchers, consultants, showed that these stakeholders were more interested in how agronomic practices should be adjusted on gravelly soil types than in the effect of soil gravel content (gv%) per se on recommendation systems:

1.1 Even though it is often used as a quantitative input for fertiliser and liming decision making, the gv% is not often sampled or estimated correctly.

1.2 In soil test based fertilizer recommendations, gv% is used by fertilizer companies to adjust the supply of available soil P and K downwards (and fertilizer rates upwards) even though the unadjusted figure is what was used to determine the soil test calibration curves. This is double accounting and would require further work to show that it is justifiable.

1.3 If nutrient buffering capacity is used to adjust recommendations for soil type effects then it too should take account of the gv%.

1.4 The gv% adjustments are probably appropriate for N fertilizer advice.

1.5 Lime recommendations are appropriately adjusted for gv%.

1.6 Granular pesticides are concentrated by gravel in soils but gv% is not used to adjust recommended rates.

1.7 The gv% is considered to be irrelevant in the use of liquid herbicides and pesticides because it is assumed that the gravels immobilize the chemicals (i.e. does not concentrate them) and that the response curves of weeds and pests to these inputs are so flat that any adjustment would have a minor, if any, effect at all.

1.8 The sequestration of soil carbon is calculated on analyses carried out on the fines. To express the answers in tonnes carbon/hectare it is necessary to adjust the analyses for soil bulk density (BD) and for gv%. While care is taken to adjust for BD, very little effort is taken to measure gv% which in fact can vary more widely than BD.

The issues raised above need to be addressed by the relevant stakeholders.

2. Gravel and soil water

If gravel is inert to water in soils then it simply acts as a diluent – there will be only (1-gv%/100) of soil fines to interact with inputs such as water. It will reduce water held at field capacity (drained upper limit – DUL) which means a given input of infiltrating rain will wet deeper and faster and this will impact on nutrient and chemical availability through leaching and water drainage from the rooting profile. The water held at wilting point (crop lower limit – CLL) would also be reduced by inert gravel. Most importantly, the plant available water capacity (PAWC = DUL-CLL) would be reduced with consequences for the amounts of stored soil water which allows crops and pastures to survive spells of no rainfall, the most common of which is the end of season or terminal drought.

Gravel can act as a mulch and reduce soil water evaporative losses. It can also cause less infiltrating surface and result in more run-off. However, if gravel causes puddling then you may get increased infiltration and less run-off.

The main question to answer here is whether gravel does or does not absorb water (i.e. is it inert)? If it does hold water, then how large is the DUL and PAWC of any given gravel? Obviously there will be a range of values depending on the nature of the gravel.

Unfortunately this study was reduced to a regression investigation because there was neither time nor resources to carry out direct measurements on gravels. A data base was constructed which consisted of 87 sites with soil water content (DUL, CLL and PAWC) and gv% measures taken in 10cm intervals to one metre depth. The data were investigated statistically in several ways.

The main study fitted water content profiles as a function of gv% averaged across sites grouped into three soil types or two regions. An index of “inertness” of the gravel in these groups of sites was calculated by comparing the fitted (actual mean) water content profiles at gv% = 20, with those calculated from the fitted values at gv% = 0 reduced by 20%, assuming the gravel was inert. The results for surface soil and soil at 50 cm depth, are summarised in the table below. As expected, the inertness of the gravel to water varies markedly.

	Gravel inertness percentage			
water content	DUL	DUL	PAWC	PAWC
group\depth	0 cm	50 cm	0 cm	50 cm
37 duplex	90.1	61.3	11.8	52.4
18 uniform	71.1	55.3	74.4	54.2
32 gradational	2.2	11.7	36.7	-7.8
25 west/forest	74.6	68.5	58.8	50.8
62 east/wheatbelt	74.1	39.6	-3.7	0.0

In most circumstances, gravel does have the property of reducing soil water contents but not to the extent expected if gravel was inert. This suggests that gravel can not only hold water but can hold significant quantities of plant available water in some circumstances. The fitted surface for DUL says that soils with higher gv% hold less water against drainage. This implies that soil mobile nutrients and agricultural chemicals will be moved deeper and faster on gravelly soils with any given amount of infiltrating rain. Also having gravel in a soil could well provide preferred pathways for

water infiltration and drainage across the more vertical gravel surfaces in the soil. Direct measurements of infiltration rates with a rainfall simulator would help resolve these issues.

The variability of the effect of gv% on PAWC makes it difficult to draw conclusions about the impact of gravel on plant growth, soil water storage and the ability for crops to survive non rainfall periods particularly during the terminal drought at the end of the season in a Mediterranean environment. Some of the DUL and CLL curves from this analysis could be fed into a simulation model to be run over a range of seasons to see how the variability in crop yields is affected by gv%.

Gravel could have an indirect effect on soil water relations via its effect on soil wettability. Non-wetting soils often have high OC% and low clay contents in the fines. For the same dry matter production, or net organic carbon input into the soil a soil with high gv% will have an increased measured OC% in the fines. This can cause more water repellency with implications for run off and drainage.

If anything, this section has raised more questions than it has resolved. At the moment, direct measurements of things like soil water profiles, infiltration and run off will be better than trying to adjust theoretical moisture properties/profiles according to measured gravel contents.

3. Gravel and root exploration

The presence of objects in a soil which cannot be penetrated by roots obviously has a major effect on root growth, root architecture and root length densities through time and space. This in turn will affect nutrient and water uptake with implications for crop growth and nutrient management decisions. Obvious questions to answer are:

1. Will the presence of gravel increase the uptake of soil immobile nutrients (copper, zinc, manganese and phosphorus on high fixing soils) by increasing root exploration of the fertile zones of the soil?
2. Will the presence of gravel cause the root depth penetration rate to increase enough for the crop to better take up soil mobile (leachable nitrate and sulphate) nutrients and water?
3. Will increased and earlier root competition caused by gravel content force roots to explore new soil laterally more rapidly? That is, will roots explore the inter row more rapidly in gravelly soils?

Resources did not allow the direct investigation questions about the impact of gravel on root growth dynamics using observations and/or experiments. Some of the issues were investigated using the root growth model, Rootmap (Dunbabin, Diggle et al).

Findings from Rootmap study:

At 8% gravel greater root length and root length densities were induced in the gravel zone. At the 29% gravel level total root length is not increased, but root length density was increased by 30%. The amount of P at the same initial concentration is also reduced by 30% but P uptake remains the same. Which means that uptake efficiency as measured by the fraction of available P depleted, has risen by about 30 to 40% in the presence of 29% gravel.

How these nutrient uptake efficiencies change with level and distribution of gravel, level and placement of the nutrients, mobility and buffering capacity of the nutrient, the wetting and drying patterns of the soil, as well as the genetics of the cropping species and how this affects root architecture responses to gravel. With more resources to contract programmers, all of these and other issues could and should be studied further, initially with the Rootmap model and then perhaps with direct observational and experimental work.

This study addressed the question “do plants grown in the presence of gravel, send roots sideways and deeper more rapidly than plants grown in the same soil without gravel”? The findings were ambiguous. The roots did appear to go sideways (into the inter-row faster but the deeper, faster, question depends on the conditions and so is yet to be resolved.-

Project conclusions

- If nutrition or carbon budgeting is carried out on a unit area basis, then gv%, like bulk density should be taken into account when chemical analyses of the non-gravel (fines) component of soils are adjusted to a whole soil basis.
- Some fertilizer recommendation systems (e.g. for P and K) should NOT adjust the analyses to a whole soil basis, particularly if soil test calibration curves are the backbone of the system.
- If adjustments for gv% are appropriate then care must be taken in sampling for and/or estimating gv%.
- Gravel is not always inert to water absorption and/or interactions with nutrients so care must be taken when adjustments to recommendations and management are made.
- The question of whether roots go sideways (into the inter-row) and/or deeper, faster, on gravelly soils has not been resolved.
- Advisers, consultants and research workers are interested in how or whether gravelly soils should be managed differently, but are less sure about whether they should make quantitative adjustments for the gv% of soils.
- This project has raised more questions than it has answered.

Future work

- Direct measurement of the water contents (DUL and CLL) of a range of gravels from a range of soils should be carried out in the field.
- A new database containing the water content parameters as well as OC% and clay% for all depths should be constructed.
- The Rootmap model could be used to further study the effects of a range of factors which interact with gv% and affect nutrient uptake and water relations.
- The APSIM model could be used to characterise the impact of gravels of different water holding capacities on nutrient leaching, crop growth and yield under different management and seasonal conditions.

1.0 Introduction

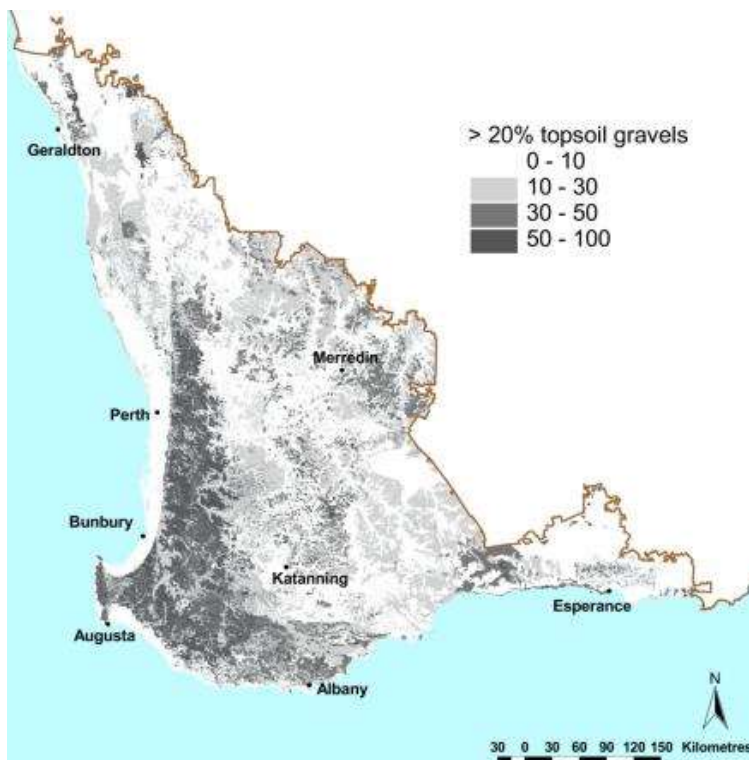
Aim

The aim of the COGGO gravel project was to determine whether adjustments needed to be made to a range of decision support systems (DSSs) to account for the effect of gravel on various agricultural management options. Limited resources meant that the project was constrained to a desktop study.

Background

Gravel soils are ubiquitous, particularly in the high rainfall zone (HRZ) of Western Australia (WA). However, the gravel content of soils is largely ignored or handled in a cursory manner in quantitative, input, and management decision making.

Figure 1. Distribution in WA, of soils with greater than 20% gravel in their topsoils



Gravel, as an inert component of a soil, has a diluting effect on the amount of stored water and nutrients. At the same time, it has a concentrating effect on inputs such as herbicides, fertilisers, organic carbon, acidity and soil ameliorants such as lime and gypsum. It has implications for infiltration and runoff rates, for load bearing and compaction. It is an essential parameter for the calculation of carbon and soil fertility budgets. Soils are discriminated by farmers for management and explanation on the basis of visible surface gravel. Some classes of gravels are not necessarily inert and can absorb water and nutrients. Gravels introduce heterogeneity into soils and this can have positive and/or negative effects on crop production. Gravels increase root length density and may even increase root lengths

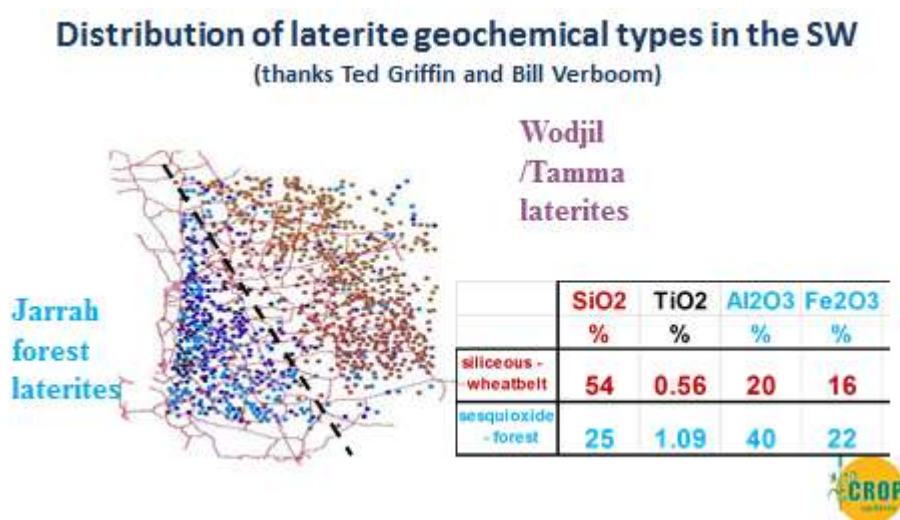
This project uses an understanding of the gravel content of soils to re-investigate a range of soil processes with the objective of better managing agricultural inputs to gravelly soils of WA. The results will have relevance for the wide geographic distribution of gravelly and stony soils cropped in Australia. An understanding of how the gravel content of the soil interacts with the water balance, plant nutrition and crop growth is an area worthy of study in WA, particularly as the cropping centre of gravity moves into the high rainfall zone where gravelly forest and woodland soils dominate the landscape.

Gravel in WA and its effect on soil properties

Here, gravel is understood to be a mineral, soil constituent which is retained on a 2mm screen and can range from 'buckshot' particles through to stones and boulders. In what follows, particles which pass through a 2mm screen are termed "fines" or the "matrix". Gravel can be inert (as with chips of rock where it acts as a diluent of the physically and chemically active fines) or it can be as reactive (if not more so) than the matrix in which it sits (as with clay mottles and porous aggregates).

In WA, gravel is mainly lateritic (i.e. made up of iron and aluminium oxide concretions). At the grossest level, two main types of gravel (iron/aluminum rich and silica rich) have can be distinguished.

Figure 2. Distribution of sites with different gravel chemistry



Usually in characterising soils we carry out physical (e.g. texturing) and chemical analyses (e.g. buffering capacity, cation exchange capacity (CEC) and nutrient analyses – as concentrations) on the fines, but require our outputs (e.g. carbon storage, nutrient availability) and inputs (e.g. fertilizer, ameliorants) to be expressed on a whole soil or surface area (e.g. kg/ha) basis. To quantitatively make the conversion from unit matrix measures to per hectare budgets, we need to account for the bulk density of the soil ($BD = \text{gm/cc}$ or t/cubic metre), the gravel content (as a percent) and the depth we are considering.

A major problem is that BD is rarely measured – so we tend to default to a reasonable guess (when in doubt use 1.5) but it can range from 1.0 to 1.8 for the matrix of WA soils. The BD of gravels is also variable though for lateritic gravels in WA a number between 2 to 2.4 is usual. In lieu of measurements, relatively informed approximations of BD will usually be in error by less than 15%.

Estimates of the gravel content of the soil raise several problems. Should they be done on a weight/weight (w/w) or volume/volume (v/v) percentage, or indeed on an exposed surface area basis? Gravel contents (gv%) of WA soils (on any basis) can range from zero to 100% (massive laterite?) though our WA lateritic gravelly soils are more often in the 5% (below which we hardly notice the presence) to 80% (beyond which we would not call them soils). So ignoring gravel content in our recommendation systems has the potential to influence the conversion from matrix concentration to a whole soil basis by a factor of 400 or 500% for some soil properties and input levels.

Add to that the fact that many of our sampling methods for soil testing purposes, exclude (or sometimes, pulverize) the gravel before it can be quantitatively estimated in the laboratory. **If the gravel content of the soil is to be used for adjusting recommendations or expressing fines data on a whole soil basis, then it must be sampled and measured correctly.**

2.0 Gravel and agricultural inputs

This section addresses the main output of the project, namely “is the gravel content of the soil used in existing input recommendation systems? If so is it used appropriately and if not, should adjustments be made?”

Survey of stakeholders on the importance of gravel content of soils for management decisions

An informal email survey requesting the views on the role of gravel in our farming systems, of about 50 selected Decision Support System (DSS) providers, agronomists, specialists and growers was carried out and about 30 replied. With some exceptions, the general feeling was that gravel and gravelly soils were an important part of our agricultural systems and that a project focused on gravel would raise, if not solve some issues of importance to growers.

The main DSS providers for crop and pasture nutrition and liming, currently take account of soil gravel content and have provided the detail of how they do this. The gravel is usually considered to reduce soil nutrient availability in a linear fashion for whole soil or unit area calculations. This is reasonable when plant roots respond to amounts of nutrients rather than to concentrations. This question of response to concentration or amount is equally relevant to the addition of fertilizer nutrients on gravelly soils. Which of these two propositions hold for which nutrients and in which situations will be the subject of further analysis and possible suggested changes to the recommendation systems.

None of the pathologists, entomologists or weeds experts take any specific account of gravel in their pesticide recommendation systems. They do recognize that the ecology of their disciplines can be different on gravel soils but that this is more likely to be related to correlates such as pH and non-wetting soils than to gravel per-se. Lip service is paid to the fact that gravel could increase the leaching of soil mobile pesticides to depth with consequences for the effectiveness. The concentrating effects of gravel on pesticide inputs and a need for a reduction of rates is denied either because outcomes are very insensitive to rates of application, or because the gravel is considered to be active and as such, holds pesticides such that the concentrations in the matrix do not vary much with gravel content.

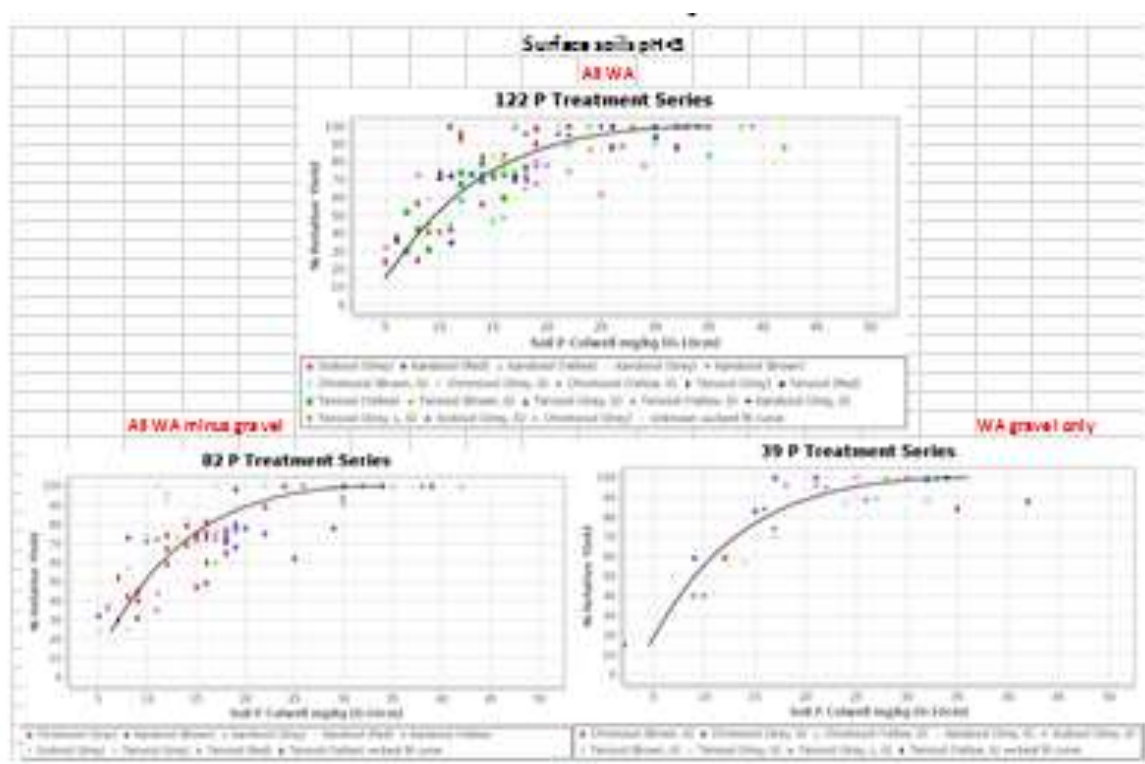
The advisers and growers were more interested in what management adjustments might be needed for gravelly soils (and all that correlates with them), than for the effect of gravel in soils on the recommendations. Answers for such questions will depend on what constitutes a “gravelly soil” in WA from the practitioners’ point of view. Soil scientists have their definitions but how much gravel and where in both the profile and the landscape is it recognizable and significant for growers?

Fertiliser recommendation systems

Fertiliser recommendation systems in WA largely rely on a locally determined calibration curves. These are experimentally determined correlations between soil supplies and crop response to nutrient inputs across a range of sites of differing nutrient status. For macro-nutrients like phosphorous (P) and potassium (K) (and sulphur (S)?) the calibration curves plot yield with zero nutrient as a fraction of the nutrient non-limiting yield versus soil test levels with appropriate adjustments for crop, soil type, season etc. These correlations already take account of gravel in the soil either through separate calibration curves for gravelly soils or in the spread of points for more robust correlations for non-differentiated soil group. Any quantitative adjustment for gv% needs to be justified by demonstrable improvements to the accuracy of the calibration curves.

Figure 3. Soil test calibration curves for wheat responses to P in WA (from the BFDC data base)

Top, all sites, bottom left, all sites minus gravel sites, bottom right all gravel sites.



In the above example for P, there is no evidence outside of error that the gravelly soils behave any differently to non-gravel soils. **However several fertilizer recommendation systems adjust available soil P downwards (and fertilizer rates upwards), according to estimates of the gv% of the soil.**

A more mechanistic approach to determining soil supplies is made for nitrogen (N) recommendations where available N from rotational and soil organic matter sources is combined with soil test mineral N analyses of the fines. No direct soil test calibration has been developed because very poor correlations result due to the variability in mineralization and to nitrate leaching events before and after soil sampling which depend on rainfall events. The mechanistic approach does take account of gv% for both the amounts of organic and mineral N in the soil and for its impact on leaching. This adjustment of the chemically available nutrient levels measured on the fines, to a whole soil basis reduces the availability by the factor $(1 - \text{gravel percentage}/100) = (1 - \text{gv\%})/100$. There are circumstances where increasing the gv%, can **increase** the availability of fertilizer inputs.

For the soil mobile nutrients (N, S, K) it increases the concentration at a given level of liquid and soluble granular fertilizer inputs. For soil immobile nutrients (P on high Phosphorous Buffering Index (PBI) soils, copper, zinc and manganese on most soils) and with granular fertilisers, gv% increases the probability of roots running into highly available fertilizer affected parts of the soil. Either way, the gravel can make the fertilizer nutrient input more effective and so lead to lower recommended rates.

Nitrogen (N)

The N recommendation systems which use a soil test (mineral N levels and organic carbon (OC)% as a surrogate for organic nitrogen), correctly adjust these components of the soil N availability downwards according to the gv% because N is a soil mobile nutrient and any significant replenishment of N taken up by the plant comes only from mineralization of organic matter (OM). The amount of N in the whole soil from these sources is more relevant than the measured concentrations in the fines fraction

Being a soil mobile nutrient, inert gravel can also induce more leaching of N and this may make N from both the soil and from the fertilizer sources, less available (see section 2). A tactical N fertilizer recommendation system should take account of this effect of gravel.

As a rule, WA recommendation systems for N are based more on calculation than empirical field soil test calibrations and so do adjust correctly for gv%. Imported systems from the Eastern States and overseas, do not even attempt to take account of gravel.

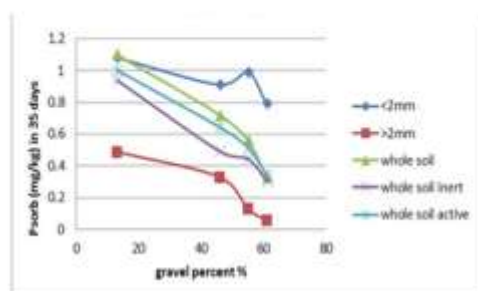
Phosphorus (P)

In the case of P soil testing, the soil type effect on the calibration curve is taken out using the PBI. High PBI usually means that the critical soil test levels are higher (P is less plant available at a given soil test level) than for low PBI soils. However, PBI is measured on the matrix and by rights, should be adjusted to a whole soil basis. This would mean that **inert gravel would reduce the critical levels for soil test P and so should decrease a P recommendation. This effect of gravel on P buffering is not taken into account when WA recommendation systems adjust for PBI.**

Weaver et al (1992) looked in detail at P sorption on gravels and whole soils (Fig 3. left, green line compared with the blue line for <2mm fines) and came to the conclusion that increasing gravel content reduced P sorption and should reduce crop and pasture P requirements (Fig 3. Right).

Figure 3. The effect of gravel content on P buffering (left) and its implication for reducing P fertilizer requirements (Weaver et al 1992)

Weaver et al 1992. Effect of gravel on P sorption
Note that here the forest gravel is not inert



Gravel content on % reduction of P required for maximum growth

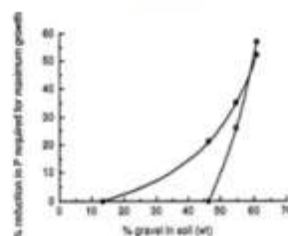


Fig. 5. Estimated reduction in P required for maximum growth of clover (●) and wheat (○) on Valence soil at different soil gravel contents.

In most commercially available WA recommendation systems, the whole soil adjustment of the soil test P reduces P availability as gv% increases and so pushes P recommendations higher.

As distinct from N, S and to a lesser extent K, there is logic which says that for a soil immobile nutrient like P on high PBI soils (and copper, zinc and manganese on most soils), the crop does not respond to the whole soil **amount** (capacity) of P but, rather responds to the matrix **concentration** (intensity) of P. Certainly this would be the case at low levels of gravel but amount may well become important at higher levels of gravel.

For soil immobile nutrients, root exploration is another major factor affecting plant availability. A dense root system depletes soil more rapidly and can push the supply side of availability from concentration driven to amount driven. Gravel has the effect of increasing root densities in the matrix and at high gv%, particularly on low PBI soils, amount of available P will become the dominant factor. The effect of gravel in increasing root density should further increase this efficiency of fertiliser P use (see section 3)

All told, this is a complicated story where gravel content should possibly be ignored and a P fertilizer recommendation system would best rely on field based soil test calibration curves and field trial based response curves to fertilizer P.

Potassium (K)

K sits between N and P in its mobility in the soil which reflects K buffering which is largely a function of CEC. The CEC of WA sandy soils are dominated by the CEC of the organic component of the soil usually expresses as OC%. On heavier textured soils, clay content (clay%) and clay mineralogy can be major contributors to CEC. Clay% and OC% are both measured on the fines component of the soil and as such they need to be adjusted to a whole soil basis if CEC is to be used in a soil test based, K fertilizer recommendation system.

The commercial systems for K which service most growers in WA do adjust to a whole soil basis using gv% when it is measured and this necessarily reduces the apparent availability of soil K. Again, this is despite the fact that the soil test calibration curves drive a line through a cloud of points which undoubtedly include gravel soils. Again we have the problem of possible double accounting except that a gravel soil calibration curve does not exist per se, so if we are lucky, the adjustment brings outlier data points closer to the line?

The systems do not take account of gravel in its effect of concentrating and possibly increasing the efficiency of fertilizer K inputs. As with P, it is probably best to ignore the gravel% adjustments for K recommendations and just rely on field based calibrations and calculations of responses to soil tests and K fertilizer.

Sulphur (S)

Even though S fertilizer recommendations are based on a chemical extraction of the fines, adjustments do not seem to be made to convert these to a whole soil basis. S behaves much like N in soils and in the absence of adequate soil test calibration curves, should be subject to the adjustment which reduces the S supply as gv% increases.

Lime

Lime recommendation systems depend very much on estimates of the pH buffering capacity (pHBC) of a soil. Sands need far less lime inputs to change the pH by one unit than do loams and clays. Optlime, the DAFWA calculator originally had an adjustment for gravel content but it is not in the latest version. However there is a web version based on Optlime which does adjust inputs for gravel content as do the commercial soil testing laboratories. Basically they say that if you have gv%=50 then you need only half as much lime to adjust the pH by one unit compared with if you have no gravel – implying that gravel is inert with respect to pH and has reduced the pHBC.

This adjustment is appropriate given that the soil matrix pH on which a recommendation is based, affects root growth via the correlated toxic aluminium levels which do not rely on amount but concentration. So gv% should not increase the toxicity at a given pH but it does affect the effectiveness of a lime dressing. We would expect that inert gravel would make a given lime dressing penetrate deeper into the soil profile faster than on the same matrix without the gravel.

By constraining roots to a smaller volume of soil fines, gravel could increase the chances of those roots being affected by toxic aluminium hot spots. Also, for the same crop production, soils with gravel should have faster acidification rates than the same soils without gravel.

Herbicides

The herbicide experts say that they do not take account of gravel content of a soil though they might adjust recommendations for gravelly soils depending on things like differences in texture and pH which might correlate with gravel in soils. Those experts do not believe that gravel concentrates the amount of herbicide in the fines and so imply reduced rates can be used. Rather they believe that the sprays they apply wet matrix and exposed gravel equally and that the herbicide on the gravel does not wash off and into the matrix but stays put on the gravel. This implies that at the relatively low volumes of spray applied (100 L/ha = 0.01mm of rain) is absorbed by the relatively porous gravel. Little if no work is available to confirm or deny this implication.

The other argument against adjusting recommendations for gv% is that responses to herbicide rates are so flat that it does not matter if the gravel does concentrate them – it will not be toxic to the crop species, only to the weeds. The costs of application should come into this argument though dose response curves are not often the issue with herbicide recommendations.

Some herbicides are soil mobile and as such may well be leached into (or out of) important soil layers for weed control. Gv% can affect both the infiltration and the movement of water through the soil.

Pesticides

The pesticide people also do not take account of gv% of soils in the rates they recommend for much the same reasons as the herbicide people. However when pushed, I did get one to admit that if 50% of the soil volume was occupied by gravel then soil pests would have a lot more difficulty in avoiding toxic areas around granular pesticides – implying that rates of application could be reduced on gravelly soils.

Conclusions to gravel and inputs section

In fertilizer recommendation systems in WA, the availability of nutrients in the soil is reduced as the gv% increases. This is probably correct for N recommendations but may be wrong for less soil mobile nutrients such as P and K. Increasing gv% will decrease the whole soil buffering power and this will mean that granular fertilizer applications may well be more effective than on non-gravel soils. Gravel will reduce the pHBC and so make lime more effective in changing pH and will probably make such soils go acid more rapidly than their non-gravel counterparts. Gravel can change soil water relations and if inert, should increase infiltration rates and leaching. This can affect the effectiveness of mobile nutrients and agricultural chemicals.

If the gravel content of soils is to be used in recommendation systems, then more care is needed in sampling and measuring it correctly.

3.0 Gravel and soil water relations

If gv% affects soil water storage, it has an effect not only on the amount of water available to plants but also on how much of a given shower of rain infiltrates or runs off the soil. It can also impact on how much and how deep the rain drains and potentially, leaches nutrients and chemicals. These are important properties from plant growth and input management perspectives and so this has received considerable attention in this project.

Water is stored in soils in pores between, and on the surfaces of, soil particles. Different soil constituents store different amounts of water at different tensions (degrees of dryness). From a plant growth point of view we are interested in how much water is stored in a soil at field capacity or drained upper limit (DUL) or about 0.1 bar or 100 cm tension - $pF = 2.0$) and at wilting point, crop lower limit (CLL) or without the plant, 15 bar or about 15,000 cm tension - $pF = 4.2$). The difference in water content between these two limits is known as the plant available water content of the soil (PAWC) which can be expressed on a weight to weight (w/w) basis or more commonly on a volume to volume (v/v) basis. The BD of the soil (kg/kL) is required to convert w/w to v/v – i.e. $v/v = BD * w/w$.

Water contents can go above DUL to saturation if some factor prevents drainage. The saturated water content of a soil should represent the porosity of a soil (the airspace of the oven dry soil). The porosity of a soil can be estimated using the BD of the soil compared with the BD of the rock from which it is derived (usually a BD of 2.65 is used for granitic rocks from which most WA soils are derived). Thus a soil of $BD = 1.325$ would have 50% porosity and a soil of $BD = 1.59$ would have a porosity or v/v saturated water content of $(2.65 - 1.59) / 2.65 = 0.4 = 40\%$.

Obviously, water contents can also go below the CLL due to evaporation and reach air dry contents. Bare surface soils in WA in summer can dry down to almost zero water or the oven dry water content. Surface gravel can also act as a mulch and reduce such evaporation.

Inert gravel in a soil should reduce the water storage capacity of that soil by the simple dilution principle (50% gravel = half the stored water as the same soil without gravel). That is, soils of high inert gv% should have a lower water storage capacity than the analogous soils without gravel. For a given infiltration of rain, you would expect that water would wet to twice the depth on a 50% (v/v) gravel content than on the same soil without gravel. Many simple calculators and models use soil texture to estimate water content (e.g. fig 3.3.1 of Moore 1998) and then adjust to a whole soil basis assuming any gravel is inert. Unfortunately life is not always that simple: gravel may not be inert.

In WA field soils, gv% sometimes correlates positively, sometimes negatively and sometimes not at all with soil clay content as it varies with depth (e.g. McArthur 2004). Clay usually holds much more water (w/w) than the coarser soil fractions and so even with inert gravel we can expect that applying the simple dilution principle will often be wrong if we assume that the presence of gravel in a soil layer means that layer holds less water. Further if gravel is not inert but is porous and can absorb water then there can be a positive correlation of water content with gravel content all else being equal'.

Methods

In this desktop study, we attempted to determine the contribution of gravel to the soil water contents of WA soils using a simple regression approach.

To do this, a database was prepared that not only had unambiguous measures of DUL, CLL and gv% (in 10cm depths to 100cm) but also clay% and OC% (15 cm depths to 45 cm) so that the gravel contribution could be compared with the contribution of the other components of the soil including the remaining soil matrix after gv%, clay% and OC% had been allowed for. Unfortunately the OC% and clay% samples were taken 10 years before the water and gravel measurements were taken (and before GPS locations were available). The poor fit of the regression models using this full data set (reported in the gravel and water attachment) suggests that there were major problems in matching sampling locations.

The study reported here, uses the soil water and gravel data which were collected within a year of each other and for which there is no ambiguity about location, though there are always problems in adequately sampling to 100 cm because of short distance variability with depth. For this database the data from 87 sites was collated, with most of the sites sampled in 10 cm depth intervals to one metre. The only covariates for water content measures were gv% and depth.

The analysis (with much help from Mario D'Antuono, DAFWA) was aimed at determining the contribution of gravel to soil water contents and falls into three parts:-

- Describing the distribution of fitted water content coefficients in gravel and fines/matrix for the 87 individual sites.
- Fitting a combined water content surface (as a function of gv% and depth) for the total data set when it was grouped into 3 soil types.
- Fitting a combined water content surface (as a function of gv% and depth) for the total data set when it was grouped into 2 geographic regions representing 2 different gravel types.

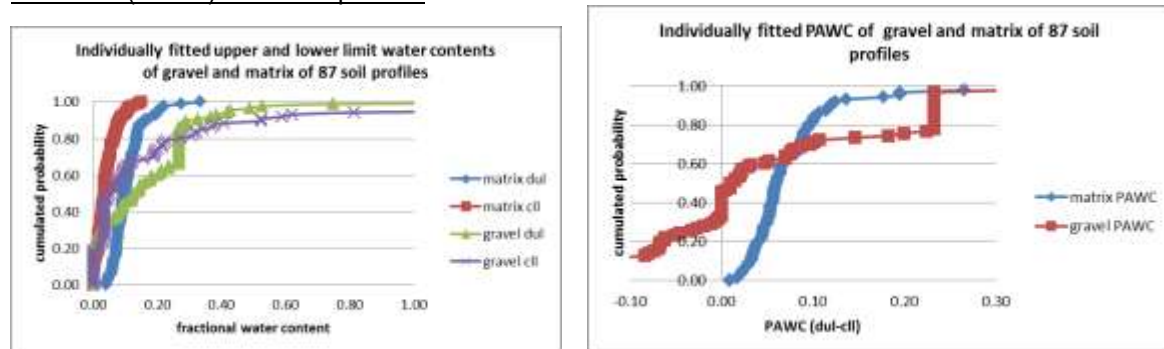
Analysing each site profile separately

It was possible to individually fit each set of site data to a model which gave us the water contents of the gravel and the remaining matrix.

$$\text{Water content (\%)} = \text{Kwc gravel} * \text{gv\%} + \text{Kwc matrix} * (100 - \text{gv\%}) \quad (1)$$

However for this database, the model cannot allow for the water held separately by the clay and OC% so their contributions to water content are combined into that of the matrix. Results are summarised for all 87 sites in Figure. 5 below.

Figure 5. Cumulated frequency distributions of the fitted DULs, CLLs and PAWCs of the gravel and fines (matrix) of 87 soil profiles



Note that these are fitted parameters and not direct measures of the water contents of the individual soil components. At each site, the observed soil profile water contents (DUL or CLL or PAWC) are shared between the gravel content and the remaining fines in each layer to give one DUL value for gravel and another for the matrix. This process is objective but can come up with some silly numbers because the model is a very simple representation of a complex soil system. Things like the clay%, the OC% and nature of the pore structure all can have soil storage properties which are NOT identified in this process. DULs should never be greater than the porosity (which for gravel should not be greater than 0.25) and CLLs should be even lower unless the water is completely unavailable for evapotranspiration.

The measured PAWC values [= (DUL-CLL) fitted at each site at each site to the 10 individual layer values] for the data set had less than 1% of negative values yet the fitted values for the gravel had about 30% negative values. Negative values are by definition impossible, so those in the measured whole soil data are due to sampling (and less likely, measurement) errors. The fitted negative values for the gravel component are due to the statistical sharing of the variation between the components. Having said all of that, it is interesting that this model fitting process comes up with over 80% of the sites having positive DUL and CLL values assigned to the gravel and that 50% have positive PAWC values. The 30% of sites with fitted negative PAWC values for gravel serve as a warning about coming to firm conclusions about the role of gravel for soil water relations using this regression process. Only with direct measurements of the water contents of the gravel and matrix components could this issue of negative values be removed.

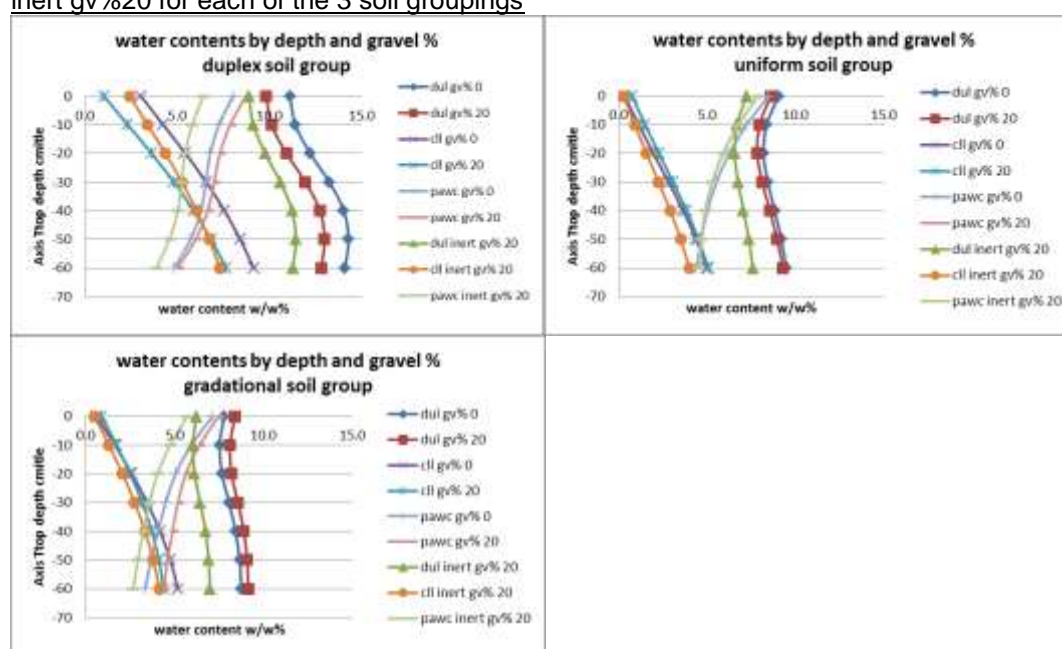
It should be possible to come up with better information on the water absorption properties of the gravels from this data base by finding the best fit surfaces of water contents (DUL, CLL and PAWC) of different groupings of soils. In this case we grouped soils according to three soil types and then according to two regions.

Group analysis of 87 profile water contents as a function of soil type, depth and gravel content

For grouped analysis, the 87 sites in this database were categorised into the three soil types discriminated here by the Northcote key, soil classification system. These grouped soil types became: 1. duplex (D, n=37), 2. uniform (U, n=18) and 3. gradational (G, n=32).

The main question we wanted to answer was whether gravel is inert and simply dilutes the water content parameters in strict proportion to gv% or whether it holds water? Could this method tell us whether the gravel in different soil type groupings holds more or less water i.e. how inert is the gravel on each soil type? The surface fitting method cannot discriminate the alternatives because even if gravel holds no water, other water holding components of the soil could well correlate with the gravel. Only measurements will determine the difference. However, Figure 6. shows the difference between the fitted $gv\%=20$ lines and those calculated for inert gravel at $gv\%=20$ i.e. the line is plotted at 80% of the $gv\%=0$ lines.

Figure 6. Is gravel inert? A summary of water content profiles for $gv\%$ 0, 20 and assumed inert $gv\%20$ for each of the 3 soil groupings



For all three soil groups, the DUL lines for inert gravel calculations markedly under predict the actual fitted values. So assuming that drainage and leaching will be greater on gravelly soils will be wrong. Any adjustment of the CLL for assuming inert gravel would not make much difference to the already low values. The plant available water storage (PAWC) would be much under estimated if gravel is assumed to be inert except for the uniform soil grouping. An attempt was made to calculate the percentage inertness of the gravel by comparing the actual (fitted surface) measures of water content at 20% gravel with those predicted by assuming the gravel did not absorb water and adjusting the actual (fitted) zero gravel values down by 20%.

Table 1. The inertness of gravel to water at zero and 50 cm for three groupings of soil types

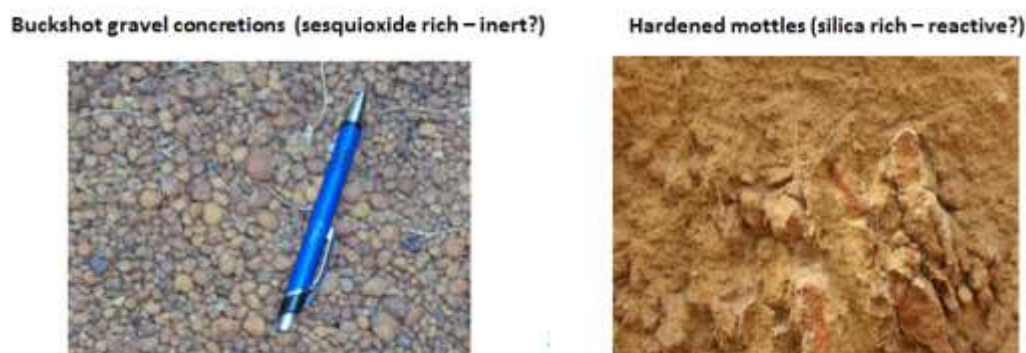
	Gravel inertness percentage			
	DUL	DUL	PAWC	PAWC
group\depth	0 cm	50 cm	0 cm	50 cm
37 duplex	90.1	61.3	11.8	52.4
18 uniform	71.1	55.3	74.4	54.2
32 gradational	2.2	11.7	36.7	-7.8

The gradational soils show the least inertness or greatest ability to absorb water at the DUL and PAWC.

Group analysis of 87 profile water contents as a function of location, depth and gravel content

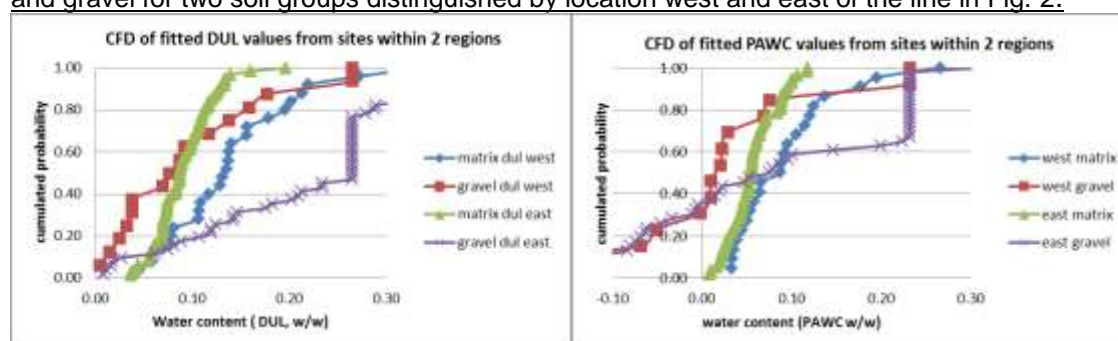
Can the differences in the water absorbing properties of gravels be discriminated according to differences in the chemistry or origins of the gravel? The 87 sites were broken into two groups according to the line in Fig 2. above. There were 25 sites to the west of the line in the forest country and 62 to the east in the wheatbelt. It was hypothesized that the sesquioxide rich gravels in the forest country are more inert than the silica rich gravels in the wheatbelt (Fig. 7.)

Figure 7. Buckshot gravel typically found in the forest country (left) and hardened clay mottles often found in the subsoils of the wheatbelt (right)



The water contents of the gravel and the fines/matrix at each site were determined by fitting the model shown in equation 1. above.

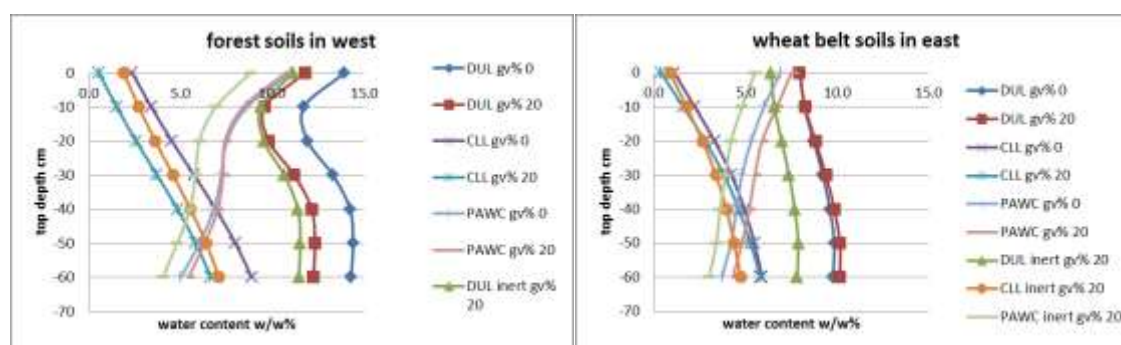
Figure 8. Cumulated Frequency distributions (CFDs) of DUL and PAWC parameters for matrix and gravel for two soil groups distinguished by location west and east of the line in Fig. 2.



Remember that these fitted parameters are site specific and the one value is for all (10) depths of the profile. This is obviously incorrect in reality where water holding components of the soil (e.g. clay and OC %) can vary markedly with depth. It is also clear that the matrix (fines) for the soils from the west have higher water holding contents and plant available water than the matrix of soils from the east. The same general findings hold for the CLL though the data are not shown here. The gravel from the west has markedly lower water holding properties than the gravel from the east – in keeping with our prejudices shown in Figure 7.

As for the soil type groupings above, water content surfaces as a function of gv% and depth were fitted to the two regionally based data sets. The detail of this analysis is given in the gravel and water attachment in Appendix 2. Here the work is summarized visually in Figure 9 which shows the difference between the fitted $gv\%=20$ lines and those calculated for inert gravel at $gv\%=20$; i.e. the inert line is plotted at 80% of the $gv\%=0$ lines.

Figure 9. Is gravel inert? A summary of water content profiles for gv% 0, gv% 20 and assumed inert gv%20 for forest and wheatbelt site groupings



Note that assuming gravel is inert for the drainage (leaching) upper limit (DUL) of the forest soils is a reasonable prediction but overestimates the effect for the wheatbelt soils (i.e. wheatbelt gravels are not inert). In both soil groups, assuming gravel is inert, over-estimates water left (CLL) in the surface layers which implies that surface gravel actually has a mulching effect. For plant available water storage (PAWC) the assumption that gravel is inert, underestimates reality for both soil groups. For the forest soil where it is most likely that gravel is inert, higher root densities for longer times in the surface layers could explain the effect of gravel on PAWC. For the wheat belt soil group, the gravel appears to hold water at the upper limit.

Again the percentage inertness of the gravel was calculated by comparing the actual (fitted surface) measures of water content at 20% gravel with those predicted by assuming the gravel did not absorb water and adjusting the actual (fitted) zero gravel values down by 20%.

Table 2. The inertness of gravel to water for the two location groupings at zero and 50 cm depth.

	Gravel inertness percentage			
water content	DUL	DUL	PAWC	PAWC
group\depth	0 cm	50 cm	0 cm	50 cm
25 west/forest	74.6	68.5	58.8	50.8
62 east/wheatbelt	74.1	39.6	-3.7	0.0

The forest gravel in soils to the west appear to be more inert (hold proportionately less water) than the gravel in soils to the east

Conclusions - soil water

The water relations of soils are critical for understanding and for better managing crops and pastures grown on them. Whether special account should be taken of the gravel content of soils when estimating yield potentials, nutrient leaching, run off and infiltration is a moot point. "Should we adjust the timing and rates of nitrogen on gravelly soils because there may be more leaching?" is one example of how the water relations affect management decisions. "Will the gravel in soils reduce moisture storage to a level where earlier maturing varieties should be used on gravelly soils to prevent haying off at the end of the season?" is another such question. Unfortunately, this project has not answered those sorts of questions definitively.

In most circumstances, gravel does have the property of reducing soil water contents but not to the extent expected if gravel was inert. This suggests that gravel can not only hold water but can hold significant quantities of plant available water in some circumstances. The fitted surface for DUL says that soils with higher gv% hold less water against drainage. This implies that soil mobile nutrients and agricultural chemicals will be moved deeper and faster on gravelly soils with any given amount of infiltrating rain. The problem with this general finding is that it does not consider the effect of gv% on the amount of rain which infiltrates versus that which runs off. Logically the reduced DUL with gravel should mean that there would be higher run off but this ignores the fact that in some circumstances, a rough gravelly surface can increase water puddling and so allow more time for infiltration before run off occurs. Also having gravel in a soil could well provide preferred pathways for water infiltration and drainage across the more vertical gravel surfaces in the soil. Direct measurements of infiltration rates with a rainfall simulator would help resolve these issues.

The variability of the effect of gv% on PAWC makes it difficult to draw conclusions about the impact of gravel on plant growth, soil water storage and the ability for crops to survive non rainfall periods particularly during the terminal drought at the end of the season in a Mediterranean environment. Some of the DUL and CLL curves from this analysis could be fed into a simulation model to be run over a range of seasons to see how the variability in crop yields is affected by gv%. The water balance of such models could be affected by a "mulching" effect of gravel which could reduce soil water evaporation.

Gravel could have an indirect effect on soil water relations via its effect on soil wettability. Non-wetting soils often have high OC% and low clay contents in the fines. For the same dry matter production, or net organic carbon input into the soil a soil with high gv% will have an increased measured OC% in the fines. This can cause more water repellency with implications for run off and drainage.

If anything, this section has raised more questions than it has resolved. At the moment, direct measurements of things like soil water profiles, infiltration and run off will be better than trying to adjust theoretical moisture properties/profiles according to measured gravel contents.

Future work

There are indications that some of the lateritic gravels in this study hold water at both the DUL and CLL and that they can indeed have a plant available water capacity. These indications can only be confirmed via work which directly measures the DUL and CLL of both the gravel and the fines/matrix components of the soil. Because of the marked variability in the properties of gravels in soils, this work would have to be done across a large range of gravelly soils.

Here we have only touched the surface. In the absence of such work there may be a case for collecting a new database which contains measures of gv%, OC%, clay% and the water characteristics DUL, CLL and PAWC of whole soils.

4.0 Gravel and Root Growth

Thank you to Dr. Vanessa Dunbabin who did the Rootmap model runs and analysis.

The presence of objects in a soil which cannot be penetrated by roots obviously has a major effect on root growth, root architecture and root length densities through time and space. This in turn will affect nutrient and water uptake with implications for crop growth and nutrient management decisions.

Obvious questions to answer are:

1. Will the presence of gravel increase the uptake of soil immobile nutrients (copper, zinc, manganese and phosphorus on high fixing soils) by increasing root exploration of the fertile zones of the soil?
2. Will the presence of gravel cause the root depth penetration rate to increase enough for the crop to better take up soil mobile (leachable nitrate and sulphate) nutrients and water?
3. Will increased and earlier root competition caused by gravel content force roots to explore new soil laterally more rapidly? That is, will roots explore the inter row more rapidly in gravelly soils?

Resources did not allow us to investigate questions about the impact of gravel on root growth dynamics using direct observations and/or experiments, so we decided to explore some of the issues using the root growth model, Rootmap (Dunbabin, Diggle et al). With answers to these questions we could speculate about nutrient (and water) uptake from gravel soils in the context of how gravel changes water relations and nutrient availability dynamics.

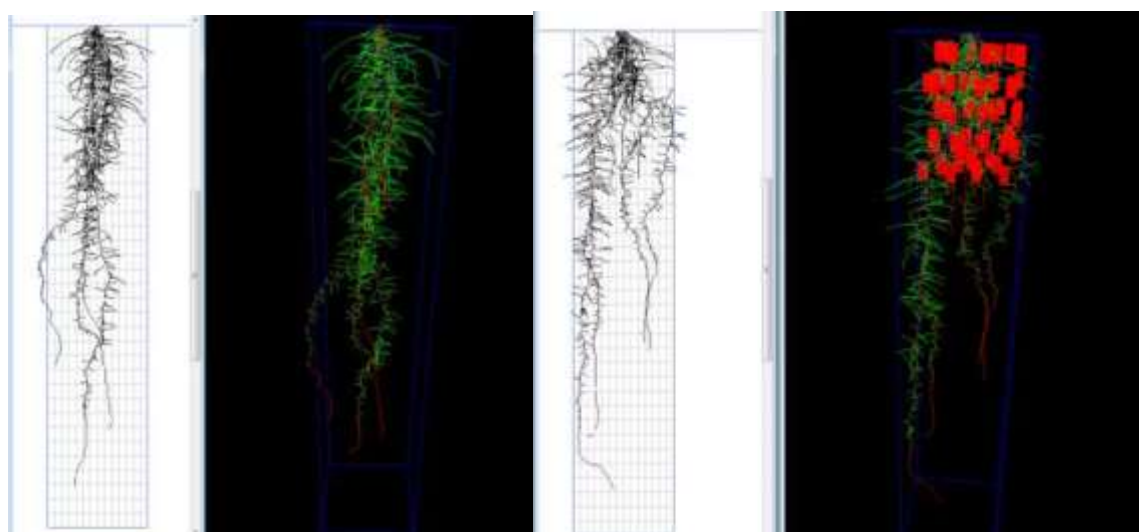
We asked Dr Vanessa Dunbabin to carry out some preliminary studies using Rootmap. Her work fell into two parts. In the first section she looked at the impact of inserting inert objects into the soil volume on root growth and nutrient uptake. In the second, Vanessa did a preliminary study on how root density (set up by changing plant density in the row) affected root exploration in three dimensions; our interest being in the rate of root penetration to depth and into the inter-row.

Below are the reports on those two studies. For a more comprehensive report go to the gravel and roots attachment in Appendix 3.

1. The effect of inert objects on root growth and nutrient uptake

Gravel (inert objects-1cm by 1cm by 2cm cubes) were placed in the top 10cm of a root growth column (14 cm by 14 cm by 70cm). The root map model was run for 28 days for treatments with and without gravel (8% v/v in the surface, graveled zone) for various distributions of N and P. Other runs were done for 29% inert objects and for genotypes with different root branching dynamics. Below is a largely visual summary of some of the findings.

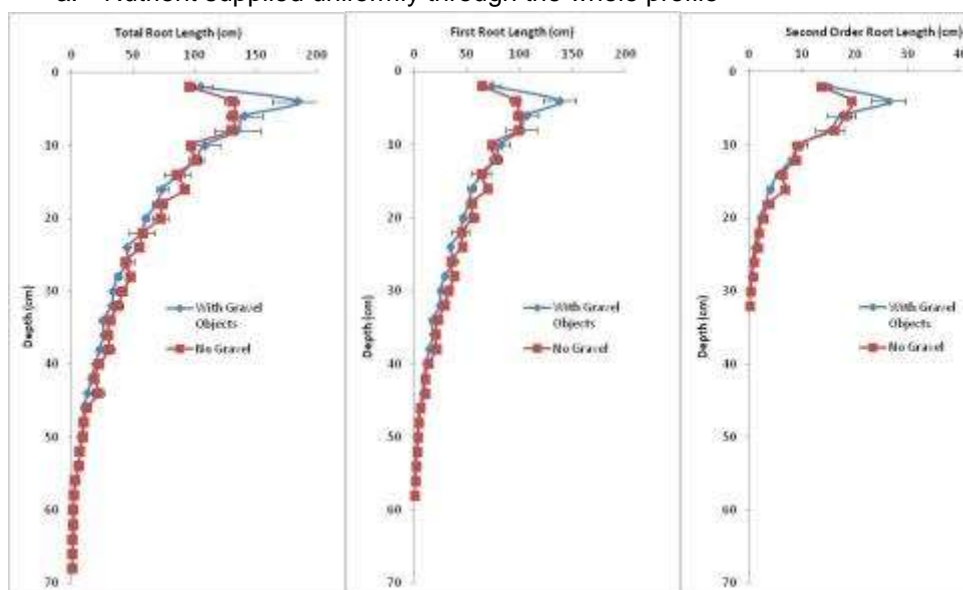
Figure 11. The effect of 8% gravel (inert objects) on root growth after 28 days. Rootmap runs with no gravel (left) and 8% (v/v) gravel (right).



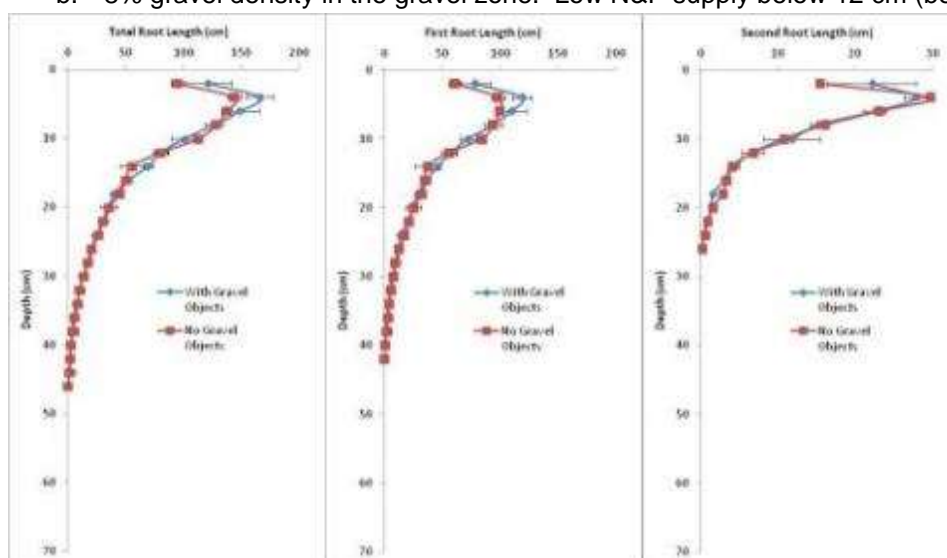
Root length has increased in the gravel zone (top 10cm). Note that apart from a root axis which found the side of the container where there was no impediment to root penetration with inert objects, the gravel seems to have reduced the rate of root penetration to depth.

Figure 12. The effect of 8% gravel content on total root length (cm) through the soil profile.

a. Nutrient supplied uniformly through the whole profile



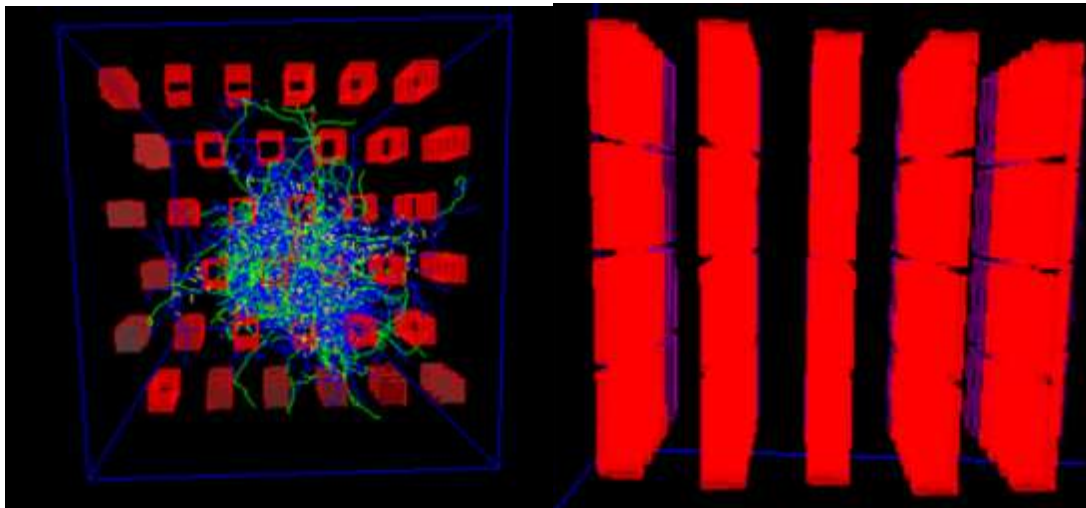
b. 8% gravel density in the gravel zone. Low N&P supply below 12 cm (below the gravel zone)



Note that gravel promotes root length in the gravel zone at the surface, and more so when N and P nutrition is uniformly distributed through the profile.

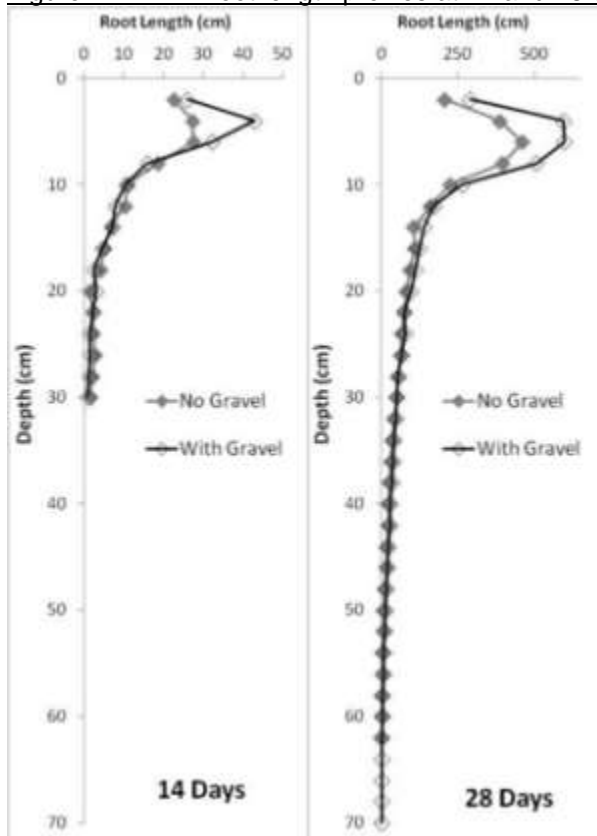
The above findings are in contrast to the output from some runs with Rootmap which looked at the effect of gravel on the uptake rates of P from a banded P source. The inert object arrangement was simplified (see Fig 7.) to an array of columns. (Total Labile P = 13.3 $\mu\text{g/g}$ in a narrow 6 cm band, placed from a depth of 2cm to 8cm. Total Labile P = 2 $\mu\text{g/g}$ outside of this narrow band).

Figure 13. Plan (top) and front view (bottom) for the banded P runs of Rootmap



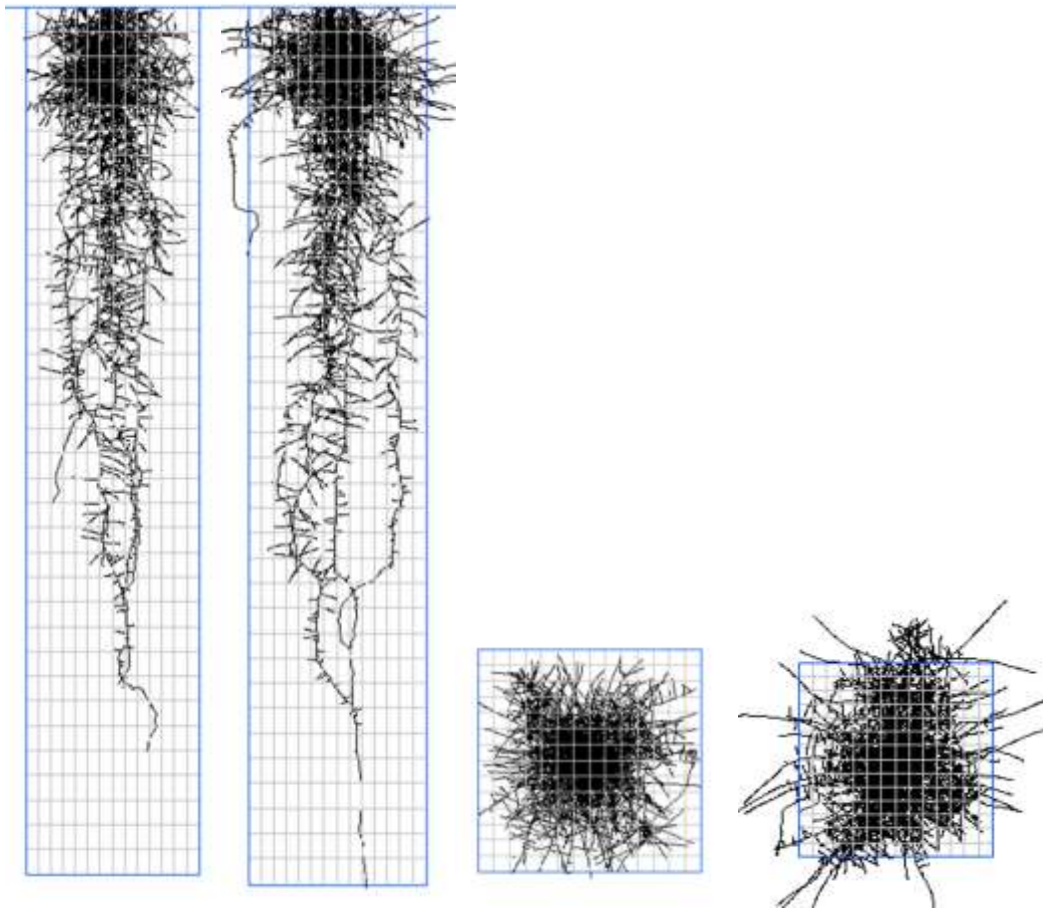
There is a distinct increase in root proliferation in the zone of the nutrient band at both 14 days and 28 days. By 28 days the plants growing in gravel have both increased root proliferation in the band zone (also gravel in that zone), and deeper rooting

Figure 14. Root length profiles at 14 and 28 days for banded P with and without 8% gravel



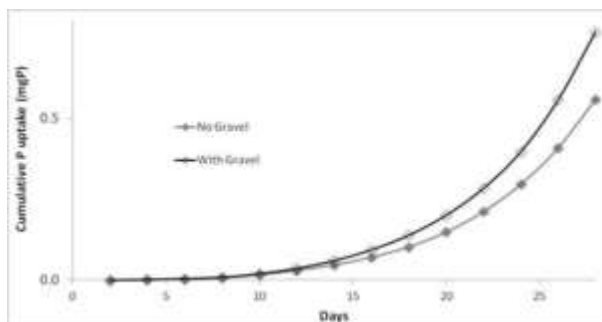
In this case, by 28 days, the roots with 8% gravel are deeper and also are longer in the surface gravel layer.

Figure 15. Projections of root growth profiles from the side (left) and from above (bottom right). With no inert objects (left) and with objects (right)



The dynamics of P uptake in this system are shown in Fig.16.

Figure 16. Phosphorus uptake from a band, as a function of time for a soil with and without inert columns



It is worth noting that the root and nutrient uptake parameters will be sensitive to genetic root growth parameter settings, levels of water in the soil, levels of nutrients in the soil, nutrient distribution, soil buffering and water holding characteristics, as well as the dynamics of water supply. Other factors include the duration of the runs and of course our subject of interest, the gravel content, size and distribution. There were sufficient resources only for a brief look at the impact of some of these factors and their interactions on root growth.

Conclusions – inert objects and root growth

At 8% gravel greater root length and root length densities are induced in the gravel zone. At the 29% gravel level total root length is not increased, but root length density is increased by 30%. The amount of P at the same initial concentration is also reduced by 30% but P uptake remains the same. Which means that uptake efficiency as measured by the fraction of available P depleted, has risen by about 30 to 40% in the presence of 29% gravel.

How these nutrient uptake efficiencies change with level and distribution of gravel, level and placement of the nutrients, mobility and buffering capacity of the nutrient, the wetting and drying patterns of the soil, as well as the genetics of the cropping species and how this affects root architecture responses to gravel. With more resources to contract programmers, all of these and other issues could and should be studied further, initially with the Rootmap model and then perhaps with direct observational and experimental work.

5.0 Root growth responses to restricted soil volume – sowing density runs

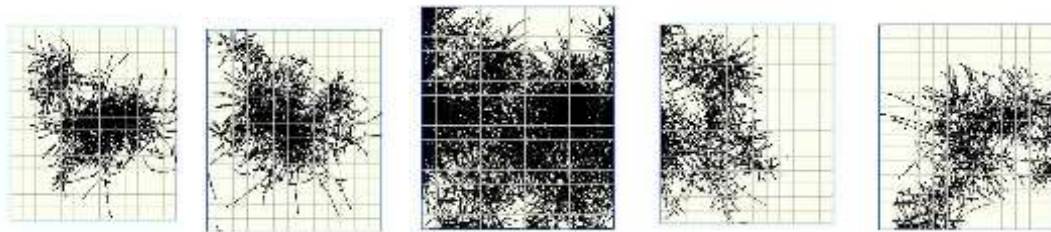
By Dr. Vanessa Dunbabin

Gravel in soils restricts the rooting volume which should result in higher root densities. The increased and more rapid competition between roots for soil resources should cause roots to access non-depleted soil to the side and at depth, more rapidly. To examine this property the Rootmap model was used to examine the effect of root competition on the dynamics of root exploration by plants sown alone (low density – no competition) and close together in the row (high density –high competition).

Results

A pictorial summary of the results of the Rootmap runs is given below.

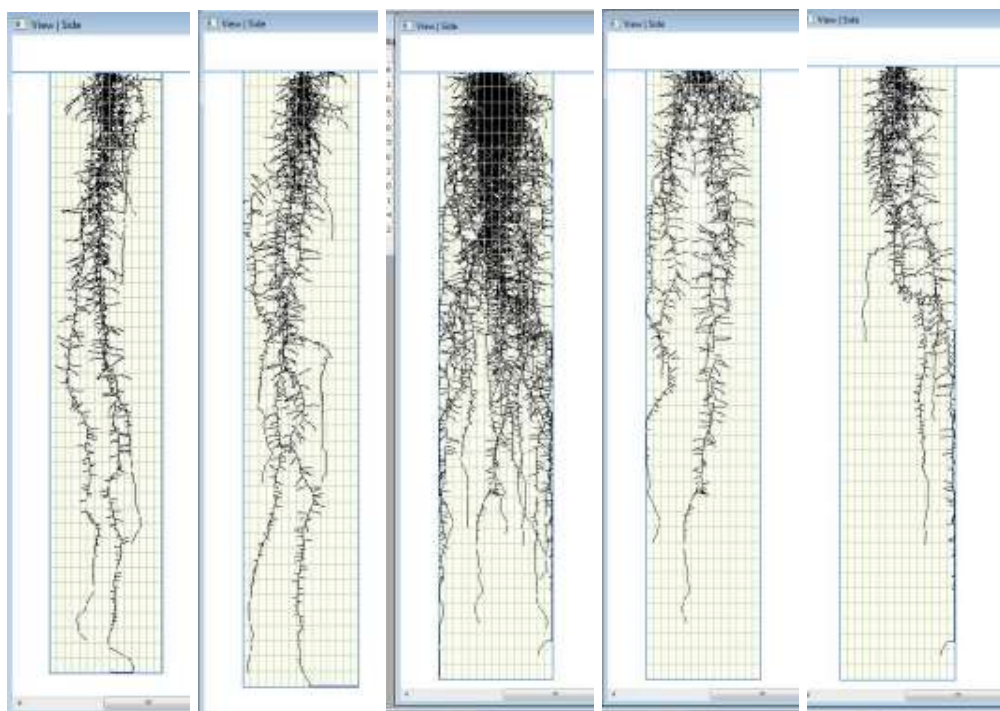
Figure 17. Plan view of root length projected into one plane. Section along the row on the horizontal axis and section across the row on the vertical axis



The central figure is an example of the root density with 5 plants present in 13 cm of row. The two figures on the left are examples of single plants at low density (50plants/M²). The two on the right are examples of a single central plant (of the 5) at high density (256 plants/M²).

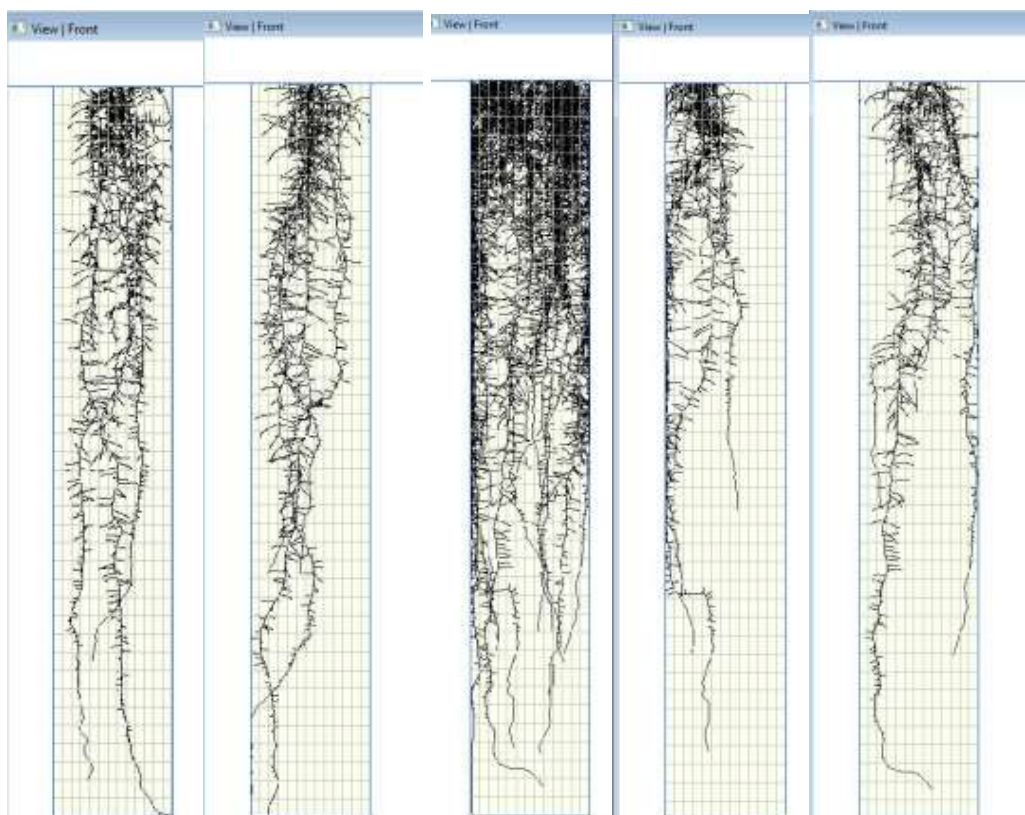
Clusters of high projected root densities reflect where root axes have followed vertical pathways, sometimes down the edge of the modelled box. The single plants (left) show far more symmetry in all directions than the individual plants (right) which grow in the centre of the array of five. The visually high density of roots in the central box reflects the high sowing density (about twice the usual wheat establishment densities) and the projection of all roots, in the 90 cm profile depth, into one plane.

Figure 18 Side view of root length projected into one plane showing the extent of proliferation into the inter row. Details of the layout are given below and in Fig. 17. above



If anything, the roots of the individual plants at high density (right) are shallower and spread more into the inter-row.

Figure 19 Front view of root length projected into one plane showing the extent of proliferation along the row. Details of the layout are given below and in Fig. 17. above

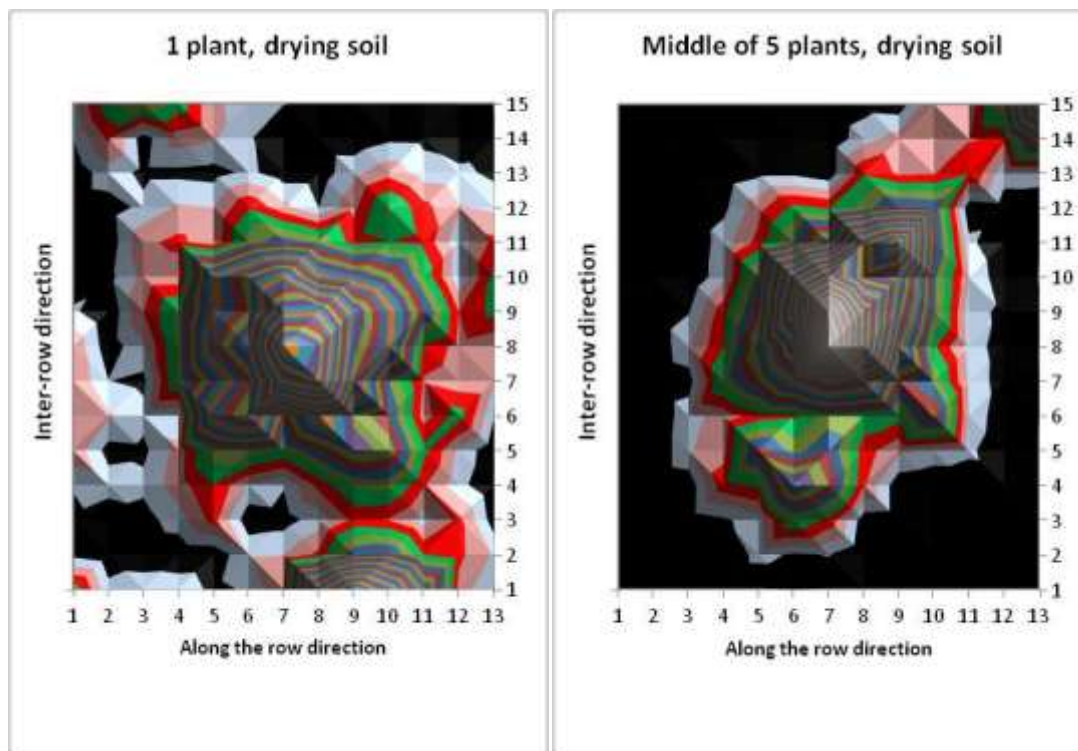


The roots of plants sown at high density (right) tend to proliferate less along the row than those sown without competition from neighbours (left). This view also shows that there is less root proliferation at depth for the individual plants sown at high density (right). However the sum of the root densities

from the five plants at high density (central) means that those roots are exploring more of the soil at depth than the low density plants (left).

A summary of the root effects is given below (Fig 20.) in a 3D contour plot for the mean of the two individual plants at each of the low and high density sowings. As expected the rooting pattern for the single plants in 3D is symmetrical in all directions. At the higher density, the 3D plots lack symmetry in that more roots proliferate into the inter-row and less along the row.

Figure 20. Total root length (cm) contour plot in excel, average of 2 reps. The black is the lowest contour (no roots - on the surface). The pictured row length is 13 cm, and the inter-row distance is 15 cm



On the left is one centrally placed plant. The root system is extending evenly in both the inter-row direction and along the row directions. No neighbouring plants are present to restrict growth in the direction along the row. On the right, is the middle plant of five plants in the same space. The root system is extending further in the inter-row direction than along the row. Neighbouring plants are restricting growth in the direction along the row.

Conclusions – gravel and root growth

This study addressed the question “do plants grown in the presence of gravel, send roots sideways and deeper more rapidly than plants grown in the same soil without gravel” ? The effect of increasing root length density by increasing the crowding of plants in the row was used as an analogy for increasing root length density by growing a plant in a soil with gravel. Individual plants at high density did proliferate roots more rapidly into the inter-row but did not seem to send roots deeper, faster. The results depended on whether soil water was maintained at adequate levels or whether the water was depleted around the roots. This indicates yet another interaction which would confound attempts to determine the effect of gravel on the dynamics of water and nutrient uptake.

Further such studies with the Rootmap model could give a lot of insights into the role of gravel in soils for crop production and perhaps even for crop management

6.0 Project outputs

- If nutrition or carbon budgeting is carried out on a unit area basis, then gv%, like bulk density should be taken into account when chemical analyses of the non-gravel (fines) component of soils are adjusted to a whole soil basis.
- Some fertilizer recommendation systems (eg for Pand K) should NOT adjust the analyses to a whole soil basis, particularly if soil test calibration curves are the backbone of the system,
- If adjustments for gv% are appropriate then care must be taken in sampling for and/or estimating gv%
- Gravel is not always inert to water absorption and/or interactions with nutrients so care must be taken when adjustments to recommendations and management are made.
- The question of whether roots go sideways (into the inter-row) and/or deeper, faster, on gravelly soils has not been resolved
- Advisers, consultants and research workers are interested in how or whether gravelly soils should be managed differently, but are less sure about whether they should make quantitative adjustments for the gv% of soils
- This project has raised more questions than it has answered.

Future work

Direct measurement of the water contents (DUL and CLL) of a range of gravels from a range of soils, should be carried out in the field.

A new database containing the water content parameters as well as OC% and clay% for all depths should be constructed.

The Rootmap model could be used to further study the effects of a range of factors which interact with gv% and affect nutrient uptake and water relations.

The APSIM model could be used to characterise the impact of gravels of different water holding capacities on nutrient leaching, crop growth and yield under different management and seasonal conditions.

7.0 References and related literature

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Thank you to COGGO for funding this project and being so patient about the problem of me not meeting deadlines.

Appendix 1. Initial list of factors which interact with gravel

Those in red have been mentioned and/or addressed in this COGGO project

Blue print for comments on missed (black) points

Soil water

Drainage

Pawc

Run-off

Infiltration

Mulch – topham, quinlan and syme/Bolgart aerial shots

Deep ploughed and mould boarded mixed landscapes bring gravel to the surface which then allows better infiltration and mulching.

Phosphorus

Fixation/buffering

Amount

Leaching

Plant availability

Roots by herbicide by moisture by other nutrients by acidity

The interactions with gravel content can be marked

Nitrogen

Amount (OC%)

Leaching

Roots

Potassium

Amount

Correlates and gamma sensing

Soils with high potassium as indicated by gamma sensing are usually the gravelly soils

Reduced CEC

pH/liming

rates of lime

pHBC

rates of acidification

Herbicides/Pesticides

Granular vs sprays

Leaching and activity by depth

Soil placed pre-emergent

Granular pesticides will be concentrated by gravel content.

Residual value for next crop

Mulching/moisture and temperature effects could slow or increase the rate of pesticide break down

Blackleg spore densities would be higher on gravelly soils for the same spore input

Weed seed densities would increase and impact on the competition for soil resources

Adsorption

Moore, Bowran and Grimm have words of wisdom on this

Sprays will adsorb onto, and be inactivated by, exposed gravel surfaces because rates of water are so low (100 L/ha = 0.01 of a mm) that droplets are unlikely to run off. If the gravel surfaces have even minimal porosity then the chemicals will be inactivated.

Weed, disease, insect ecology

Weed control on gravel ridges difficult. Why?

Disease splash- will increase/decrease on gravelly soil surfaces?

Wind dispersal of spores – rough gravel surfaces are less likely to give the air flow which enhances lift of light particles?

Soil fauna avoiding pesticides

Seed germination

Water more concentrated – puddles, saturation

Gravel could concentrate the allelopathic chemicals which come out of unweathered stubble and so induce more “silly seedling” syndrome

Root exploration

Density in matrix

Depth

Tilth – after cultivation, does gravel content improve and/or preserve tilth for better seedling root exploration?

Tortuosity and investment of carbon

Art and modelling deflections – renton – greater density but less soil explored so less resource available per unit roots and so more investment in roots vs tops

Rootmap model

Non-wetting

concentrates OC

DSS

Fertiliser

CSBP

Old

Nulogic

Summit

DAFWA

SYN

Optlime

Decide

Quinlan

N app

Wind erosion

Topham – topdressing 5-10 t/ha of gravel – Is this enough to reduce erosion of soil fines?

Grimm – gravelly soils on the mid slope are often overgrazed – and more susceptible to wind and/or water erosion?

Water erosion

Breakaway pediments – are gravelly and subject to run off from the non-wetting soils upslope of them. More erosion – but not necessarily an interaction with the gravel content of these soils

More run-off or more puddling?

Cultivation

Depth – often difficult to get to depth on gravelly soils. Rippers can raise boulders to the surface.

Disturbance, mixing does gravel help or hinder mixing?

Compaction/traffic responses to major disturbances of long term pasture soils implies that the surfaces have been compacted (among other things), Road engineers note that soils with relatively equal amounts of clay, silt sand and gravel make the most compactable roads (Riethmuller priv.com)

Mulch

Spore splash – MacLeod??

Sweetingham

Bulk density

Gravel properties

Inert or active

Composition (Verboom/Sawkins)

Sawkins/Verboom on mafic (Fe/Al gravels (high PBC, higher BD??)) vs felsic (siliceous gravels, rough, hard, lower BD?)

Porosity

Absorbs water, pesticides, fertiliser concentrates

Sucks in solutions but diffuses out (eg inactivates water and P – roots cannot get in)

Surface area active or inert

External

Internal surface physics, chemistry and porosity

Bulk density

Water holding capacity

Upper and lower limit

P adsorption

Content by weight, volume, cross sectional area?

Albedo, temperature – reflection, conduction, heat storage, frost/heat exchange

Diluent

Gravel in landscape

Origins

Mulcahy

Finkl/Gilkes

Verboom

Understanding the chemistry and genesis of different gravels gives insights into the variability in their porosity and reactivity

Position

Breakaway,

Pediment

Surface and or depth

Distribution

Van Gool, Griffin, Verboom

Agronomic management

Seedling germination, emergence, establishment –

Seeding rate – may well get more seed to seed interactions at lower seeding rates than normal because the seeds would be more concentrated per unit fines in the soil

Seeding depth – tortuosity and hypocotyl length – will seedlings have more or less difficulty emerging on gravelly soils and does this have implications for choice of seeding rate, seeding depth and even cultivar choice?

Row spacing – closer if poor lateral root exploration for resources

Choice of crop

Species/rotation

Cultivar interactions of flowering window, seeding date and water relations. Do we need a shorter growing season cultivar because of reduced stored water capacity on gravelly soils?

Mechanics

Furrow integrity

Tyre design and wear

Appendix 2. Gravel and soil water relations

If gravel content (gv%) affects soil water storage, it has an effect not only on the amount of water available to plants but also on how much of a given shower of rain infiltrates or runs off the soil, as well as how much and how deep it drains and potentially, leaches nutrients and chemicals. These are important properties from plant growth and input management perspectives and so have received considerable attention in this project.

Gravel and soil water content - introduction

Water is stored in soils in pores between, and on the surfaces of, soil particles. Different soil constituents store different amounts of water at different tensions (degrees of dryness). From a plant growth point of view we are interested in how much water is stored in a soil at field capacity or drained upper limit (DUL, or about 0.1 bar or 100 cm tension - $pF = 2.0$) and at wilting point, crop lower limit (CLL, or without the plant, 15 bar or about 15,000 cm tension - $pF = 4.2$). The difference in water content between these two limits is known as the plant available water content of the soil (PAWC) which can be expressed on a weight to weight (w/w) basis or more commonly on a volume to volume (v/v) basis. The bulk density (BD) of the soil (kg/kL) is required to convert w/w to v/v - i.e. $v/v = BD \cdot w/w$.

Water contents can go above DUL to saturation if some factor prevents drainage. The saturated water content of a soil should represent the porosity of a soil (the airspace of the oven dry soil). The porosity of a soil can be estimated using the BD of the soil compared with the BD of the rock from which it is derived (usually a BD of 2.65 is used for granitic rocks from which most WA soils are derived). Thus a soil of $BD = 1.325$ would have 50% porosity and a soil of $BD = 1.59$ would have a porosity or v/v saturated water content of $(2.65 - 1.59)/2.65 = 0.4 = 40\%$.

Obviously, water contents can also go below the CLL due to evaporation and reach air dry contents. Bare surface soils in WA in summer can dry down to almost zero water or the oven dry water content. Surface gravel can also act as a mulch and reduce such evaporation.

Inert gravel in a soil should reduce the water storage capacity of that soil by the simple dilution principle (50% gravel = half the stored water as the same soil without gravel). That is, soils of high inert gv% should have a lower water storage capacity than the analogous soils without gravel. For a given infiltration of rain, you would expect that water would wet to twice the depth on a 50% (v/v) gravel content than on the same soil without gravel. Many simple calculators and models use soil texture to estimate water content (e.g. fig 3.3.1 of Moore 1998) and then adjust to a whole soil basis assuming any gravel is inert. Unfortunately life is not always that simple: gravel may not be inert.

The bulk density of gravels ranges widely (magnetite gravels can have BDs as high as 5) but in WA numbers between 2.0 and 2.4 have been measured for lateritic gravels (Sudmeyer, Lemon, Hall, priv. com.). The porosity for gravel with a $BD = 2.0$ would be approximately $(2.65 - 2.0)/2.65 = 0.25$. However the sesquioxides in gravels may have different (higher) particle densities than the 2.65 assumed here.

In WA field soils, gv% sometimes correlates positively, sometimes negatively and sometimes not at all with soil clay content as it varies with depth (e.g. McArthur 2004). Clay usually holds much more water (w/w) than the coarser soil fractions and so even with inert gravel we can expect that applying the simple dilution principle will often be wrong if we assume that the presence of gravel in a soil layer means that layer holds less water. Further if gravel is not inert but is porous and can absorb water then there can be a positive correlation of water content with gravel content all else being equal.

In this desktop study, I attempted to determine the contribution of gravel to the soil water contents of WA soils using a simple regression approach. To do this, I had to prepare a database that not only had unambiguous measures of DUL, CLL, and gv% but also clay% and OC% so that the gravel contribution could be compared with the contribution of the other components of the soil including the remaining soil matrix after gv%, clay% and OC% had been allowed for. Most available databases are short of some of the desired components.

One of the greatest problems in finding suitable databases is knowing just how the gv% was determined. At best it is done visually (a subjective v/v approximation) on whole soil samples. Often it is a guess on samples submitted to a laboratory which may or may not have all the gravel included

and/or ground to finer size classes during sampling or processing. The water contents are often laboratory measurements carried out on disturbed samples. For these reasons I prepared (with some difficulty!) my own databases where all the components are measured on a w/w basis.

Methods

This study is broken into two parts.

- A. The first uses a data base which has measures of soil water contents, clay, gravel and organic carbon (OC%) for three 15 cm layers to 45 cm from 63 sites.
- B. The second study uses only the water and gv% measures taken in 10 cm intervals to a depth of 100 cm at 87 sites.

A.-The 3 layer, clay%, organic carbon% and gv% database

This database was prepared from site profile (0-15, 15-30 and 30-45cm depth) measurements of OC% and clay% (among others) made on a series of 140 nitrogen (N) trials in the years 1975 onwards (Mason unpublished). In 1984, further funds were found to revisit as many sites as possible and characterise the DUL and CLL as well as the gv% (w/w). In this case, profile samples were taken in 10cm intervals to 100cm, once in the winter after there was enough rain to wet the profiles to beyond 90 cm (DUL), and again after the harvest of a good crop under a dry finish to the season (CLL).

It should be noted that there is an inherent problem with this data base. There is no guarantee of the exact coincidence of the 5 bulked profile samples taken in the '70s with the 2 sets of 3 individually sampled profiles for the soil water and gravel measurements taken 10 years later. Poor fits of the regression models can be due to both poor models and to inadequate positioning and sampling.

Weighted means of the top 50 cm of water and gravel data were calculated to match the 15 cm intervals of the OC% and clay% data for each site. This meant that there were 3 depth layers for the five measured parameters. To fit water data as a function of four soil constituents we needed many sets of observations, so three groups of soil types were derived using clay% differences between layers as the discriminator. If clay% increased by greater than 5% between any consecutive sampling depths, then the soil was called "duplex" of which there were 24 sites. If no two layers differed by >5% then they were considered uniform (21sites) and for the remainder, the clay% increased gradually with depth with the deepest of the 3 layers having >5% clay difference from the surface layer (18 sites). The properties of these 3 soil groupings are given below in table 1.

Table 1. Measured properties of the three groups of soils where %gv, DUL and CLL all are expressed on a whole soil w/w% basis and clay and OC are a w/w% of the non-gravel "fines" fraction.

	24 duplex soils					21 uniform soils					18 gradational soils				
	gv%	DUL	CLL	clay%	OC%	gv%	DUL	CLL	clay%	OC%	gv%	DUL	CLL	clay%	OC%
min	0.0	4.3	0.1	0.5	0.2	0.0	3.1	0.0	0.5	0.1	0.0	2.8	0.0	3.0	0.1
med	11.2	9.7	2.6	15.0	0.8	4.8	7.8	1.2	5.0	0.6	1.9	8.0	1.4	13.0	0.6
max	71.3	22.7	10.6	47.5	6.4	64.8	18.1	8.9	15.5	5.5	41.2	14.2	5.0	36.5	1.5
depth cm	profile medians					profile medians					profile medians				
0-15	10.1	9.1	1.4	6.2	0.9	1.9	7.9	0.7	3.5	0.8	1.2	7.8	0.9	9.3	0.7
15-30	12.5	9.9	3.4	14.0	0.5	15.2	7.0	1.3	5.0	0.3	1.5	8.0	2.0	14.3	0.4
30-45	11.2	12.1	5.4	26.3	0.4	11.9	8.2	3.2	7.0	0.3	5.3	8.4	3.4	18.8	0.2

Data analyses and results

1. The four constituent (gravel, clay, OC and the matrix) model of soil water content.

A four parameter regression model was fitted to the data using solver. The main problem with this very simple approach is how the variation in the one measure of soil water content (say DUL) is shared between the soil constituents.

The model used here, allocated a fractional water content (w/w) to each of gv%, clay%, OC% and the remaining matrix. Because the clay% and OC% are both expressed as a % of the fines (<2mm soil fraction), they have to be adjusted to a whole soil basis by multiplying by (1-gv%/100). The “matrix” fraction was given by (1-gv%/100)*(1-OC%/100-clay%/100).

The full model for water content WC% (either DUL or CLL) was:

$$WC\% = K_{gv} \cdot gv\% + (100 - gv\%) \cdot [K_{oc} \cdot OC\% + K_{clay} \cdot clay\% + K_{matrix} \cdot (100 - OC\% - clay\%)] \quad 1.$$

Here the fitted parameters K_{gv} , K_{oc} , K_{clay} and K_{matrix} , were the fractional water contents of gravel, OC, clay and the remaining matrix respectively.

Table 2. Fitted water contents (w/w) at the DUL, CLL and the difference (PAWC), for gravel, clay, OC and the remaining matrix, for 3 groups of WA cropping soils.

	24 duplex soils			21 uniform soils			18 gradational soils		
	DUL	CLL	PAWC	DUL	CLL	PAWC	DUL	CLL	PAWC
matrix	0.05	0.01	0.05	0.05	0.01	0.04	0.05	0.01	0.04
gravel	0.11	0.01	0.10	0.07	0.03	0.04	0.12	0.04	0.09
clay	0.26	0.20	0.06	0.24	0.13	0.11	0.16	0.07	0.09
oc	2.78	0.35	2.43	2.73	0.00	2.73	2.84	0.00	2.84
R ² =	0.33	0.46		0.22	0.06		0.13	0.09	

Here $R^2 = (1 - \text{rss}/\text{tss})$ where rss is the sum of squares of differences between observed and calculated/modelled water contents and tss is the sums of squares of the difference between the observed water contents and the mean water content. The fits are not very good; they reflect either the complexity of the water holding processes (I have ignored BDs, porosities and pore size distributions), or (more likely) the inadequacies in sampling noted above.

When the fitting process allows some of the variance to go to the other soil constituents (OC%, clay% and gv%), the remaining matrix has remarkably similar values for DUL and CLL across all soil groups.

The OC holds 2-3 times its weight of water at the DUL with 0.35 for the CLL on the duplex soils and zero for the CLL on the other soil groups. This could well be because the highest levels of OC are in the top 15 cm layer and that this layer could have been dried below the CLL when the summer/autumn measurements were made. Because OC% is so low in most soils and depths, it makes only a very small absolute contribution to the whole soil water contents.

There was no surprise that the clay fractions had the highest water contents of the mineral components at both limits.

However I was surprised by the amount of water stored at the DUL and also the PAWC of the gravel component from these fits. Gravel does not appear to be inert w.r.t. water. This should and could be tested by direct measurements on gravel and sieved soil at both water limits.

The above (Table 2) gives interesting results but we should remember that regression modelling is an arbitrary tool which cannot replace direct measurements. The adage, “correlation is not causation” must be remembered with this simple sort of modelling. When one or two or even three of the soil constituents are omitted from the fitting process, the variation will be shared differently between the remaining constituents.

For example, setting the OC contribution to zero (Table 3.) and refitting the data not only affects the goodness of fit (R^2) on the 21 soil group, but also changes the water holding capacity of the remaining constituents.

Table 3. Water contents (w/w) at the DUL, CLL and the difference (PAWC), for gravel, clay and the remaining matrix, for 3 groups of WA cropping soils and their values relative to those in Table 2.

	24 duplex soils			21 uniform soils			18 gradational soils		
	DUL	CLL	PAWC	DUL	CLL	PAWC	DUL	CLL	PAWC
matrix	0.08	0.01	0.07	0.07	0.01	0.06	0.07	0.01	0.06
gravel	0.15	0.01	0.14	0.09	0.03	0.06	0.11	0.04	0.07
clay	0.21	0.19	0.02	0.15	0.13	0.02	0.12	0.07	0.06
R ² =	0.15	0.46		0.03	0.06		0.05	0.09	
Re-allocation of water content variation - table 2. values divided by those in table 3.									
matrix	0.65	0.63	0.66	0.74	1.00	0.68	0.68	1.00	0.63
gravel	0.74	0.68	0.75	0.79	1.00	0.72	1.16	1.00	1.24
clay	1.21	1.03	2.80	1.67	1.00	6.87	1.26	1.00	1.57

In summary, the answers we got depended on which constituents of the soil which were included in the water holding capacity model. For the data sets used here, the R² values were often insensitive to which constituents were included.

Table 4. The proportion of variation accounted for (R²) by ignoring the contribution of different components of soil water storage - using equation 1.

	R ² for 3 fitting points for each of (n) sites					
	duplex (24)		uniform (21)		gradational (18)	
	DUL	CLL	DUL	CLL	DUL	CLL
all	0.33	0.46	0.21	0.06	0.13	0.09
all-gv	0.06	0.45	-0.33	-0.12	-0.13	0.02
all-oc	0.15	0.46	0.03	-0.03	0.05	0.09
all-clay	-0.12	-0.23	0.12	0.01	-0.12	-0.05
all-oc-gv	-0.38	0.44	-1.09	-0.13	-0.15	0.02
all-oc-clay	-0.18	-0.23	0.00	-0.03	-0.12	-0.02
all-gv-clay	-0.68	-0.32	-0.54	-0.20	-0.33	-0.12

Negative R² values mean that using the average water content for the (n) soils by 3 depths is better than using the model indicated in the left hand column. The average water content model would have an R² value of 0.00. The blue bold numbers in table 4 indicate reasonable fits were obtained only on the duplex soil group. On that group, assuming gravel and OC have no water holding capacity at the CLL, does not affect the fits

2. Ignoring gravel effects on soil water storage

Most studies on soil water storage ignore direct influences of gravel content though it is indirectly taken into account for whole soil data collected on gravelly soils. In this study we can see the impact of gravel by interpretation of the model outcomes.

For the four parameter model above we can turn water reactive gravel into inert gravel simply by fitting the model with K_{gv} = 0. The second line (all-gv) of R² values in Table 4. above does exactly this. The R² values do not fall much so assuming the gravel is inert and is acting only as a diluent of the finer fractions does not detract from the goodness of fits.

We can go further and see if it is worth measuring gravel content at all by reducing the model to a simple regression on measured water contents vs measures of clay, OC (and even gravel). Equation 1. then becomes:

$$WC\% = [K_{oc} \cdot OC\% + K_{clay} \cdot clay\% + K_{matrix} \cdot (100 - OC\% - clay\%)] \quad 2.$$

An even simpler model finds the average value (K_{av}) of the DUL and CLL. This model finds the mean value for water contents and in fact for this data base can sometimes have the highest R^2 (namely 0.00) because the $rss = tss$. This model is represented by:

$$WC\% = 100 \cdot K_{av}$$

3.

The amazing (for me!) thing about these regression analyses, is that often, the simpler the model, the more of the variance is accounted for (see table 5 below). The models (or the data in the database) are not very special!

Table 5. Goodness of fit (R^2) for the models represented by equations 1, 2. and 3. above

Goodness of fit (R^2) of the 3 models to 3 points at each of (n) sites							
terms in	model	duplex (24)		uniform (21)		gradational (18)	
eqn fit	eqn	DUL	CLL	DUL	CLL	DUL	CLL
matrix	1	-1.10	-0.32	-1.17	-0.20	-0.34	-0.12
matrix	2	-0.39	-0.28	-0.05	-0.02	-0.19	-0.07
matrix	3	0.00	0.00	0.00	0.00	0.00	0.00
mx+clay	1	-0.46	0.44	-1.10	-0.13	-0.15	0.02
mx+clay	2	0.04	0.37	-0.02	0.05	0.03	0.07
mx+cl+OC	1	0.00	0.44	-0.34	-0.13	-0.14	0.02
mx+cl+OC	2	0.27	0.37	-0.05	0.05	0.08	0.07
all (+gv)	1	0.33	0.46	0.18	0.06	0.13	0.09
best fit water contents for the equation 3 model - soil type means							
matrix	3	0.113	0.037	0.076	0.020	0.078	0.020

Conclusion –for the 3 layer, clay%, organic carbon% (OC%) and gv% database

Fits were not good, probably because of the naivety of the model and more likely, because of the problems of matching sampling sites without GPS locations. OC% and clay % were measured on separate samples taken 5-10 years prior to the gravel and water content samples. In order to determine the truth or otherwise of these naïve regression model findings, resources are needed for a study to determine the DUL, CLL and BD of whole soils together with direct measurements of these properties on the gravel and matrix separately. I reckon it would make a great little honours project!

In fact the above section A. is included only for completeness (i.e. a record of pathways followed) It provides nothing substantial except that more work needs to be done both from the point of view of taking direct measurements of the water contents of gravel and fines/matrix and perhaps the development of a better data base.

B.-The 10 layer profile, water contents and gv% database – with a major input from Mario D’Antuono

Once we recognised the problems associated with fitting a model to data from samples taken at different times and probably not at the exact location in space, we decided to look more closely at the metre depth profile samples for soil water relations and gravel contents taken at the same location albeit one set in winter and the other in summer autumn. For this database we were able to collate the data from 87 sites, most of the samples taken in 10 cm depth intervals to one metre. The only covariates for water content measures were gv% and depth. The analysis falls into three parts:-

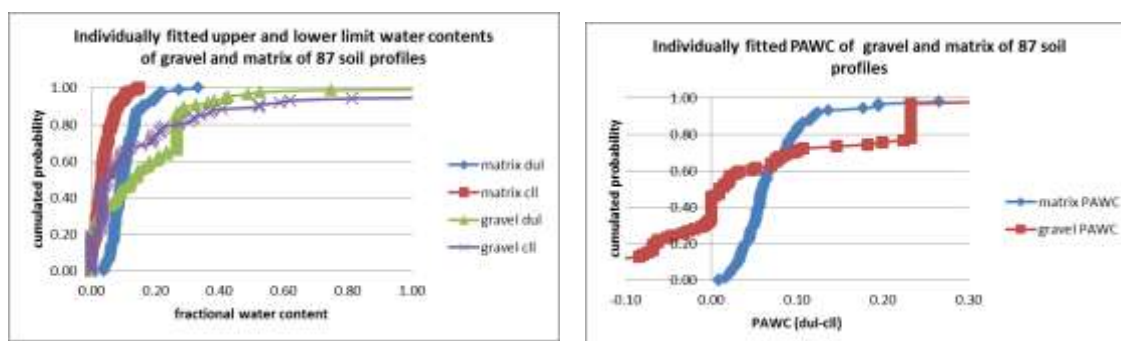
1. Describing the distribution of fitted water content coefficients for the 87 member population.
2. Fitting a combined water content surface (as a function of gv% and depth) for the total data set when it was grouped into 3 soil types.
3. Fitting a combined water content surface (as a function of gv% and depth) for the total data set when it was grouped into 2 geographic regions representing 2 different gravel types.

1. Analysing each site profile separately

It was possible to individually fit each set of site data to a model which gave us the water contents of the gravel and the remaining matrix. However for this database, the model cannot allow for the water held separately by the clay and OC% so their contributions to water content are combined into that of the matrix.

Results are summarised in Figure. 1 below.

Figure 1. Cumulated frequency distributions of the fitted DULs, CLLs and PAWCs of the gravel and fines (matrix) of 87 soil profiles



Note that these are fitted parameters and not direct measures of the water contents of the individual soil components. At each site, the observed soil profile water contents (DUL or CLL or PAWC) are shared between the gravel content and the remaining fines in each layer to give one DUL value for gravel and another for the matrix. This process is objective but can come up with some silly numbers because the model is a very simple representation of a complex soil system. Things like the clay%, the OC% and nature of the pore structure all can have soil storage properties which are NOT identified in this process. DULs should never be greater than the porosity (which for gravel should not be greater than 0.25) and CLLs should be even lower unless the water is completely unavailable for evapotranspiration.

The measured PAWC (= DUL-CLL) values for the data set had less than 1% of negative values yet the fitted values for the gravel had about 30% negative values. Negative values are by definition, impossible so those in the measured whole soil data are due to sampling (and less likely, measurement) errors. The fitted negative values for the gravel component are due to the statistical sharing of the variation between the components.

Having said all of that, it is interesting that this model fitting process comes up with over 80% of the sites having positive DUL and CLL values assigned to the gravel and that 50% have positive PAWC values. The 30% of sites with fitted negative PAWC values for gravel serve as a warning about coming to firm conclusions about the role of gravel for soil water relations using this regression process. The gravel PAWC curve is tending towards symmetry about the vertical axis at the 50 percent point and this behaviour sometimes indicates that the hypothesis (in this case that gravel holds available water) is invalid. Breaking the 87 sites into groups of known soil types and/or locations could help with the interpretation as could revisiting the data and the sites where silly fitted values (too high or negative) were obtained. If we were rigorous we would have to apply the same scrutiny to the individual data from every site.

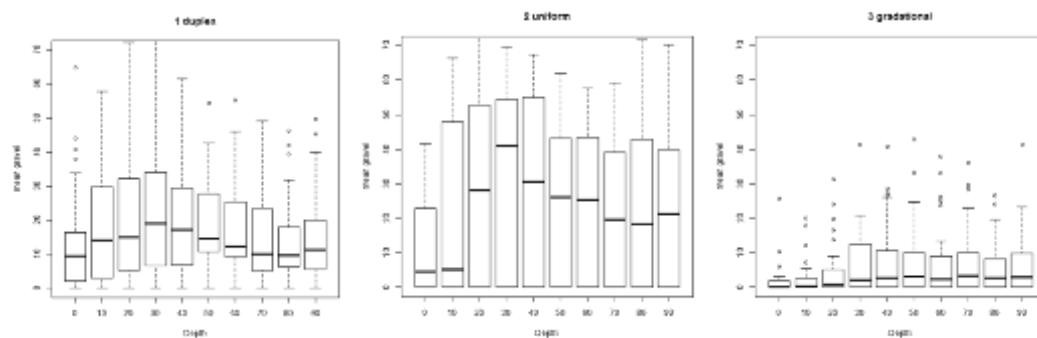
Only with direct measurements of the water contents of the gravel and matrix components could this issue of negative values be removed.

2. Group Analysis of 87 profile water contents as a function of **soil type**, depth and gravel content

For grouped analysis, the 87 sites in this database were categorised into the 3 soil types discriminated here by the Northcote key, soil classification system. These grouped soil types became:- 1. duplex (D, n=37), 2. uniform (U, n=18) and 3. gradational (G, n=32)

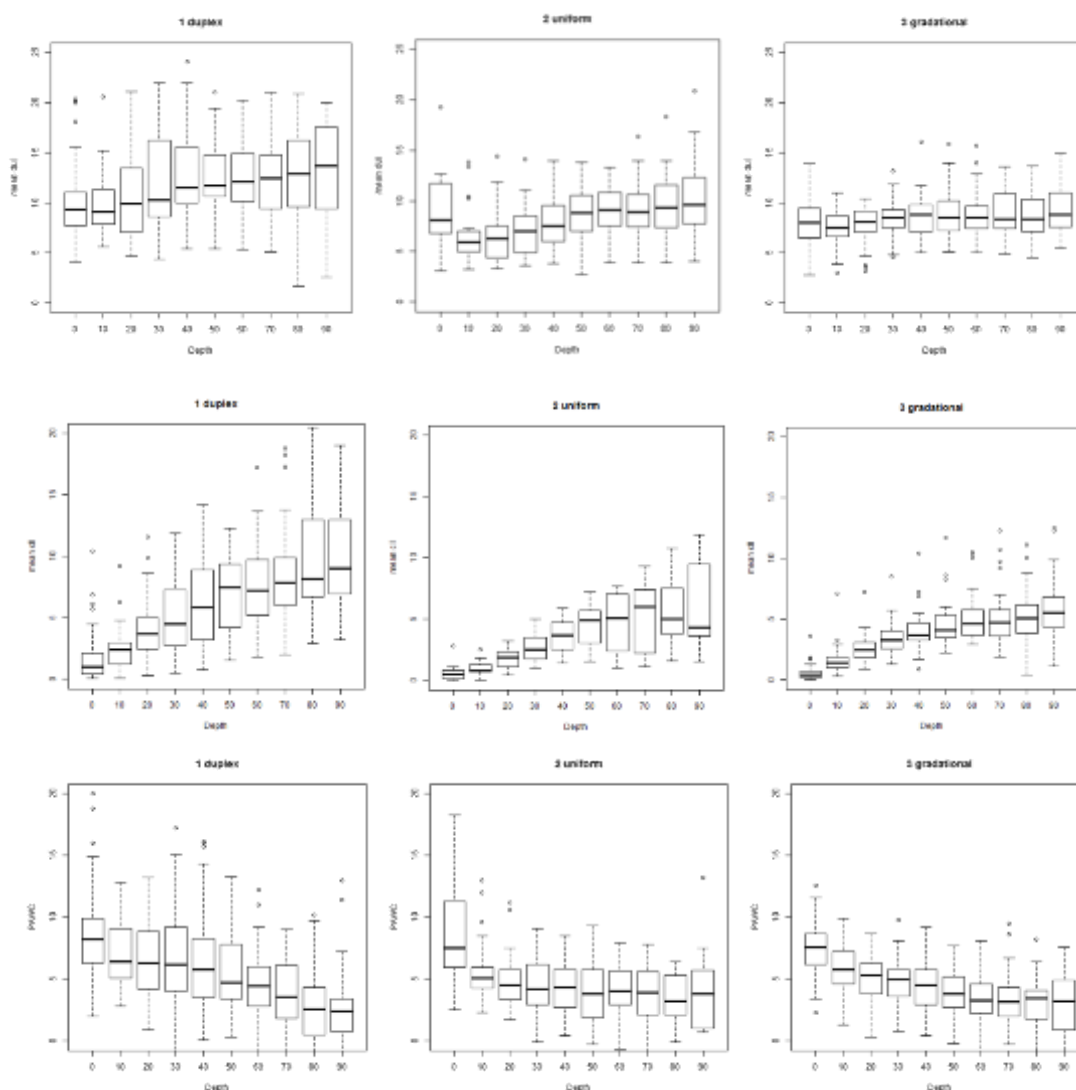
The variability in measured gravel contents with depth are summarised for these 3 soil types in Figure. 2 and the measured soil water content data are summarised in Figure. 3., below.

Figure 2. Gravel contents (%gv w/w) by depth for the 3 soil types.



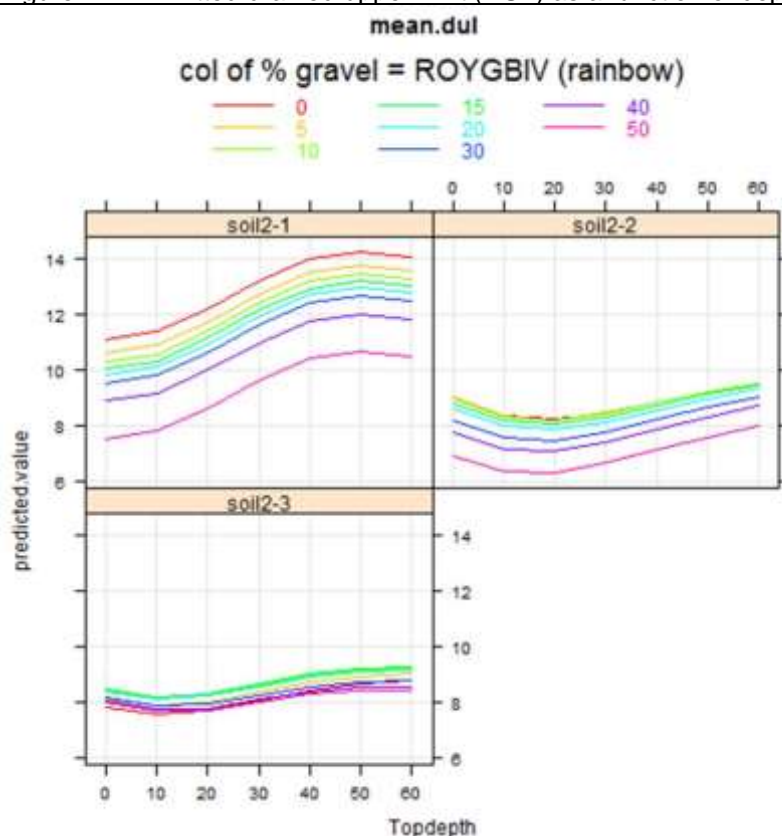
The boxplots show the 25 percentile to 75percentile (rectangle) and include the median point (bar). The hairs represent the estimated minimum and maximum values on the assumption of normality. The open circles beyond the maximum hairs represent outlier high values.

Figure 3. Soil water (DUL, CLL and PAWC) data for three soil types and 10 cm depth intervals. Box plot explanations as for figure 2.



In this analysis the three measured water content values at each point were fitted with a smoothing spline function within a linear mixed model (ASReml –R software, Butler et al 2009) for each of the three soils, as a function of gravel content and depth. The fitted curves combine and smooth the information in Figures 2. and 3. above and are summarised in the Figures 4. to 6.

Figure 4. Fitted drained upper limit (DUL) as a function of depth and gravel for 3 soil types

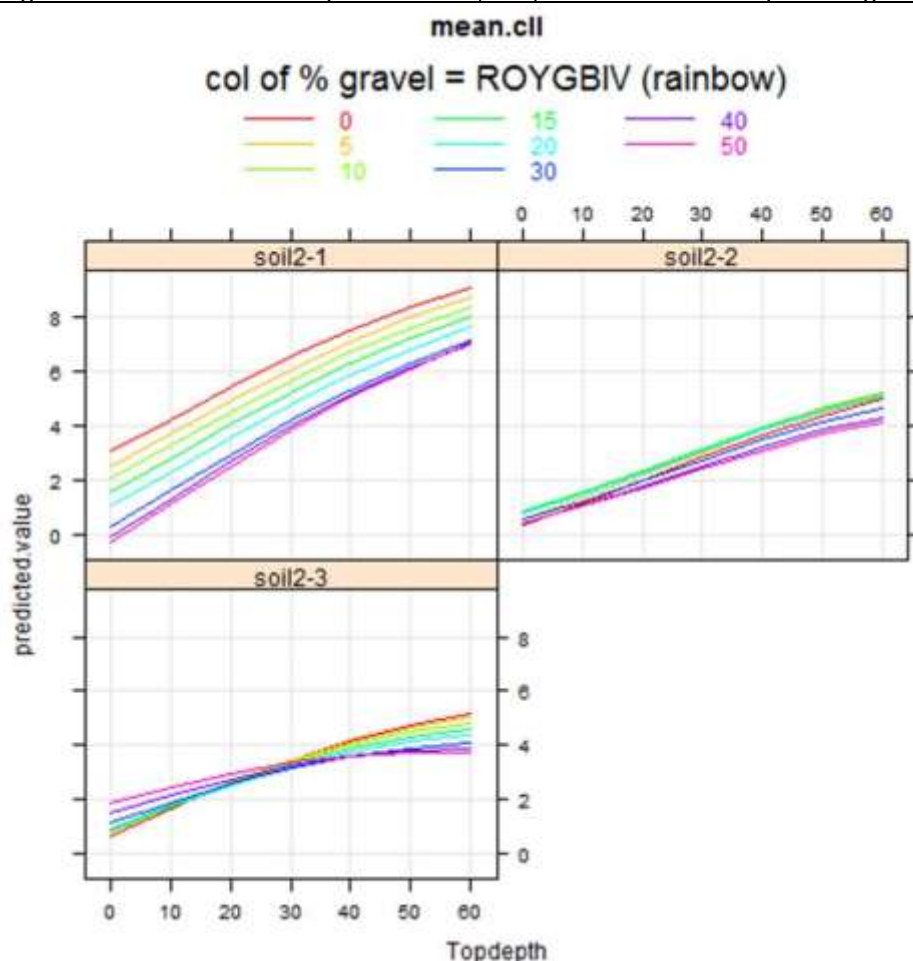


The high gravel content soils have lower DUL at all depths for all soils, supporting the hypothesis that gravel content is a diluent of DUL measured on a whole soil basis. However when gravel makes up 50% of the soil (w/w) the DUL is less than halved so either gravel holds some water or the non-gravel fraction has higher water holding capacity (e.g. higher clay) at those higher gravel contents.

On the duplex soil (1), the increase in DUL with depth logically reflects increasing clay content into duplex layers. The aggregated uniform soil (2) represents mainly sandy soils with far lower DUL values. The tendency for DUL to be higher in the top couple of layers is probably because the specific DUL of soil organic matter is high and can have a noticeable effect at low background DUL levels. The DUL values on the gradational soils (3) are surprisingly low given that they normally have increasing clay content with depth. The fitted impact of gravel is also low because the range of gravel contents is far lower than on the other two soils (Fig 2.)

The higher DUL values without gravel imply lower drainage rates and lower leaching of mobile soil chemicals.

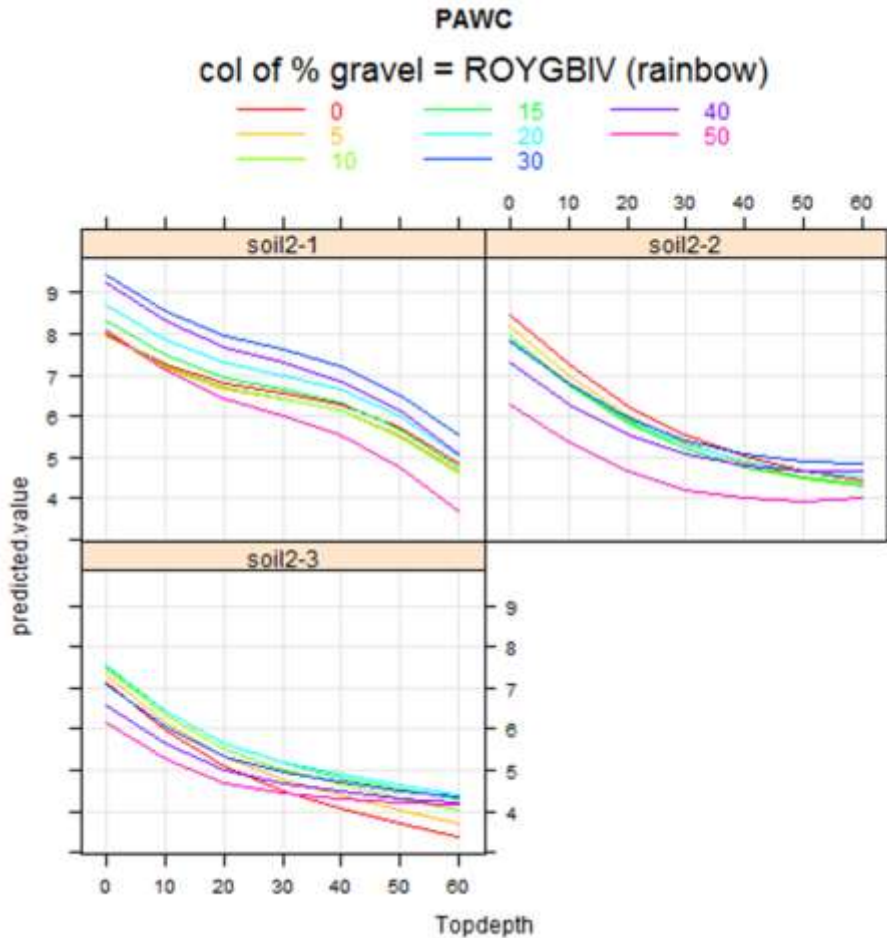
Figure 5. The fitted crop lower limit (CLL) as a function of depth and gravel for 3 soil types.



The lower limit of soil water held after a reasonable crop (CLL) will always be lowest in the surface layers and will increase with depth. The surface layers can be subject to evaporation below the water content from which plants can do their job. The maximum root densities occur in the surface layers and the roots there are present and extracting water for a far longer time than the roots at depth. The effect of gv% varies across the soil types both in effect and direction. The highest gv% always has a lower CLL than the lower gv%s except on the gradational soil (3) where there is a crossover of effects at about 30 cm.

Gravel content has less of an effect on the CLL (it has a much lower range of water contents than DUL). CLL increases almost linearly with depth as would be expected because the ability of crop roots to deplete water is a function of how long the roots spend in a layer and this obviously decreases as depth increases. Also clay% usually increases with depth on WA soils and clay would hold more water at CLL than the coarser soil fractions.

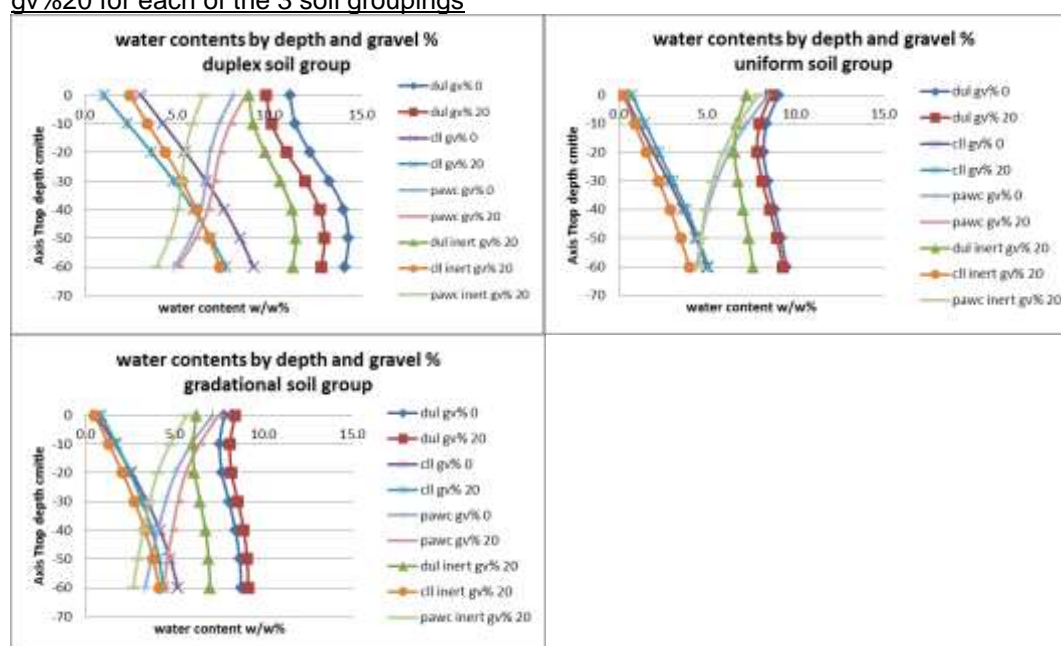
Figure 6. Plant available water content (PAWC) as a function of depth and gravel for 3 soils



The PAWC was calculated for each layer at each site as the difference between the DUL and the CLL. The fitted (smoothed) surface of PAWC as a function of depth and gv% for each of the 3 soil types shows complex relationships. As expected, the PAWCs always decrease with depth but only on the uniform soil (2) does gv% consistently reduce PAWC. For the duplex soil, it seems that PAWC increases with gv% except for gv% of 50 (and greater). Either gravel stores plant available water, or there is a correlated increase in clay content with increasing gv% except where gravel is so high that clay content cannot increase. On the gradational soil (3) the values of gv% are low as is the range of fitted PAWCs across gv%. Gv% in the range 5-20% seems to hold the most PAWC on this soil type.

The question remains of whether gravel is inert and simply dilutes the water content parameters in strict proportion to gv% or whether it holds water. The surface fitting method cannot discriminate the alternatives because even if gravel holds no water, other water holding components of the soil could well correlate with the gravel. Only measurements will determine the difference. However, Figure7. shows the difference between the fitted gv%=20 lines and those calculated for inert gravel at gv%=20 ; i.e. the line is plotted at 80% of the gv%=0 lines

Figure 7. Is gravel inert? A summary of water content profiles for gv% 0, 20 and assumed inert gv%20 for each of the 3 soil groupings



For all 3 soil groups the DUL lines for inert gravel calculations markedly under predict the actual fitted values. So assuming that drainage and leaching will be greater on gravelly soils will be wrong. Any adjustment of the CLL for assuming inert gravel would not make much difference to the already low values. The plant available water storage (PAWC) is much under estimated if gravel is assumed to be inert except for the uniform soil grouping.

3. Group Analysis of 87 profile water contents as a function of **location**, depth and gravel content

Gravel is a very loose term which covers coarse (<2mm) soil mineral particles ranging in reactivity from inert rock particles to soft mottles which differ from soil only in that roots cannot penetrate them. In this study we have been dealing almost exclusively with lateritic gravels which have markedly different properties which vary with geographical distribution. In this section we carried out a similar analysis to that used above to discriminate soils. The 87 sites in this database were categorised into two groups as determined by location west and east of a line which separates the high sesquioxide forest gravels (25) from the high silicate content, wheatbelt gravels (62), (Figure 8.)

Figure 8. Distribution of gravel types in WA. 25 sites west of the line and 62 east of the line used in the surface fitting analysis

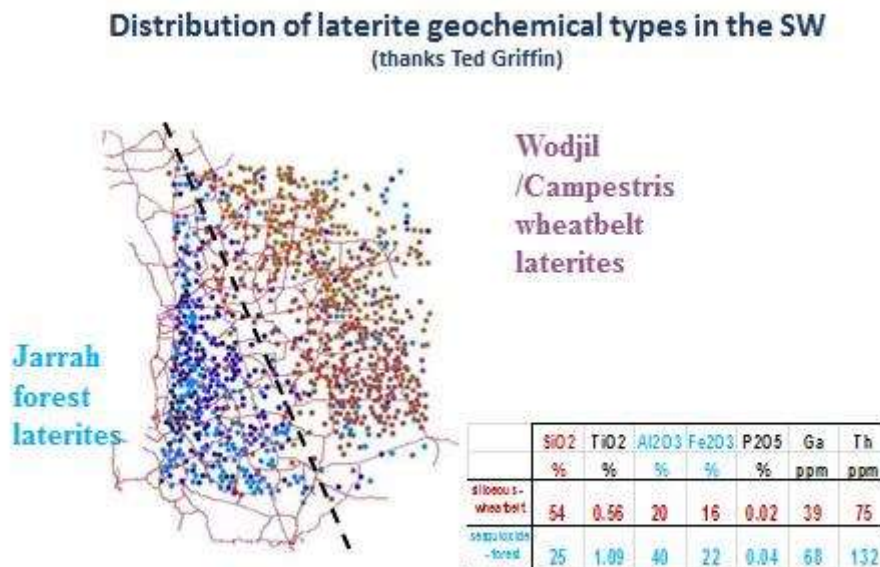
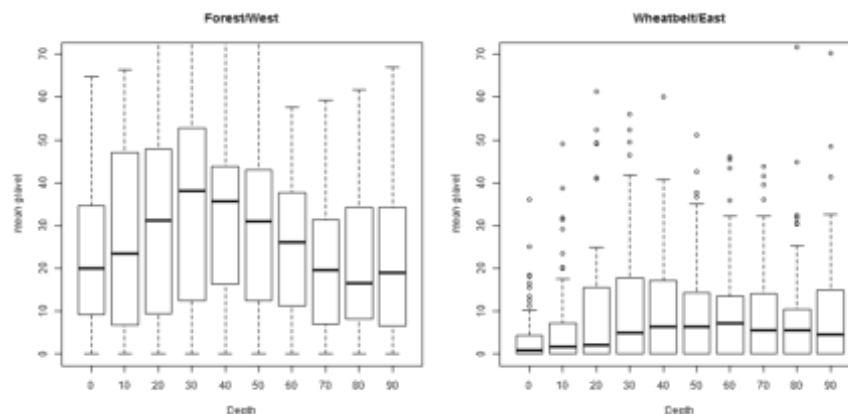


Figure 9 Buckshot gravel typically found in the forest country (left) and hardened clay mottles often found in the subsoils of the wheatbelt (right)



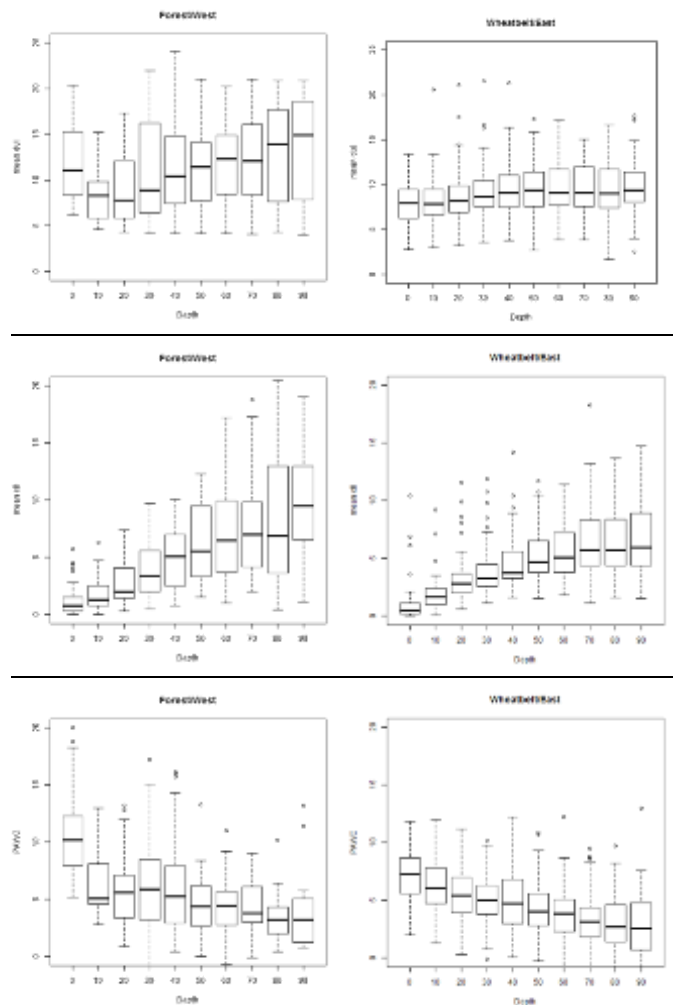
The distribution of the measured gv% and the 3 water holding properties by depth for the 2 regional groupings of sites, are shown in figures 10 and 11.

Figure 10. Gravel contents (%gv w/w) by depth for the 2 regions. Forest sites (25) west of the line in Fig. 8. wheatbelt sites (62) east of the line in Fig. 8.



The boxplots show the 25 percentile to 75 percentile (rectangle) and include the median point (bar). The hairs represent the estimated minimum and maximum values on the assumption of normality. The open circles beyond the maximum hairs represent outlier high values.

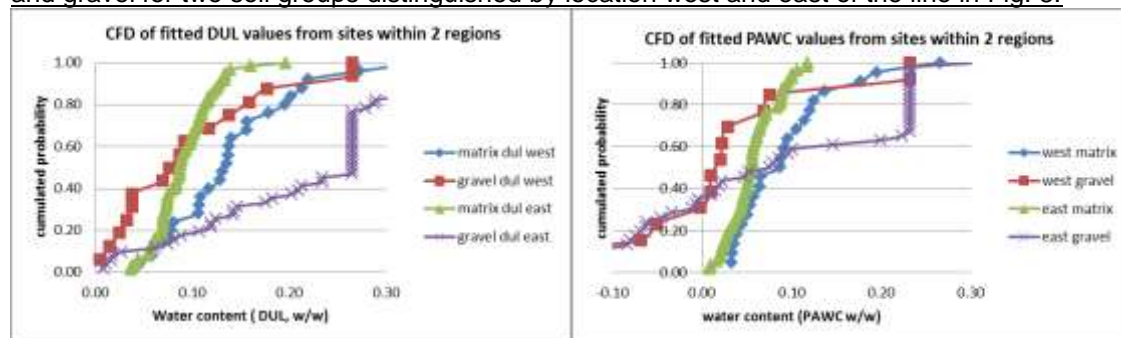
Figure 11. Measured soil water (DUL, CLL and PAWC) data for 2 regions and 10 cm depth intervals.



Box plot explanations as for figure 10.

The cumulated frequency distributions of water content parameters for gravel and matrix, fitted individually to each site within the two regions are shown in Fig 10.

Figure 10. Cumulated Frequency distributions (CFDs) of DUL and PAWC parameters for matrix and gravel for two soil groups distinguished by location west and east of the line in Fig. 8.



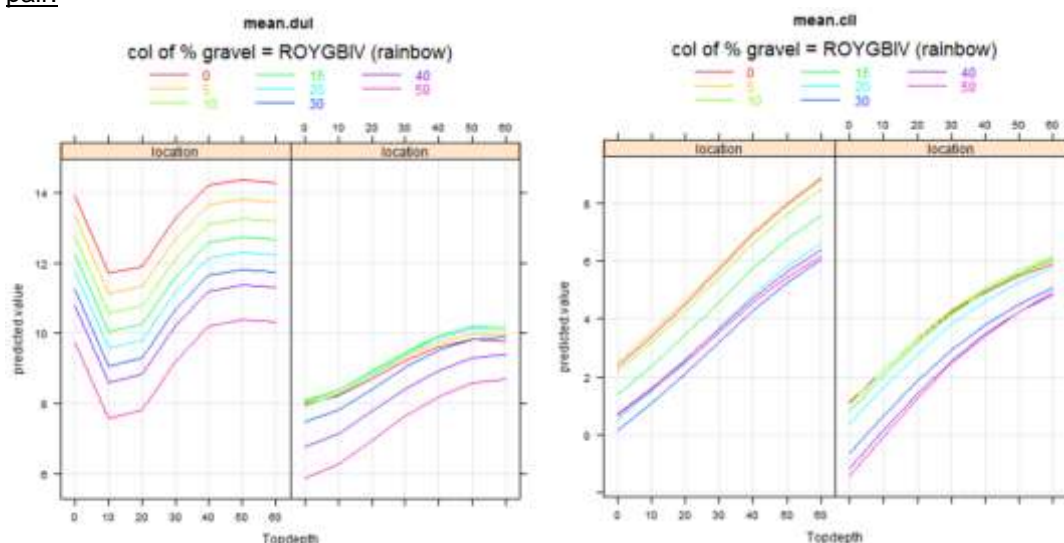
Remember that these fitted parameters are site specific and the one value is for all (10) depths of the profile. This is obviously incorrect in reality where water holding components of the soil (e.g. clay and OC%) can vary markedly with depth.

It is also clear that the matrix (fines) for the soils from the west have higher water holding contents and plant available water than the matrix of soils from the east. The same general findings hold for the CLL though the data are not shown here. The gravel from the west has markedly lower water holding properties than the gravel from the east – in keeping with our prejudices shown in Fig. 9

Smoothing the data for the two regions – the fitted gravel by depth water content surfaces.

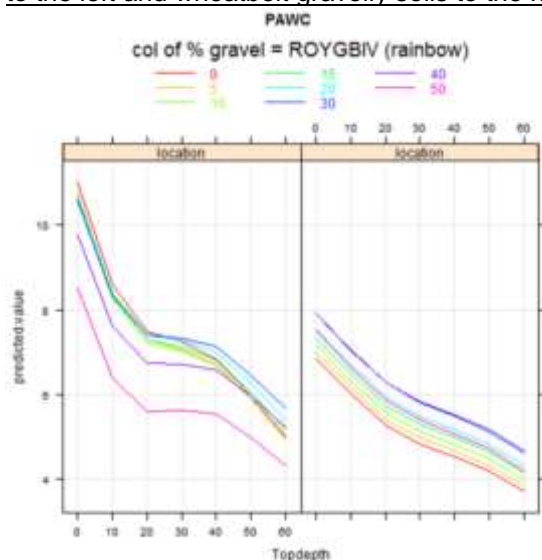
Surfaces of water content versus depth and gravel content were fitted to all sites within each region (25 west and 62 east) and the results are shown below. This process comes up with an average soil type for each region so obviously does not give the characteristics observed at any one site.

Figure 11. The effect of gravel and depth on the DUL (left pair) and CLL (right pair) for 2 location groups – forest gravelly soils to the left in each pair and wheatbelt gravelly soils to the right in each pair.



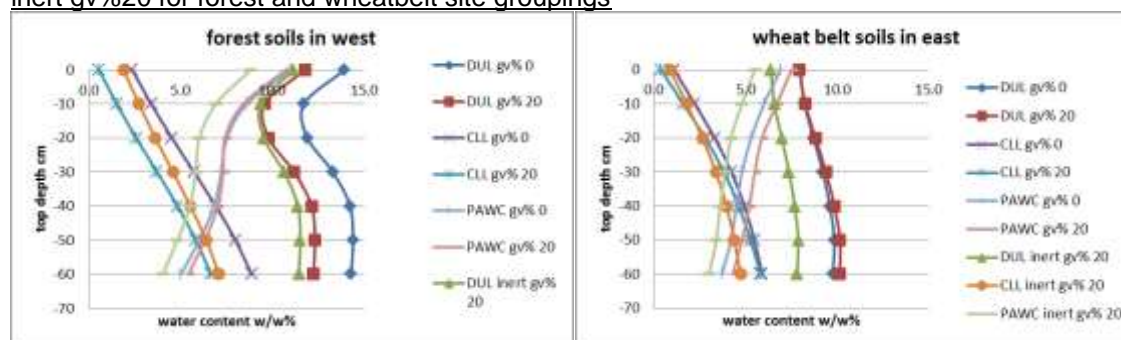
The DUL of the forest soils varies markedly and proportionately with gravel content suggesting that the gravel in those soils are more inert than the gravels on the wheatbelt gravelly soils. Only at very high gv% do the wheatbelt soils see gravel reducing the DUL. The CLL is reduced as gv% rises for sets of soils from both locations.

Figure 12. The effect of gravel and depth on the PAWC for 2 location groups – forest gravelly soils to the left and wheatbelt gravelly soils to the right



There is no consistent effect of gv% on the PAWC of the forest soils except at the two highest gv%. In contrast, the PAWCs of the wheat belt soils increases with gv% up to 40%. This implies that the gravel in wheat belt soils contains plant available water above that of the matrix, and/or gravel gv% is positively correlated with clay content. In essence these wheat belt gravels may have water relations similar to those of clay (Figure 9).

Figure 13. Is gravel inert? A summary of water content profiles for gv% 0, gv% 20 and assumed inert gv%20 for forest and wheatbelt site groupings



Note that assuming gravel is inert for the drainage (leaching) upper limit (DUL) of the forest soils is a reasonable prediction but overestimates the effect for the wheatbelt soils (i.e. wheatbelt gravels are not inert). In both soil groups, assuming gravel is inert, overestimates water left (CLL) in the surface layers which implies that surface gravel has a mulching effect. For plant available water storage (PAWC) the inert gravel assumption underestimates reality for both soil groups. For the forest soil where it is most likely that gravel is inert, higher root densities for longer times in the surface layers could explain the effect of gravel on PAWC. For the wheat belt soil group, the gravel appears to hold water at the upper limit.

What is the impact of gravel on water content in our Western Australian agricultural soils?

The above analysis, which fitted the 3 water content parameter's surfaces as a function of depth and gravel content, averaged data for various groupings of soil types or regions. The average, fitted response in water content to the measured gravel content in those soils can be expressed as a percentage of the mean water contents to give a number which can be compared with the theoretical impact of gravel if indeed the gravel did not hold water – i.e. was inert. These values are shown for DUL and PAWC for the various soil and regional groupings in Table 6 below. For CLL, the range and level of figures made such calculations unreliable.

Table 6. Percentage “inertness” of gravel for soil water contents. Calculated from the fitted surfaces at 0% and 20% gravel content for the 3 soil and 2 regional groupings of sites.

	Gravel inertness percentage			
water content	DUL	DUL	PAWC	PAWC
group\depth	0 cm	50 cm	0 cm	50 cm
37 duplex	90.1	61.3	11.8	52.4
18 uniform	71.1	55.3	74.4	54.2
32 gradational	2.2	11.7	36.7	-7.8
25 west/forest	74.6	68.5	58.8	50.8
62 east/wheatbelt	74.1	39.6	-3.7	0.0

The findings from this table differ from those based on a visual appraisal of Figures 7. and 13. because splining effects were included in those figures. Also the groupings are not exclusive though there are only 2 of the gradational soils in the west/forest grouping. The gradational soil group shows least if any inertness in the gravel. Here the inertness of the gravel (closer to 100) is most consistent for the uniform soils and for the sites from the forest country to the west.

Conclusions

The water relations of soils are critical for understanding and for better managing crops and pastures grown on them. Whether special account should be taken of the gravel content of soils when estimating yield potentials, nutrient leaching, run off and infiltration is a moot point. "Should we adjust the timing and rates of nitrogen on gravelly soils because there may be more leaching?" is one example of how the water relations affect management decisions. "Will the gravel in soils reduce moisture storage to a level where earlier maturing varieties should be used on gravelly soils to prevent haying off at the end of the season?" is another such question. Unfortunately, this project has not answered those sorts of questions definitively.

In most circumstances, gravel does have the property of reducing soil water contents but not to the extent expected if gravel was inert. This suggests that gravel can not only hold water but can hold significant quantities of plant available water in some circumstances. Alternatively gv% correlates positively with other soil components (e.g. clay%) which hold more water than the standard fines fraction. Which of these two alternatives is true, can only be resolved by direct measurements of DUL and CLL on both the gravel and the fines/matrix components of the soil.

The fitted surface for DUL says that soils with higher gv% hold less water against drainage. This implies that soil mobile nutrients and agricultural chemicals will be moved deeper and faster on gravelly soils with any given amount of infiltrating rain. The problem with this general finding is that it does not consider the effect of gv% on the amount of rain which infiltrates versus that which runs off. Logically the reduced DUL with gravel should mean that there would be higher run off but this ignores the fact that in some circumstances, a rough gravelly surface can increase water puddling and so allow more time for infiltration before run off occurs. Also having gravel in a soil could well provide preferred pathways for water infiltration and drainage across the more vertical gravel surfaces in the soil. Direct measurements of infiltration rates with a rainfall simulator would help resolve these issues.

The variability of the effect of gv% on PAWC makes it difficult to draw conclusions about the impact of gravel on plant growth, soil water storage and the ability for crops to survive non rainfall periods particularly during the terminal drought at the end of the season in a Mediterranean environment. Some of the DUL and CLL curves from this analysis could be fed into a simulation model to be run over a range of seasons to see how the variability in crop yields is affected by gv%. The water balance of such models could be affected by a "mulching" effect of gravel which could reduce soil water evaporation.

Gravel could have an indirect effect on soil water relations via its effect on soil wettability. Non-wetting soils often have high OC% and low clay contents in the fines. For the same dry matter production, or net organic carbon input into the soil a soil with high gv% will have an increased measured OC% in the fines. This can cause more water repellency with implications for run off and drainage.

If anything this section has raised more questions than it has resolved. At the moment, direct measurements of things like soil water profiles, infiltration and run off will be better than trying to adjust theoretical moisture properties/profiles according to measured gravel contents.

Future work

There are indications that some of the lateritic gravels in this study hold water at both the DUL and CLL and indeed, that they can have a plant available water capacity.

These indications can only be confirmed via work which directly measures the DUL and CLL of both the gravel and the fines/matrix components of the soil. Because of the marked variability in the properties of gravels in soils, this work would have to be done across a large range of gravelly soils. Here we have only touched the surface.

In the absence of such work there may be a case for collecting a new database which contains measures of gv%, OC%, clay% and the water characteristics DUL, CLL and PAWC of whole soils.

Appendix 3. Gravel and root growth

Vanessa Dunbabin did the Rootmap model runs and analysis

The presence of objects in a soil which cannot be penetrated by roots obviously has a major effect on root growth, root architecture and root length densities through time and space. This in turn will affect nutrient and water uptake with implications for crop growth and nutrient management decisions. Obvious questions to answer are:

1. Will the presence of gravel increase the uptake of soil immobile nutrients (copper, zinc, manganese and phosphorus on high fixing soils) by increasing root exploration of the fertile zones of the soil?
2. Will the presence of gravel cause the root depth penetration rate to increase enough for the crop to better take up soil mobile (leachable nitrate and sulphate) nutrients and water?
3. Will increased and earlier root competition caused by gravel content force roots to explore new soil laterally more rapidly? That is, will roots explore the inter row more rapidly in gravelly soils?

Resources did not allow us to investigate questions about the impact of gravel on root growth dynamics using direct observations and/or experiments, so we decided to explore some of the issues using the root growth model Rootmap (Dunbabin, Diggle et al). With answers to these questions we could speculate about nutrient (and water) uptake from gravel soils in the context of how gravel changes water relations and nutrient availability dynamics.

We asked Dr Vanessa Dunbabin to carry out some preliminary studies using Rootmap. Her work fell into two parts. In the first section she looked at the impact of inserting inert objects into the soil volume on root growth and nutrient uptake. In the second Vanessa did a preliminary study on how root density (set up by changing plant density in the row) affected root exploration in three dimensions; our interest being in the rate of root penetration to depth and into the inter-row.

Below are the reports on those two studies:

1. The effect of inert objects on root growth and nutrient uptake

It is worth noting that the root and nutrient uptake parameters will be sensitive to genetic root growth parameter settings, levels of water in the soil, levels of nutrients in the soil, nutrient distribution, soil buffering and water holding characteristics, as well as the dynamics of water supply. Other factors include the duration of the runs and of course our subject of interest, the gravel content, size and distribution. There were sufficient resources only for a brief look at the impact of some of these factors and their interactions.

Model set up

Overall Soil Volume of 14cmx14cmx70cm

PBI = 40

DUL = 0.12 v/v

WC = 0.12 v/v

LL/WP = 0.03 v/v

BD = 1.55 Mg/m³

N content = 5 µg/g

Total Labile P = 8 µg/g

Soil water content was either maintained during the simulation, or the soil was allowed to dry out. No rainfall events during the simulation.

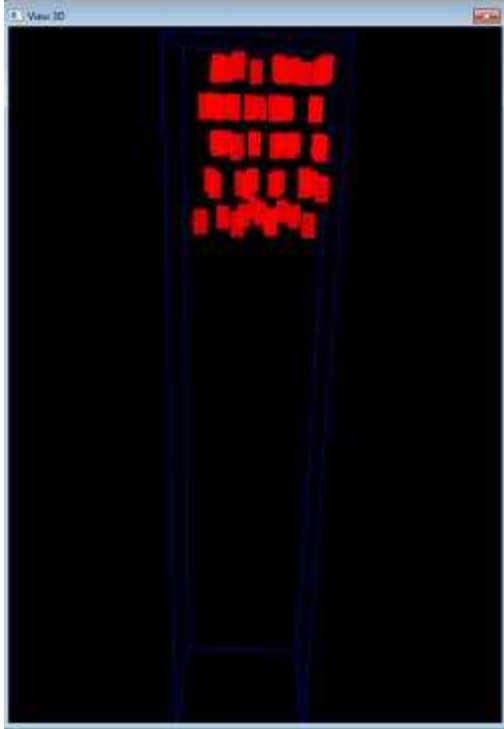
Simulation time = 28 days

Simulations:

1. No objects in soil - 3 reps
2. Addition of inert objects in the soil. Rectangular prisms - 1 cm x 1 cm x 2 cm = 2 cm³. 65 prisms placed randomly in a 12 cm x 12 cm x 11 cm column of soil from 1 cm to 12 cm depth. 130 cm³ of inert prisms in 1584 cm³ of soil gives a gravel content of 8 % v/v. 3 reps.
3. Gravel content of 8 % in gravel zone, plus restricted the nutrient content to the gravel zone. Below 12 cm N content = 1 µg/g, and Total Labile P = 2 µg/g. 3 reps.

4. Addition of inert objects in the soil. Rectangular prisms - $0.9 \text{ cm} \times 0.9 \text{ cm} \times 1.9 \text{ cm} = 1.5 \text{ cm}^3$. 180 prisms placed randomly in a $11 \text{ cm} \times 11 \text{ cm} \times 8 \text{ cm}$ column of soil from 1 cm to 9 cm depth. 277 cm^3 of inert prisms in 968 cm^3 of soil gives a gravel content of 29 % v/v. 3 reps.
5. Gravel content of 29 % in gravel zone, plus restricted the nutrient content to the gravel zone. Below 10 cm N content = $1 \mu\text{g/g}$, and Total Labile P = $2 \mu\text{g/g}$. 3 reps.
6. Gravel content of 29 % in gravel zone, plus restricted the nutrient content to the gravel zone. Plus increased the branching density (1st, 2nd and 3rd order branches) to see how that affected the exploration of the gravel zone. 3 reps.

Figure 1. 3D arrangement of inert objects in the simulated soil column



Inert rectangular objects placed randomly in a column of soil from 1cm to 12 cm depth. 8% gravel content in gravel zone. Model set up logistics and run times prevented the use of inert objects throughout the whole soil profile.

Results

The outputs from the modelling runs are presented in tables 1-3 and figures 3-6 below.

Table 1. Summary of mean, total root length (TRL) and its components (first roots, second roots and the root axes), from Rootmap 28 day runs with and without inert gravel objects.

	TRL (cm)	1st RL (cm)	2nd RL (cm)	Axis RL (cm)
8% Gravel content in the gravel zone, uniform nutrient content.				
No Inert Objects	1508.8 ±3.4	1089.4 ±0.3	109.6 ±0.5	309.8 ±2.7
With Inert Objects	1503.1 ±6.5	1084.7 ±6.4	109.8 ±0.3	308.6 ±1.5
8% Gravel content in the gravel zone, reduced N & P below 12 cm.				
No Inert Objects	1028.0 ±22.8	707.1 ±17.3	114.3 ±1.0	206.5 ±5.5
With Inert Objects	1083.0 ±34.0	750.0 ±27.8	117.5 ±2.4	214.4 ±4.2
29% Gravel content in the gravel zone, uniform nutrient content.				
No Inert Objects	1508.8 ±3.4	1089.4 ±0.3	109.6 ±0.5	309.8 ±2.7
With Inert Objects	1525.1 ±5.5	1095.8 ±5.2	112.5 ±1.3	311.8 ±2.5
29% Gravel content in the gravel zone, reduced N & P below 10 cm.				
No Inert Objects	998.3 ±16.6	705.0 ±18.4	93.1 ±0.7	206.9 ±3.2
With Inert Objects	1007.4 ±10.9	705.2 ±9.6	93.4 ±0.4	208.8 ±1.0
29% Gravel content in the gravel zone, reduced N & P below 10 cm, increased branching				
No Inert Objects	3448.7 ±73.3	1307.6 ±27.3	1761.1 ±42	207.6 ±2.8
With Inert Objects	3398.9 ±126.4	1262.1 ±37.7	1756.7 ±79.0	202.1 ±2.7

Table 2. Phosphorus and nitrogen uptake summary for the Rootmap runs detailed in table 1.

	P Up (mgP)	N Up (mg N)
8% Gravel content in the gravel zone, uniform nutrient content.		
No Inert Objects	0.38	4.7
With Inert Objects	0.38	4.8
8% Gravel content in the gravel zone, reduced N & P below 12 cm.		
No Inert Objects	0.20	2.84
With Inert Objects	0.21	2.99
29% Gravel content in the gravel zone, uniform nutrient content.		
No Inert Objects	0.38	4.7
With Inert Objects	0.38	4.6
29% Gravel content in the gravel zone, reduced N & P below 10 cm.		
No Inert Objects	0.2	2.5
With Inert Objects	0.2	2.7
29% Gravel content in gravel zone, reduced N & P below 10 cm, increased branching		
No Inert Objects	0.54	3.33
With Inert Objects	0.53	2.90

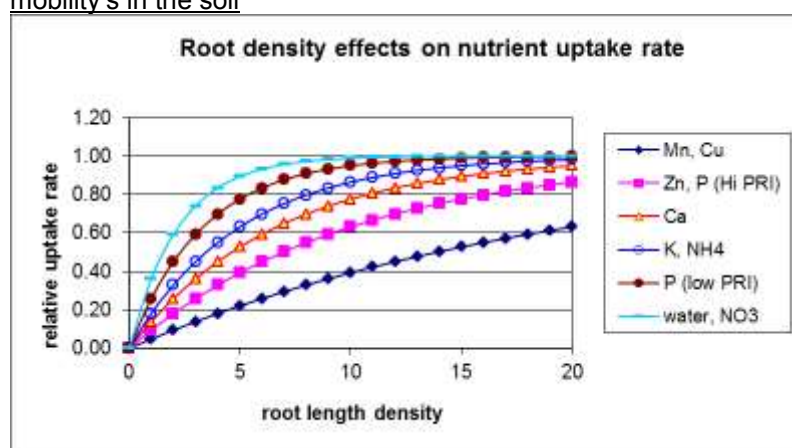
As would be expected there is little difference between the two scenarios in terms of total root length or N and P uptake. The simulation is over a relatively short time frame, water is at DUL for the whole time and the objects are placed in a subset of the soil that represents a density of about 8% in that zone, but only 1% of the total available soil volume - hence water and nutrients are still readily available.

There was however a clear response in terms of where roots grow. There was an increase in fine root branching (1st and 2nd order root branches), in the surface soil when inert objects were present, with slightly less branch growth at depth. In the early stages of growth while the rooting depth was in the "gravel zone", the root system responded to the presence of the inert objects by increasing surface root branch growth. Once the root system had extended beyond the "gravel zone" the root system was little affected with access to the same nutrients at depth as in the non-gravel simulation. Reducing nutrient supply below the gravel zone reduced the total root length, reducing root growth at depth. There was greater root growth (first order branches) over the whole gravel layer, compared to the gravel-free soil.

When the gravel content was increased to 29 % there was a smaller root growth response in the "gravel zone" compared to that seen in the 8% gravel simulations. In both cases, the same root length in the gravel zone means that the density of roots in the soil matrix is increased by the factor $1/(1-\text{gravel}\%/100)$. At 29% gravel, the root length density (RLD) in the matrix is increased by about 40% ($=100/0.71$) for the same root length.

Keith Barley (1970) postulated the relationship between RLD and nutrient uptake rate and this is illustrated in qualitative terms in Fig. 2. Below

Figure 2. Root length density effects on the uptake rate of nutrients and water with different mobility's in the soil



In principle, increasing the RLD should increase the rate of nutrient uptake – particularly of the less mobile soil nutrients – but would also increase their rate of depletion such that nutrient uptake rate would decrease in the longer term. At the same nutrient concentration in the matrix you have 29% lower total available nutrient at 29% gravel v/v. Depending on the initial conditions and the run time, we could expect any of a wide range of effects of gravel on nutrient uptake. Studies with Rootmap where we systematically vary some of these important factors and parameters could be the subject of future work. Here we just touched the surface in understanding the system.

Reducing N and P content to very low levels below 10 cm, reduced N and P uptake. The shape of the root profile changed, with reduced root growth below 10 cm and a concentration of root growth in the surface layers. There was a small difference in the growth of 1st order branches between the gravel and no gravel simulations.

When the total P uptake is expressed as a percentage of the high P in the surface layer, zero gravel gives 0.7%. the soil with 8% gravel gives 0.8% and the soil with 29% gravel gave 1.2% because of the higher RLD (0.30, 0.34 and 0.36 cm/cc respectively) and lower initial amount of P in the reduced amount of matrix in the high P zone (29, 27 and 17 mgm P respectively)

The reason for the small difference between the gravel and non-gravel simulations was not clear to me (VD), so I thought I would play with the parameters a bit. I was wondering if it was related to the way the roots were colonising the gravel zone. I tried simulations with substantially higher branching density and an increased deflection index to see if increased root colonisation affected the results, but again there was little difference between gravel and non-gravel. Without gravel objects present, root systems are responding to the local supply of nutrients by concentrating root proliferation in the surface layers. The addition of gravel doesn't seem to be causing an additive response on top of that already occurring in response to uneven nutrient supply.

The phosphorus buffering index (PBI) was increased to 80 to see if there was a response to P supply, but this resulted in even less difference between the gravel and no gravel simulations. Additional simulation runs were carried out in which the root growth plasticity response of the wheat to soil N & P supply was increased (genotype 2.).

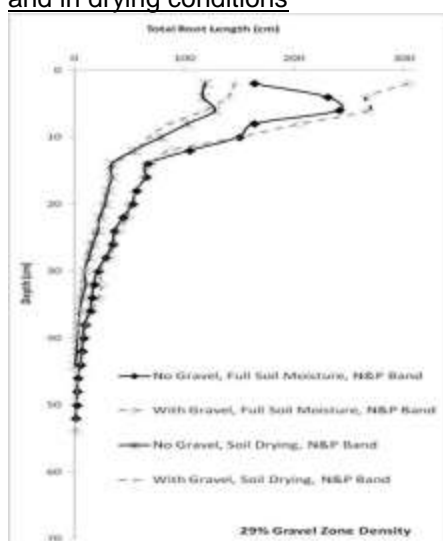
Table 3. Summary of N and P uptake for the flexible/plastic genotype. Runs with and without 29% gravel, nutrients through the whole profile or only in the topsoil gravel zone and for moist or drying conditions.

	With 29% Gravel Objects					With 29% Gravel Objects				
	Phosphorus uptake (mgP)					Nitrogen uptake (mgN)				
	R1	R2		avg	s.e.	R1	R2		avg	s.e.
No Gravel, Full N&P, soil moisture maintained	0.580	0.626		0.60	0.023	6.34	6.72		6.53	0.19
With Gravel, Full N&P, soil moisture maintained	0.567	0.580		0.57	0.0065	6.47	6.38		6.43	0.045
No Gravel, Topsoil N&P, Soil moisture maintained	0.257	0.249		0.25	0.004	3.04	2.97		3.01	0.035
With Gravel, Topsoil N&P, Soil moisture maintained	0.308	0.310		0.31	0.001	3.13	3.84		3.49	0.355
No Gravel, Topsoil N&P, soil drying	0.116	0.104		0.11	0.006	2.66	2.54		2.60	0.06
With Gravel, Topsoil N&P, soil drying	0.104	0.123		0.11	0.0095	2.1	2.66		2.38	0.28

As expected, root growth and N & P uptake decreased as water and nutrient supply decreased. Decreasing N&P supply at depth decreased root growth at depth and nutrient uptake. Allowing the soil to dry out during the simulation further decreased root growth and nutrient uptake.

When N&P supply was reduced below 10 cm, root growth at depth was reduced, but root growth in the topsoil layers was maintained. This treatment showed the biggest response to the presence of gravel. With 29% gravel objects present, root proliferation increased in the gravel and nutrient zone, above the no gravel case. Increased early root proliferation lead to a higher density of fine root branches in the gravel zone which enhanced N&P uptake, with adequate soil moisture and over a relatively short time-frame (28 days). For all the other treatments, the addition of gravel reduced N & P uptake.

Figure 3. Root length profiles in the presence (29% v/v) and absence of gravel in continuously moist and in drying conditions

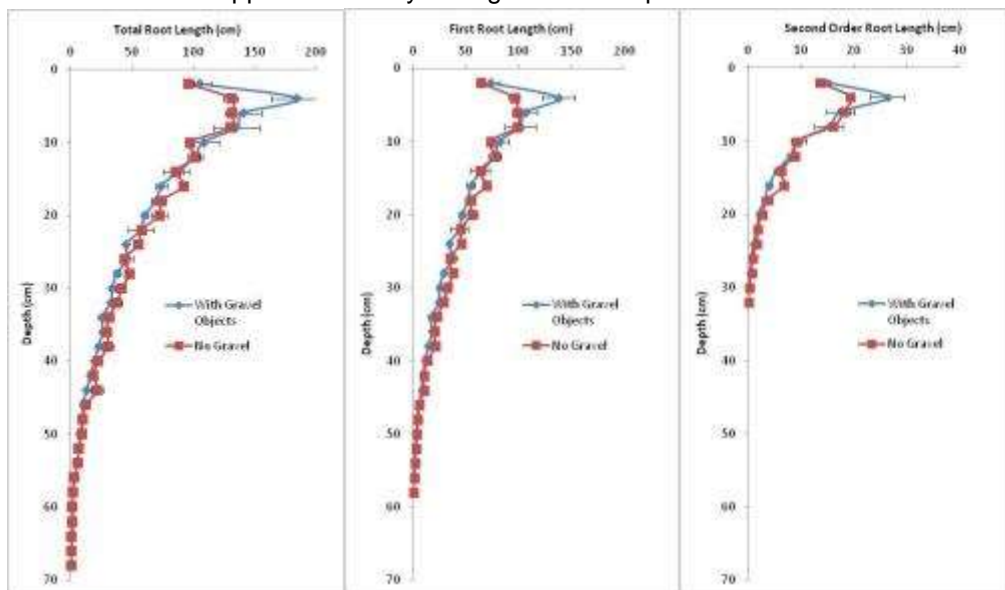


This suggests that crop root systems could respond to local restrictions in soil volume (as when gravel is present), by increasing root proliferation and root foraging for soil resources. Adequate soil resources do, however, need to be available before this response is of benefit, allowing the plant to compensate for the presence of gravel. The short simulation time and the adequate soil moisture meant that there was sufficient N & P availability in the surface layers for the root proliferation response in the gravel zone to be beneficial.

In the treatment in which the soil progressively dried over time, there was insufficient soil water content and nutrient availability for any increased root proliferation in the gravel zone to be of benefit, hence N&P uptake was reduced in the presence of gravel.

These simulations suggest that to compensate for the presence of gravel in soil, sufficient nutrient availability is needed early in the season when there is adequate soil moisture.

Figure 4. The effect of 8% gravel content on total root length (cm) through the soil profile.
c. Nutrient supplied uniformly through the whole profile



d. 8% gravel density in the gravel zone. Low N&P supply below 12 cm (below the gravel zone)

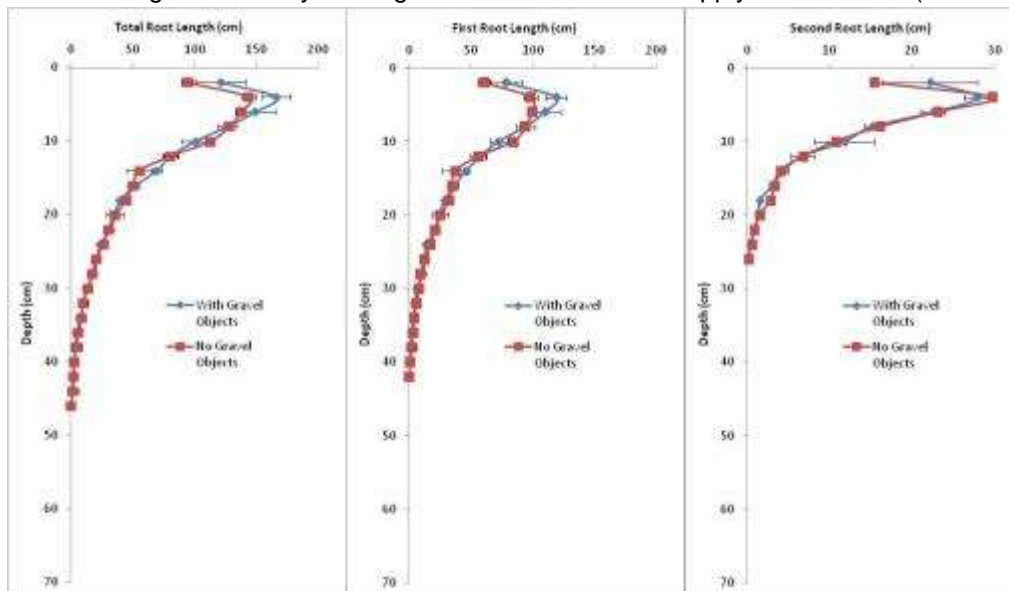
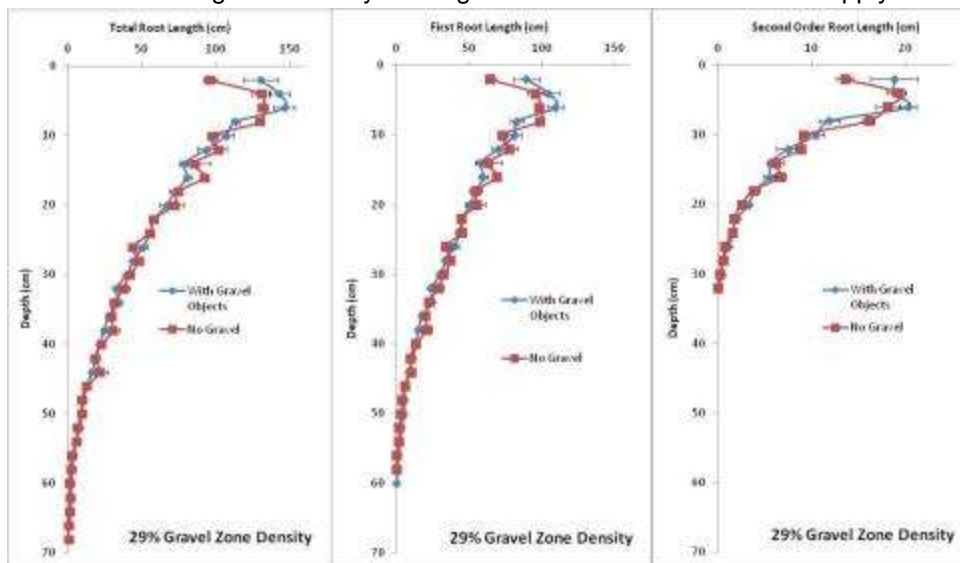
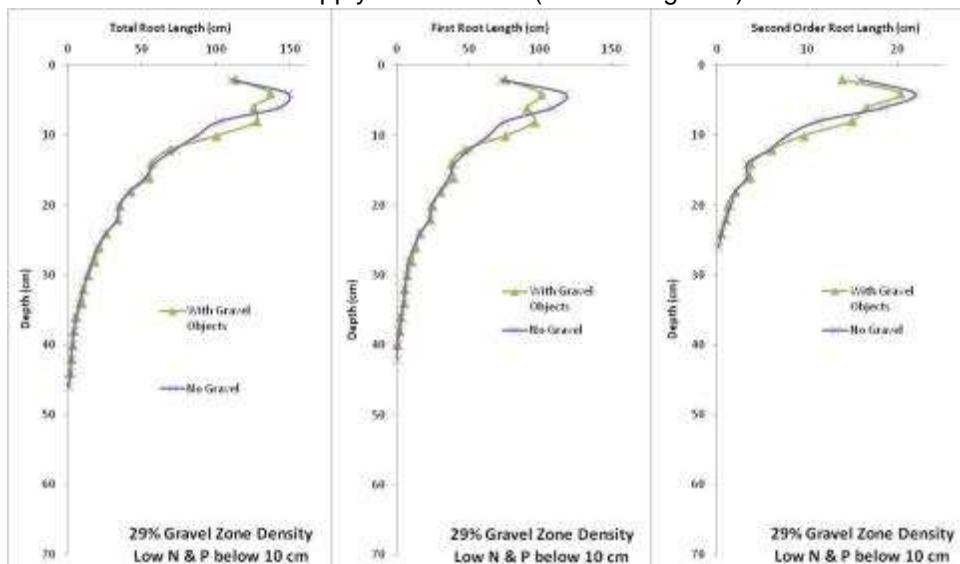


Figure 5. The effect of 29% gravel content on total root length (cm) through the soil profile.

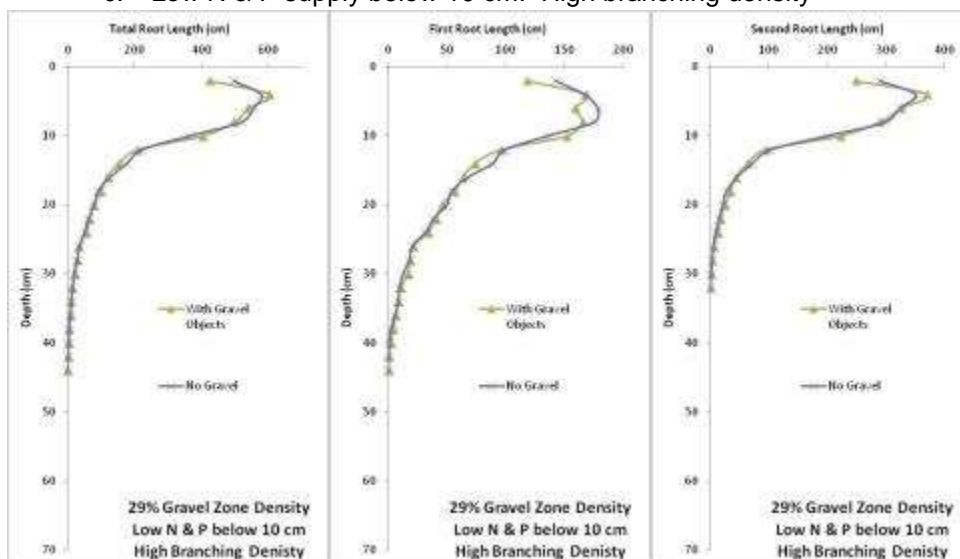
a. 29% gravel density in the gravel zone. Uniform nutrient supply.



b. Low N & P supply below 10 cm (below the gravel)



c. Low N & P supply below 10 cm. High branching density



d. Low N & P supply below 10 cm. Regular branching density, PBI increased to 80, simulation time increased to 35 days to enable sufficient growth given the lower P supply

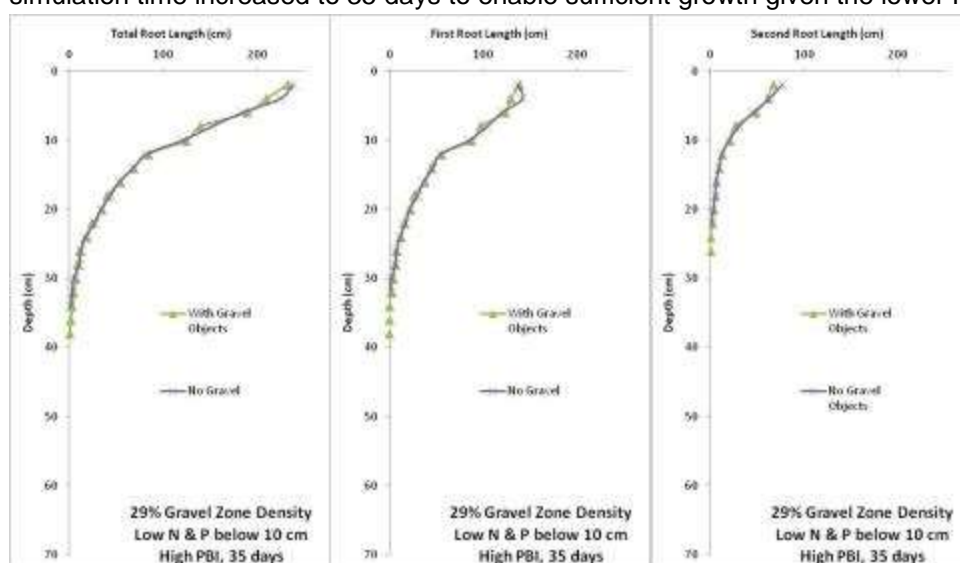
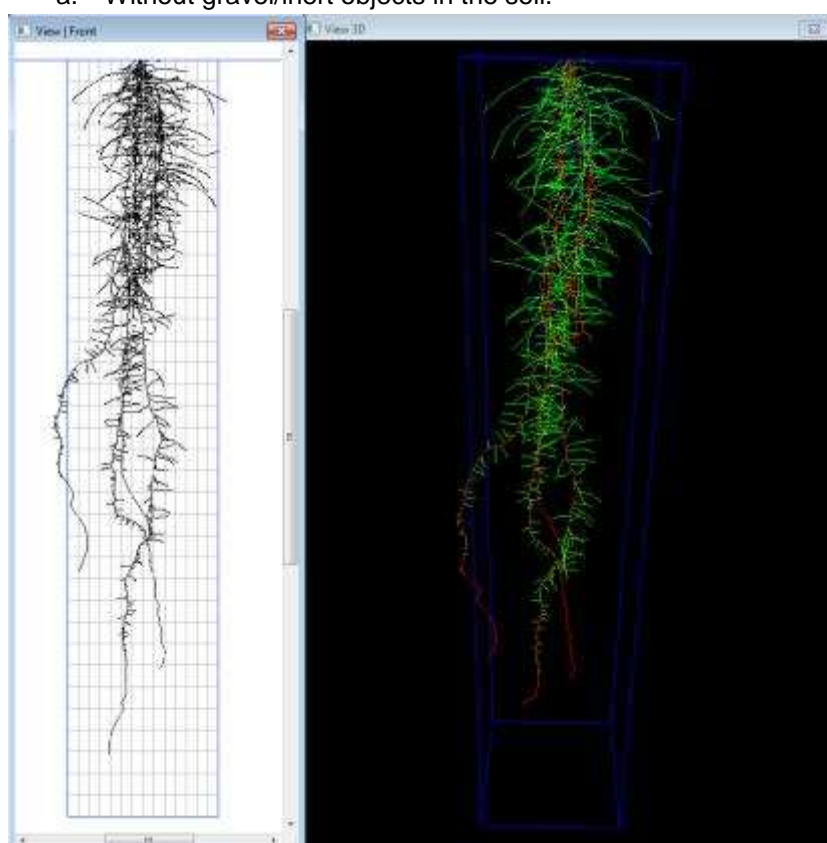
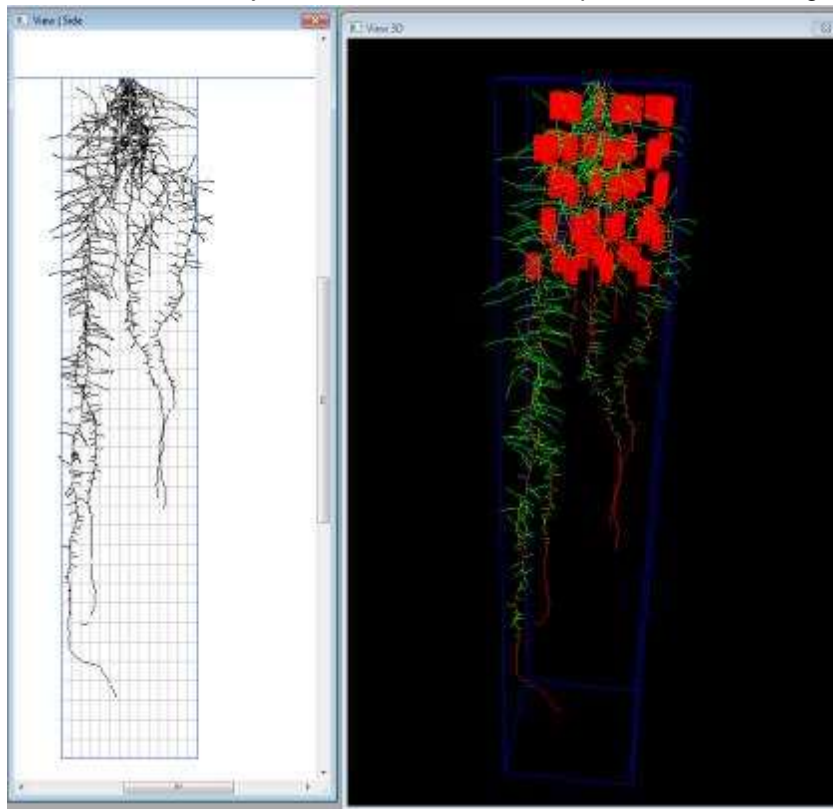


Figure 6. Graphical presentation of root architecture from Rootmap runs.
Wheat roots at 28 days, Total soil volume 14 cm x 14 cm x 70 cm
a. Without gravel/inert objects in the soil.



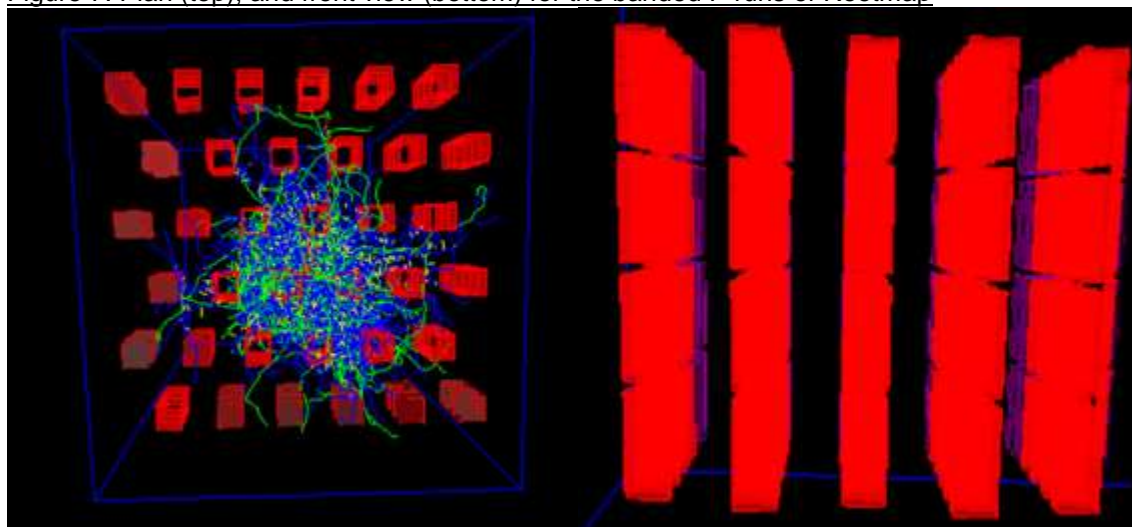
- b. With inert objects from 1 cm to 12 cm depth in the soil, 8% gravel density (v/v) in that zone.



Note that apart from a root axis which found the side of the container where there was no impediment to root penetration with inert objects, the gravel seems to have reduced the rate of root penetration to depth.

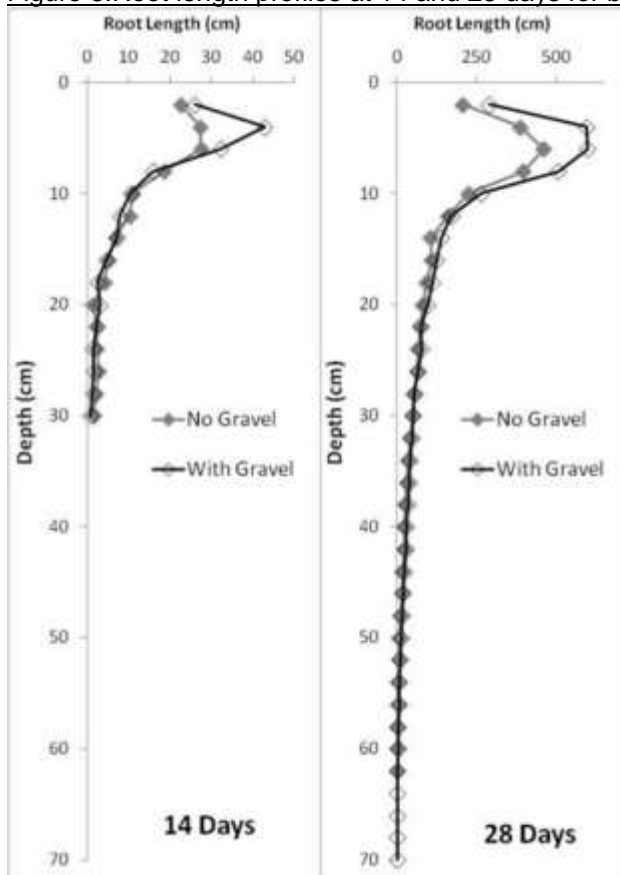
This finding is in contrast with the output from some runs with Rootmap to look at the effect of gravel on the uptake rates of P from a banded P source. The inert object arrangement was simplified (see Fig 7.) to an array of columns. Total Labile P = 13.3 $\mu\text{g/g}$ in a narrow 6 cm band, placed from a depth of 2cm to 8cm. Total Labile P = 2 $\mu\text{g/g}$ outside of this narrow band.

Figure 7. Plan (top), and front view (bottom) for the banded P runs of Rootmap



There is a distinct increase in root proliferation in the zone of the nutrient band at both 14 days and 28 days. By 28 days the plants growing in gravel have both increased root proliferation in the band zone (also gravel in that zone), and deeper rooting.

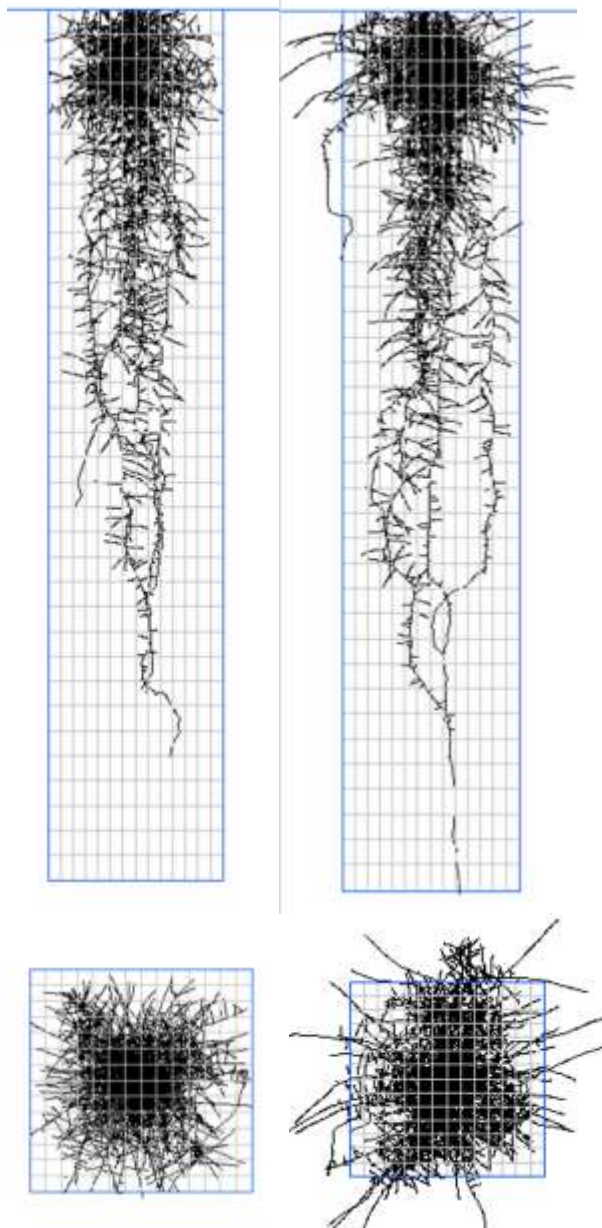
Figure 8. Root length profiles at 14 and 28 days for banded P with and without 8% gravel



By 28 days, the roots with 8% gravel are deeper and also are longer in the surface gravel layers.

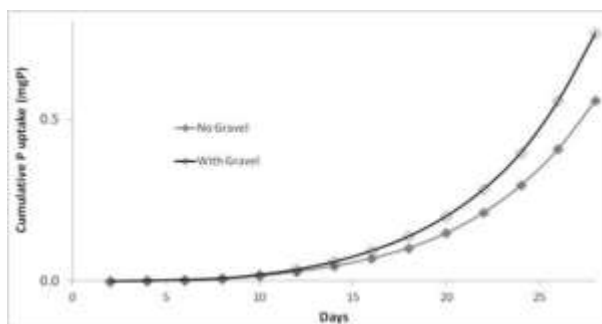
These results can be seen in visual maps: Fig. 8 below

Figure 8. Projections of root growth profiles from the side (top) and from above (bottom). With no inert objects (left) and with objects (right)



The dynamics of P uptake in this system are shown in Fig.9.

Figure 9. Phosphorus uptake for a soil with and without (inert columns) as a function of time.



In these simulations water was supplied at DUL over the whole 28 days, the gravel is only in the topsoil zone, and the plants are only grown until 28 days. Under these conditions the gravel stimulated root proliferation in the topsoil zone, enhancing N and P acquisition.

Conclusions

At 8% gravel greater root length and root length densities are induced in the gravel zone. At the 29% gravel level total root length is not increased, but root length density is increased by 30%. The amount of P at the same initial concentration is also reduced by 30% but P uptake remains the same. Which means that uptake efficiency as measured by the fraction of available P depleted, has risen by about 30 to 40% in the presence of 29% gravel.

How these nutrient uptake efficiencies change with level and distribution of gravel, level and placement of the nutrients, mobility and buffering capacity of the nutrient, the wetting and drying patterns of the soil, as well as the genetics of the cropping species and how this affects root architecture responses to gravel is open to question and further study. With more resources to contract programmers, all of these and other issues could and should be studied further, initially with the Rootmap model and then perhaps with direct observational and experimental work.

Appendix 4. Root growth responses to restricted soil volume – sowing density runs

By Vanessa Dunbabin

Gravel in soils restricts the rooting volume which should result in higher root densities. The increased and more rapid competition between roots for soil resources should cause roots to access non-depleted soil to the side and at depth, more rapidly. To examine this property the Rootmap model was used to examine the effect of root competition on the dynamics of root exploration by plants sown alone (low density – no competition) and close together in the row (high density –high competition).

Set Up

Uniform N & P & W contents and soil properties as follows:

PBI = 40

DUL = 0.12 v/v

WC = 0.12 v/v

LL/WP = 0.03 v/v

BD = 1.55 Mg/m³

N content = 5 µg/g

Total Labile P = 8 µg/g

No rainfall events during the simulation.

Simulation time = 28 days

Simulating increasing plant density:

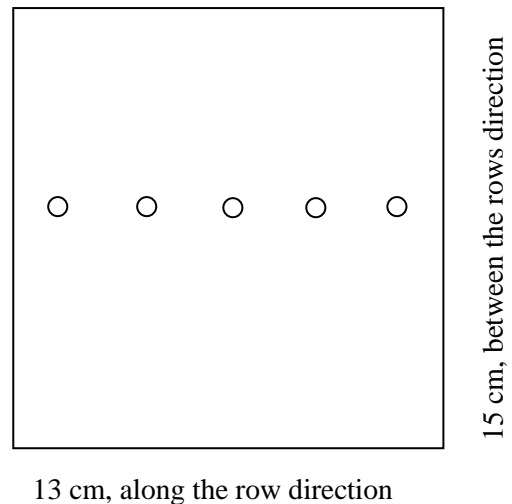
Bounded root box that is 13 cm x 15 cm x 90 cm.

1 plant = 50 plants/m²

5 plants = 256 plants/m²

All plants were simulated as unique individuals (not an array of the same plant).

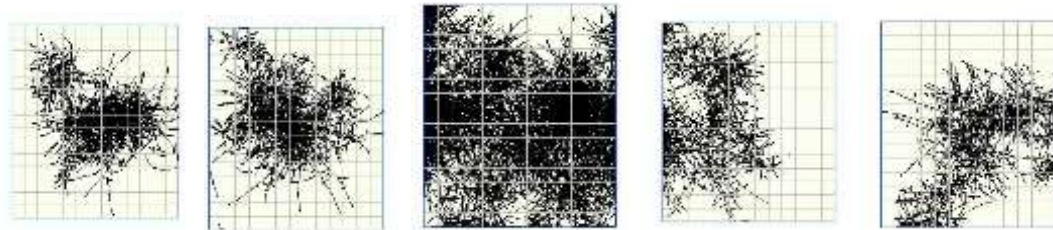
2 genotypes: Genotype 1, lower root proliferation response to soil N&P supply. Genotype 2, higher root proliferation response to soil N&P supply.



Results

1. Pictorial results of Rootmap runs of sowing density effects on root distributions

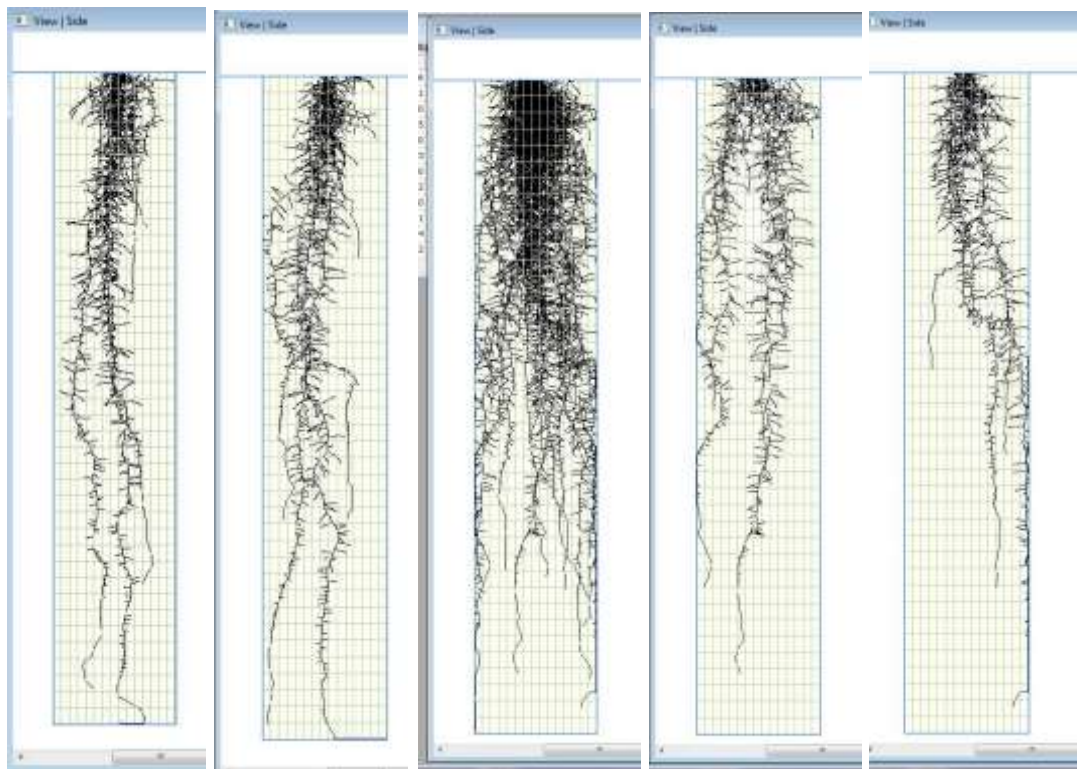
Figure 1. Plan view of root length projected into one plane. Section along the row on the horizontal axis and section across the row on the vertical axis



The central figure is an example of the root density with 5 plants present in 13 cm of row. The two figures on the left are examples of a single plant at low density (50plants/M²). The two on the right are examples of a single central plant (of the 5) at high density (256 plants/M²).

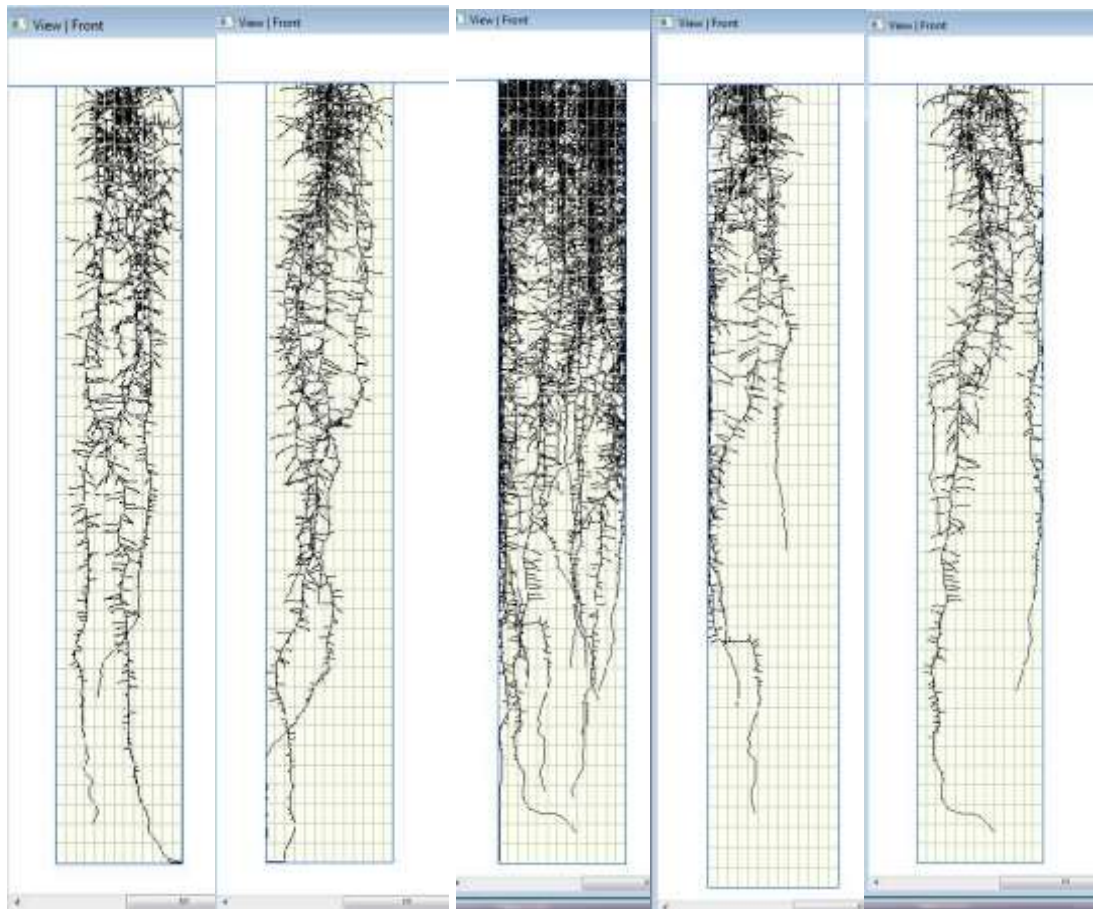
Clusters of high projected root densities reflect where root axes have followed vertical pathways, sometimes down the edge of the modelled box. The single plants (left) show far more symmetry in all directions than the individual plants (right) which grow in the array of 5 in the centre. The visually high density of roots in the central box reflects the high sowing density (about twice the usual wheat establishment densities) and the projection of all roots in the 90 cm profile depth into one plane.

Figure 2 Side view of root length projected into one plane showing the extent of proliferation into the inter row. Details of the layout are given below Fig. 1.above



If anything, the roots of the individual plants at high density (right) are shallower and spread more into the inter-row.

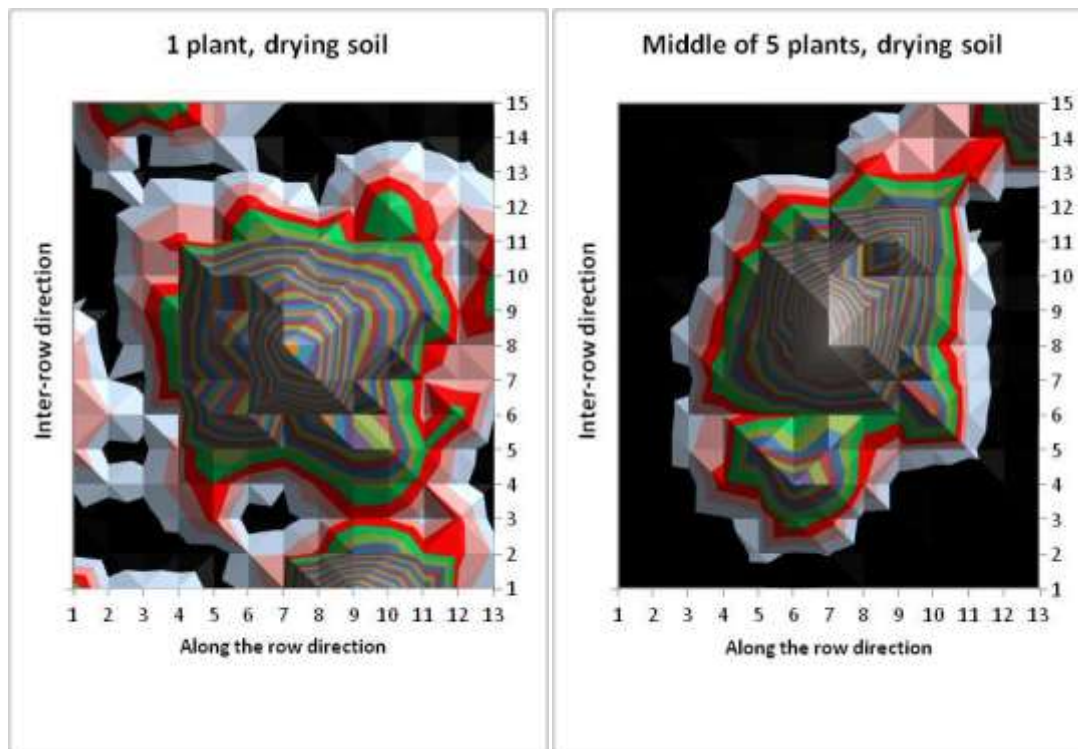
Figure 3 Front view of root length projected into one plane showing the extent of proliferation along the row. Details of the layout are given below Fig. 1.above



The roots of plants sown at high density (right) tend to proliferate less along the row than those sown without competition from neighbours (left). This view also shows that there is less root proliferation at depth for the individual plants sown at high density (right). However the sum of the root densities from the 5 plants at high density (central) means that those roots are exploring more of the soil at depth than the low density plants (left).

A summary of the root effects is given below (Fig 4.) in a 3D contour plot for the mean of the two individual plants at each of the low and high density sowings. As expected the rooting pattern for the single plants in 3D is symmetrical in all directions. At the higher density, the 3D plots lack symmetry in that more roots proliferate into the inter-row and less along the row

Figure 4. Total root length (cm) contour plot in excel, average of 2 reps, The black is the lowest contour (no roots - on the surface). The pictured row length is 13 cm, and the inter-row distance is 15 cm



On the left is one centrally placed plant. The root system is extending evenly in both the inter-row direction and along the row directions. No neighbouring plants are present to restrict growth in the direction along the row. On the right is the middle plant of 5 plants in the same space, the root system is extending further in the inter-row direction than along the row. Neighbouring plants are restricting growth in the direction along the row.

2. Numerical results of effects of plant density and water relations on root distributions

In this analysis remember that at the high plant density, the per plant information is multiplied by 5 to give the actual densities of roots. The question is, how analogous is this to restricting the soil volume with inert objects? Such restrictions will push up the density of roots per unit volume of soil and so give more complete exhaustion of soil resources in a unit time – just as in the dense planting exercise illustrated in this section. But will an individual plant have the same response to an increased root density created by itself, as do individual plants in a highly competitive situation with their neighbours?

With uniform N&P supply and the water content maintained at field capacity throughout the simulation, the total root length of each individual plant in the high density planting (256 plants/m²) was about 10% smaller than those in the low density planting (50 plants/m²). Most of this reduction in root length occurred in the surface soil layers (Fig. 5).

Figure 5. Total root length **per plant** (cm) with depth through the soil box. Two planting densities: high = 256 plants/m², low = 50 plants/m².

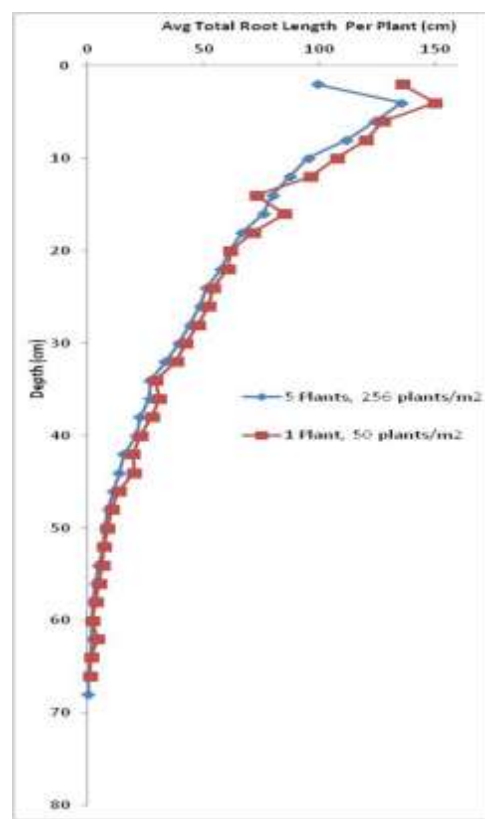
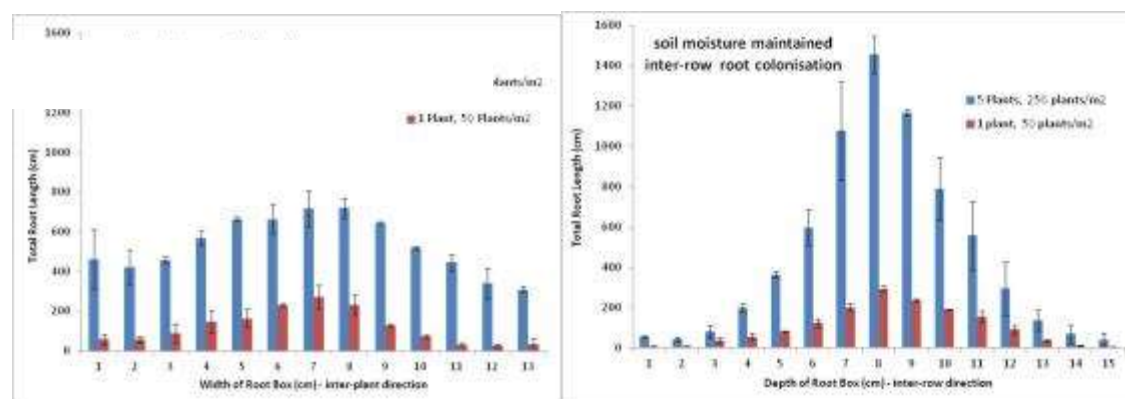
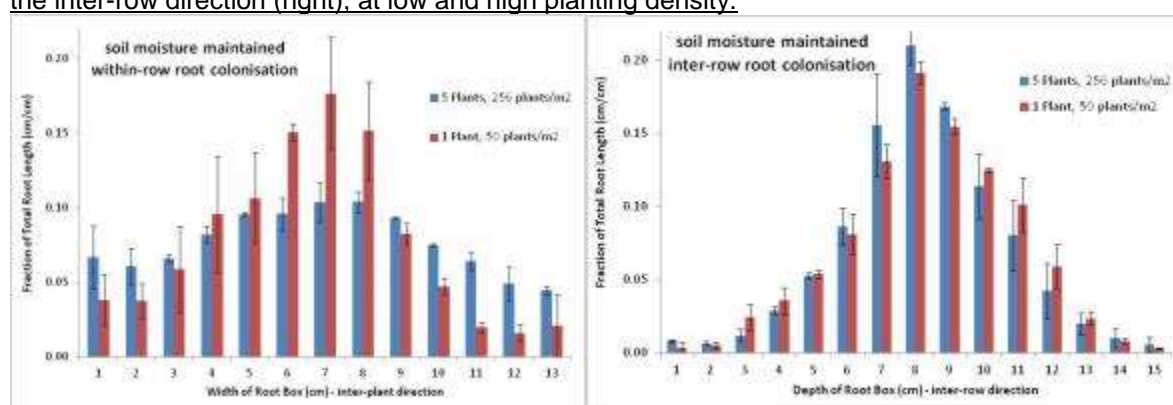


Figure 6. The distribution of the root length (cm) along the planting row (left) and between the rows (right) at low and high planting density. The row is centred in the middle of the chart.



With 5 plants in the root box there is a more even distribution of roots across the box (Fig. 5 left), than when there is only 1 plant in the centre of the box. With 5 plants, there is more root growth in the inter-row direction (Fig. 5 right) than along the rows (Fig. 5 left). There are 5 plants distributed along the 13 cm row direction, and 15 cm in the inter-row direction. This gives more space in the inter-row direction, hence greater root exploration in that dimension. When there is only 1 plant in the box the roots extend by the same amount in both directions.

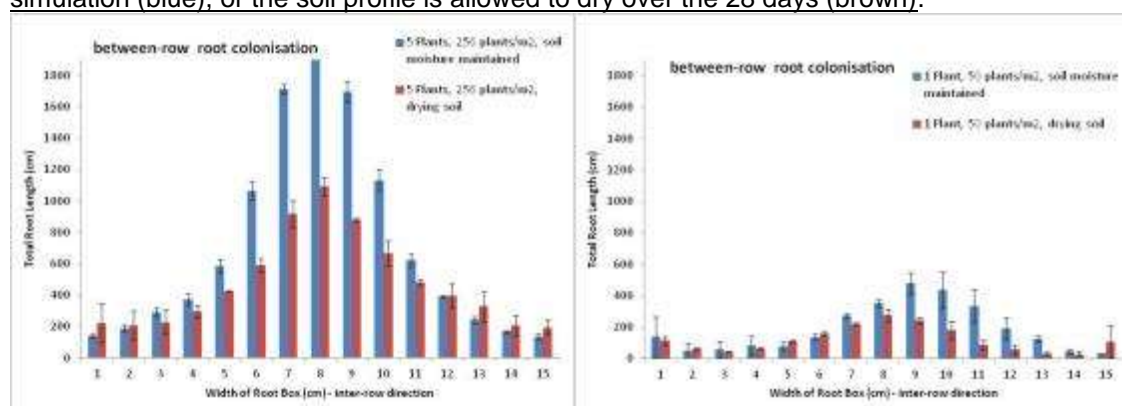
Figure 6. Normalised distribution of the root length (cm/cm) along the planting row (left) and in the inter-row direction (right), at low and high planting density.



The row is centred in the middle of the chart

These simulations are with genotype 1. The normalised root distributions scale is the ratio of the root length in a section to the total root length of the plant. This gives a sense of shifts in root distribution strategy between treatments. As expected Fig. 5 (left) shows that there are proportionally more roots in the centre of the row when there is 1 plant in the box compared to 5 plants. Obviously there is substantially more inter-row root colonisation with 5 plants present (Fig. 4), but Fig. 5 (right) suggests that each plant is investing the same proportion of its root architecture in the inter-row direction regardless of planting density.

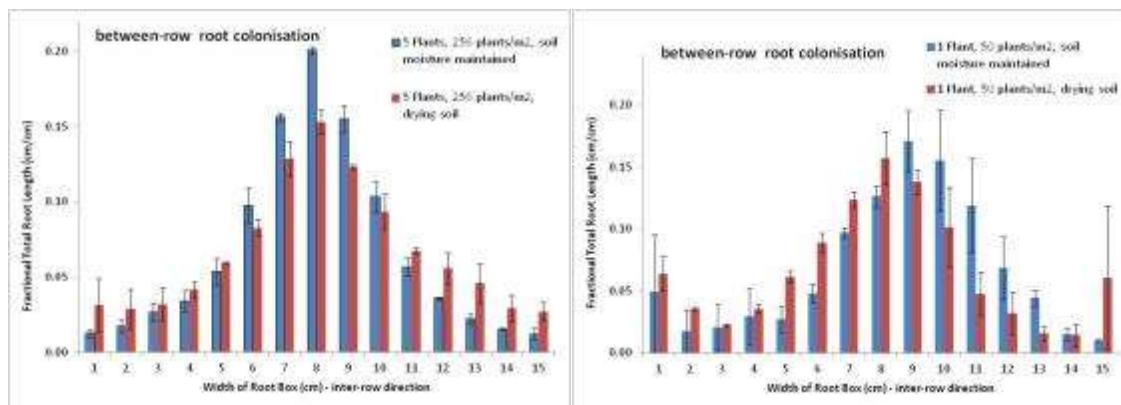
Figure 6. The distribution of the root length (cm) in the inter-row direction, at high planting density (left) and low planting density (right). Soil moisture is either maintained throughout the simulation (blue), or the soil profile is allowed to dry over the 28 days (brown).



The row is centred in the middle of the chart.

These simulations were run with Genotype 2 which has an increased root growth proliferation response to N&P supply in the soil. Treatments compare between a soil kept uniformly at field capacity, to a soil in which soil moisture declines over time. As would be expected, there was greater root growth in the moist soil. When soil water reduced over time, there was a reduction in root proliferation along the row (7-9 cm), but similar root growth out at the edges of the box, suggesting a greater relative investment in root proliferation in the areas of soil away from the centre of the row where there is less competition for soil moisture (see Fig. 5 below). Again, at high planting density there is greater root growth in the inter-row (Fig. 4a) than along the row (data not shown).

Figure 7. The normalised distribution of the root length (cm) in the inter-row direction, at high planting density (left) and low planting density (right). Soil moisture is either maintained throughout the simulation (blue), or the soil profile is allowed to dry over the 28 days (brown).



The row is centred in the middle of the chart.

As discussed above, Fig. 7 (left) shows a shift in the relative root distribution strategy in drying soil compared to soil maintained at field capacity (high planting density). In drying soil, there is a relatively greater investment in root length towards the edges of the plot where there is greater water availability. This shift in foraging strategy is less obvious at the low planting density (Fig. 7 right). These results suggest that when soil resources (space, water and nutrients) are scarce there will be a shift in root foraging strategy to compensate.

Conclusions

This study addressed the question, “do plants grown in the presence of gravel, send roots sideways and deeper more rapidly than plants grown in the same soil without gravel?” The effect of increasing root length density by increasing the crowding of plants in the row was used as an analogy for increasing root length density by growing a plant in a soil with gravel. Individual plants at high density did proliferate roots more rapidly into the inter-row but did not seem to send roots deeper, faster. The results depended on whether soil water was maintained at adequate levels or whether the water was depleted around the roots. This indicates yet another interaction which would confound attempts to determine the effect of gravel on the dynamics of water and nutrient uptake.

Further such studies with the Rootmap model could give a lot of insights into the role of gravel in soils for crop production and perhaps even for crop management.