MANIPULATING THE WATER BALANCE OF VEGETATION ON BAUXITE RESIDUE STORAGE AREAS

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Abstract

Maximising the water use of the vegetation cover of Alcoa's bauxite residue storage areas is critical to minimising the volumes of alkaline leachate requiring treatment after closure of the refineries. This study aimed to investigate if vegetation water use could be enhanced by the presence of a watertable, caused by preventing drainage from the surface layer of residue which forms the medium for plant growth. We varied drainage conditions to achieve different watertable depths within the residue, and measured the impact on vegetation water use and degree of water stress. We monitored residue water content and watertable depths to explain the measured plant responses.

We found that plant water use was limited by low water availability over summer. Even vegetation with a watertable within its root zone was unable to sustain high water use. The presence of a shallow watertable enhanced vegetation water use compared with vegetation growing over a deep or no watertable. We concluded that drainage volumes from residue storage areas could be reduced by restricting drainage from the surface layer, allowing the development of watertables to enhance vegetation water use.

1. Introduction

Understanding the water balance of residue storage areas is critical, since any water that is not used by vegetation can infiltrate the residue stack and leach alkaline material remaining in the residue. The resulting alkaline leachate will require treatment before release to the environment. The volumes of water requiring treatment at Alcoa's sites in Western Australia will depend on both the area covered by residue at each of the sites, and the water use of the vegetation established on these areas. Our aim is to maximise the water use from vegetation so that the volume requiring treatment is minimised. Unfortunately, vegetation water use is constrained by the mediterranean climate of south-western Australia. In winter months (May to August), vegetation is unlikely to capture all of the rainfall because of low rates of potential evaporation (2.7 mm/day), so drainage waters are likely be generated. Conversely, during the dry summer months, rates of potential evaporation are high (10.3 mm/day monthly mean in January), but vegetation water use is often limited by water stress once water stored in the root zone has been depleted.

In this study, we investigate the feasibility of restricting drainage from the surface capping layer to prevent drainage through the residue deposit, and to allow the development of a watertable in winter. The aim was to determine whether vegetation water use could be significantly enhanced in summer by accessing water from the watertable. The study formed part of broader study to investigate the effect of vegetation density and depth of the capping layer on the water balance of residue storage areas in Western Australia.

2. Methods

2.1 *Experimental site*

The experiment was carried out on 3 drainage lysimeters established at Alcoa's residue storage areas at Pinjarra, Western Australia in 1998. Each lysimeter is 30 × 30m square, and contains residue isolated from surrounding residue by a geomembrane liner. Two of the lysimeters are 2m deep, and the third extends to 3m. Drainage outlets are installed at the base of each lysimeter, and these outlets can be opened or closed to allow or prevent drainage. The dominant vegetation on the lysimeters is *Eucalyptus camaldulensis* at a density of approximately 3725 stems/ha (high density) on each of a 2m and 3m deep lysimeter. The density on the remaining 2 m lysimeter is 1333 stems/ha (low density). During the winter of 2001, the lysimeter with low density vegetation was allowed to drain freely, so no watertable could develop (referred to as the "drained" treatment). Drainage was prevented from the remaining lysimeters, allowing watertables to develop to approximately 0.5 m from the surface in the 2m lysimeter (named the "shallow" watertable treatment), and to approximately 1.5 m in the 3 m lysimeter (the "deep" watertable treatment).

The study period started in October 2001, when waterlogging was most severe in the undrained lysimeters. Measurements of the components of the water balance, and plant water status were repeated at approximately monthly intervals throughout the summer. Daily rainfall and pan evaporation data (used as an indicator of the potential evaporation) was collected at the site.

2.2 *Watertable depth*

Watertable levels were measured at monthly intervals in 3 shallow wells installed in each lysimeter. The depth to the watertable was calculated as the mean of the 3 measurements made in each lysimeter.

2.3 *Water content of residue in the unsaturated zone*

Residue water content was measured at 3 access tubes in each lysimeter, using a calibrated neutron water meter. Measurements were taken at 0.2m intervals throughout the entire depth of the residue profile (2.0 and 3.0 m for the shallow and deep lysimeters, respectively). The depth of residue lying above the watertable constitutes the unsaturated zone in each lysimeter. Integrating water content over this depth of residue enables comparison of the total amount of water held in the unsaturated residue. At each measurement position, water contents to the depth of the

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watertable were summed to give the total water content in the unsaturated zone. This zone extends over the entire depth of the drained lysimeter.

2.4 *Transpiration rate of vegetation*

The transpiration rate of 4 trees on each lysimeter was measured using sap flow sensors. The sensors rely on the heat pulse method, based on the technique of Marshall (1958) and refined by Swanson and Whitfield (1981). The technique measures flow velocity in the conducting tissue of the selected trees, and the electronic measuring and data -logging device is automated so that frequent measurements of transpiration are possible. Measurements of flux were made every 30 minutes, and 24-hour totals were calculated by summing the transpiration for each 30 minute interval.

2.5 *Plant water status*

Predawn and midday leaf water potentials were measured at approximately monthly intervals over the summer, as indicators of the water status (degree of water stress) of vegetation on the lysimeters. A pressure bomb was used to measure the water potential of 4 leaves, taken from the trees instrumented with heat pulse devices on each lysimeter.

2.6 *Tree leaf area*

The total leaf area of each of the 12 trees instrumented with sap flow devices was estimated on November 7, 2001. The Adelaide technique, described in Carbon et al., 1979, was used to estimate the leaf area of each of the trees. The technique involves identifying representative sections or “modules” of similar leaf area, and counting the number of modules on each of the study trees. Four similar modules were sampled from other trees on the lysimeters without heat pulse equipment. These modules were returned to the laboratory, and their leaf area determined on a planimeter. Total leaf area for each tree was then estimated by multiplying the mean leaf area of a module by the number of modules counted on the tree.

3. Results

3.1 *Climatic conditions*

The climatic conditions experienced at the site over the study period are shown in Table 1.

The high rates of pan evaporation and low rainfall over summer months reflect the hot, dry summers characteristic of the mediterranean–type climate of south-west Western Australia. In none of the months did the total rainfall exceed the total potential evaporation, indicating water deficit conditions in every month. Total rainfall over the study period from 16th October 2001 to 9th May 2002 was 200 mm.

3.2 *Watertable levels*

Depth to the watertable may influence the relative accessibility of the water to vegetation in each of the lysimeters. Figure 1 shows the watertable levels throughout the study period in the 2 undrained lysimeters.

In October, at the beginning of the study, watertable levels were 0.44 and 1.54 m in the shallow and deep treatments, respectively. Watertable depths increased progressively with time, reaching maximum depths of 0.93 and 1.76 m in April in the shallow and deep treatments, respectively. The lowering of the watertable was most rapid in the shallow treatment, where a reduction of 0.49 m occurred over the summer months between October and April. The watertable level in the deep treatment decreased by only 0.22 m over the same period.

Table 1. Monthly rainfall and Pan evaporation measured over the study period at the Pinjarra site

	Total rainfall (mm)	Pan evaporation rate (mm/day)	Monthly total pan evaporation (mm)
October	28.9	4.6	141
November	33.6	7.7	232
December	12.4	7.9	245
January	12.2	9.5	295
February	0.0	8.9	248
March	5.2	6.8	210
April	53.9	4.6	137

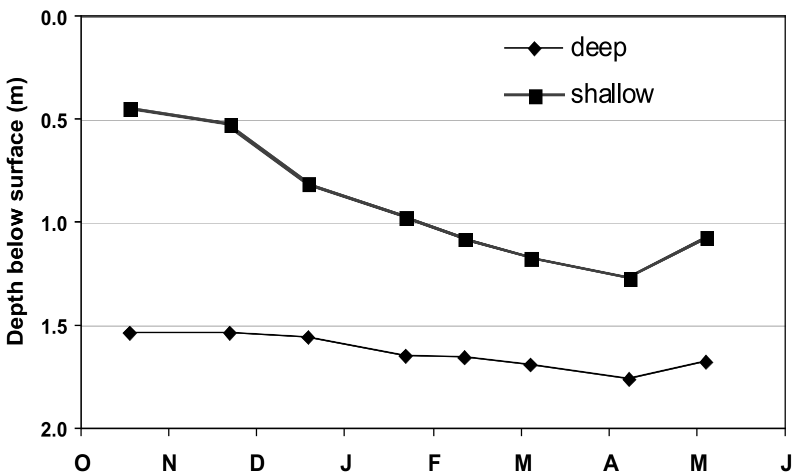

Figure 1 — Depth to the watertable measured in the shallow and deep lysimeters over the study period from October 2001 to May 2002

3.3 *Water content in the unsaturated zone*

Restricting drainage from 2 of the lysimeters over winter to allow the development of watertables, caused differences between treatments in the amount of water held in the unsaturated zone (Figure 2). At the start of the study in October, there was more water in the unsaturated zone of the drained lysimeter than from both the lysimeters with watertables (Figure 2). This was a reflection of the greater depth of unsaturated residue in the drained lysimeter.

The amount of water held in unsaturated layers of the shallow and deep treatments was similar, despite the greater depth of unsaturated residue above the deep (1.54 m) compared with the shallow (0.44 m) watertable (Figure 1). Throughout summer, water was progressively depleted from the unsaturated zone in all lysimeters, and the water contents in all treatments reached their lowest values in April 2002. Water uptake was more rapid from the unsaturated zone above the shallow watertable than from the other lysimeters. The total depletion from the unsaturated zone over the summer period between October and April was greater from the shallow treatment than from both the deep and undrained treatments.

3.4 *Plant water status*

Despite differences in watertable depth and unsaturated water contents in each of the lysimeters, predawn leaf water potentials were similar in all treatments at the start of the study in October, indicating a similar plant water status (Figure 3). On this day, the level of water stress was minimal in all treatments because of the spring conditions of high water availability and low potential evaporation.

Predawn leaf water potentials decreased with time in all treatments over summer as the trees became increasingly stressed in response to the hot and dry conditions. Vegetation over the shallow watertable was consistently less stressed than vegetation on both other lysimeters from January through to April. The greater level of stress on the drained compared with the shallow lysimeter was significant for all these measurements. Vegetation over the deep watertable was significantly more stressed than vegetation

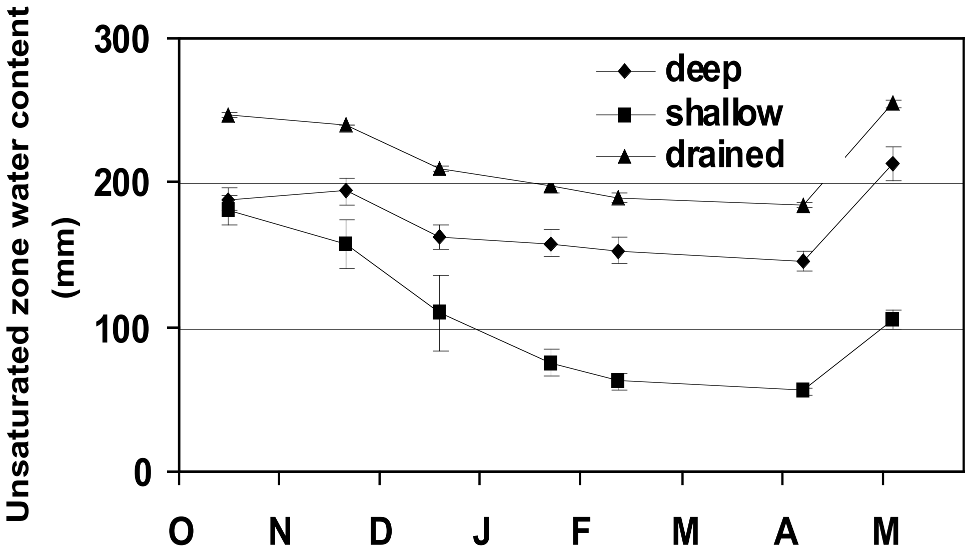

Figure 2 — Total water content in the unsaturated zone measured by neutron water meter in the shallow, deep and drained lysimeters over the study period from October 2001 to May 2002.

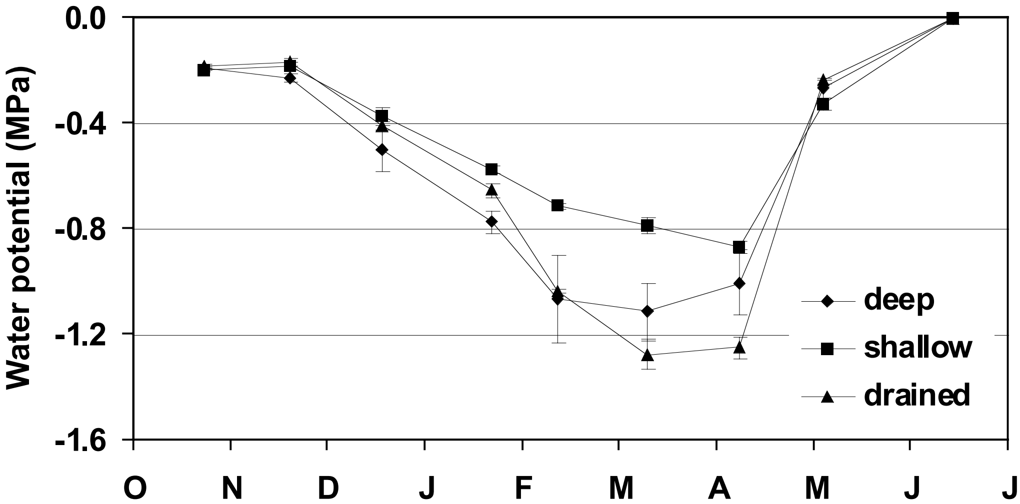

Figure 3 — Predawn leaf water potentials of trees on each of the deep, shallow, and drained lysimeters measured using a pressure chamber over the study period from October 2001 to May 2002.

over the shallow one for the January and March measurements only. There was no significant difference between the degree of stress of vegetation on the deep or drained lysimeters for any of the measurements. Autumn rainfall and cooler conditions in May brought relief from water stress in all treatments. Trends in midday leaf water potential were similar to the trends in predawn potential for all treatments throughout the study period (data not shown).

3.5 *Transpiration rates*

Mean daily transpiration rate for vegetation on each of the three lysimeters showed responses to changing climatic conditions both on a daily and on a seasonal basis (Figure 4).

Daily peaks and troughs in the transpiration data reflect day to day variation in potential evaporation and rainfall conditions. For example, low values for transpiration measured for all treatments on October 21 reflect rainy and overcast conditions. On this day the pan evaporation rate was low (1.2 mm/day) compared with the mean monthly average rate of 4.6 mm/day (Table 1), and a total rainfall of 18 mm was recorded. Transpiration rates also responded to the dry summer conditions, as a general trend of decreasing transpiration can be observed from December through to March. Some recovery in transpiration rates occurred following the 53.9 mm of rainfall recorded in April.

Figure 4 also shows differences in transpiration rates between the three treatments. Transpiration from vegetation over the deep watertable was generally the lowest throughout the study period. Transpiration was generally highest from the drained treatment from the start of the study to December, and following relief of the summer drought in April. However, throughout most of the driest months of February and March, transpiration was highest from vegetation over the shallow watertable.

The greater transpiration rates from vegetation on the drained treatment are a reflection of the greater leaf area of individual trees compared with trees on the other lysimeters. The mean leaf area of trees on the drained lysimeter containing the heat pulse equipment was 1.45 m^2, significantly greater than trees on the deep and shallow treatment which were 1.09 and 0.98 m^2 , respectively. The greater leaf area of trees on the drained treatment is probably a response to the lower density of trees compared with the other 2 lysimeters (Eastham et al., 1990). The trees were at similar densities on the lysimeters with shallow and deep watertables, and their leaf areas were not significantly different.

The transpiration rate of each tree was normalised by dividing by its leaf area, so that the response in transpiration to the different treatments applied to the lysimeters could be compared (Figure 5).

The normalised transpiration rate of trees on the deep and drained lysimeters were similar throughout the study period, suggesting that differences in their transpiration rate shown in Figure 4 were solely a function of their differing leaf areas. However, the normalised transpiration rates of trees above the shallow watertable were greater than the rates of both other treatments. These differences in normalised transpiration of trees over the shallow watertable and trees from the other treatments was greatest under the hot, dry conditions from December through to April, and smallest under the wetter, cooler conditions in October, November and April (Table 1).

4. Discussion

4.1 *The influence of watertable depth on water stress and transpiration*

The declining levels of transpiration, and increasing levels of stress observed over the study period as hot, dry conditions persisted, indicate that water availability limited the water use of all the treatments, irrespective of the presence or absence of a watertable. However, the lowering of watertables observed in both the shallow and deep lysimeters throughout the dry summer (Figure 1) suggest that trees on both lysimeters are able to access water from the saturated zone, or its capillary fringe, to support their water use. The more rapid lowering of the shallow compared with the deep watertable (Figure 1) suggests that the vegetation is better able to access water from a shallow watertable. As a result, the degree of water stress experienced over summer by trees with access to the shallow watertable was moderated compared with trees over the deeper or no watertable (Figure 3). Vegetation on the shallow lysimeter could also access water more readily from the unsaturated zone than vegetation on the other lysimeters with deeper, drier unsaturated profiles (Figure 2). As a result of the greater water availability and lower degree of water stress, trees over the shallow watertable were able to maintain greater normalised transpiration rates over the dry summer than trees on other treatments (Figure 5). In contrast, both the pre-dawn leaf

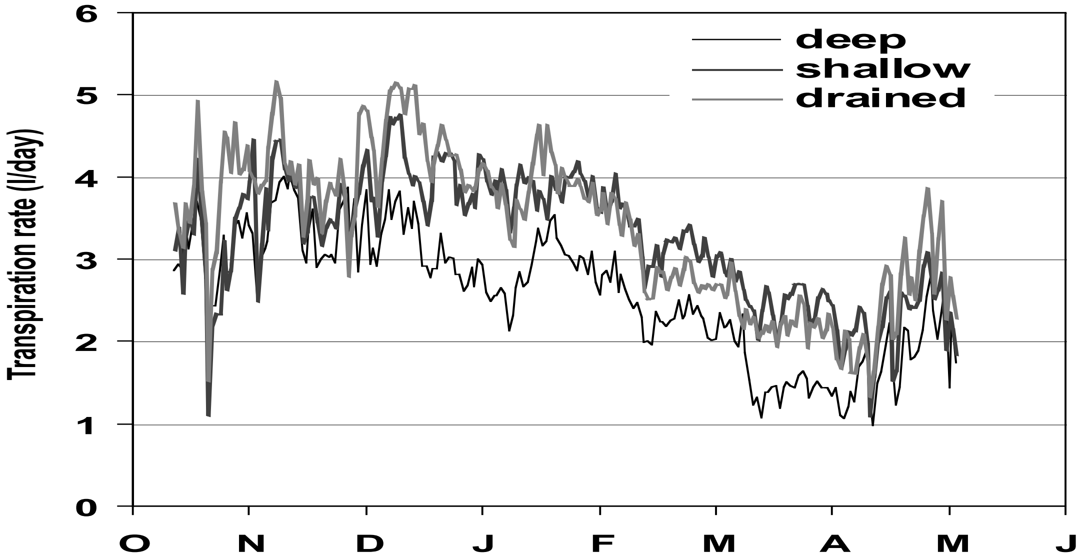

Figure 4 — Mean daily transpiration rates measured for trees on each of the deep, shallow, and drained lysimeters using sapflow sensors over the study period from October 2001 to May 2002.

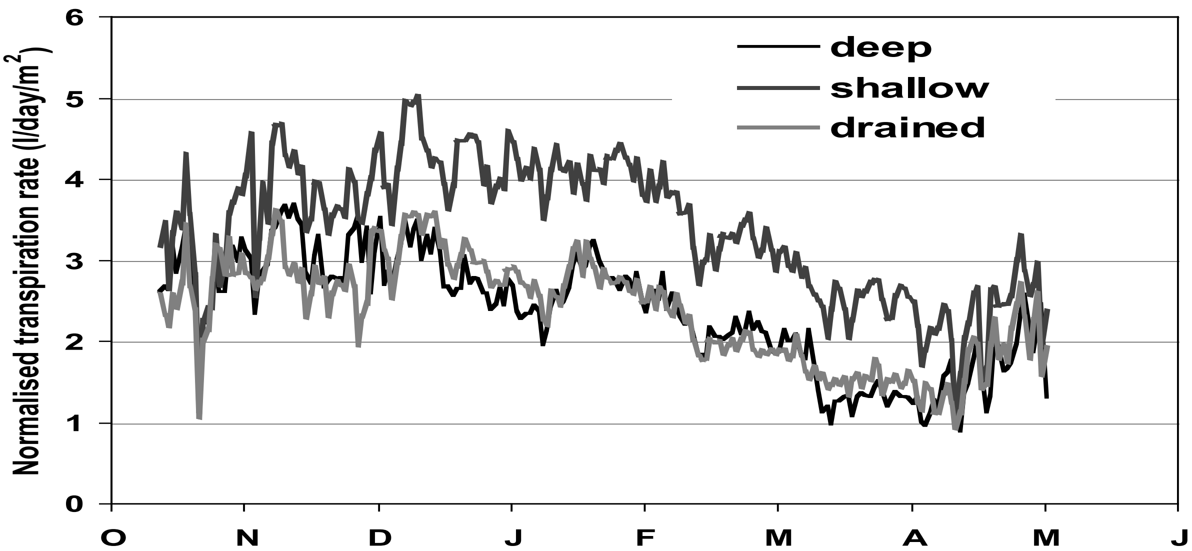

Figure 5. Mean transpiration rate normalised for the leaf area of each tree measured on the deep, shallow, and drained lysimeters over the study period from October 2001 to May 2002

water potentials (Figure 3) and normalised transpiration rates (Figure 5) of trees growing over the deep watertable were similar to those of trees growing on the drained lysimeter. This suggests that the presence of a watertable at 1.54 m in the deep treatment did not confer an advantage to the overlying vegetation. However, the comparison between these 2 treatments is complicated by the lower density of vegetation on the drained lysimeter. This results in a greater volume of water being accessible by individual trees from the unsaturated zone on the drained lysimeter, because of less competition from neighbouring plants. However, since trees growing over the deep watertable were able to access water from the deep watertable (or its capillary fringe), we can hypothesise that trees over a deep watertable would have lower stress levels and greater transpiration rates than trees at a similar density on drained residue.

4.2 *The importance of root distribution in watertable accessibility*

Clearly, the presence of a shallow watertable confers a greater advantage than a deep one to the water status and transpiration of the young vegetation growing on the lysimeters (Figures 3 and 5). The uptake of water from deep horizons, and its transport through the root system to the surface is disadvantaged by the lower gravitational potential of water held at depth compared with water in surface horizons. This factor alone could cause lower expected rates of uptake from deeper water sources. However, the accessibility of water from watertables will also depend on the rooting depth, and the density and distribution of roots throughout the residue profile. Although the roots of the young trees extend to a depth of 1.8 m in the lysimeters, approximately 95 % of the total root length, lies in the upper 0.6 m of the residue profile (data not shown). Root densities at depth are very low compared with surface horizons. For example, the root length density of the horizons overlying the shallow and deep watertables were 2354 and 722 m/m^3, respectively. Both of these values are below the density of 10,000-20,000 m/m^3, which Bowen (1985) suggests is sufficient for rapid water uptake in most soils, based on theoretical and experimental observations. Whilst we may expect that low root density is less critical for water uptake from soils close to saturation, the root densities above the deep watertable are almost 2 orders of magnitude less than Bowen's figure. Thus low rates of uptake from the deep watertable almost certainly result from inadequate root length.

Mature vegetation growing on bauxite residue storage areas may be better able to access deep watertables if it is deeper rooted, and has greater root densities at depth than the young trees (3 years old) growing on residue in this study. Quantitative studies on the rooting patterns of mature vegetation on Alcoa's bauxite residue storage areas in Western Australia have not been carried out. However, numerous qualitative studies have concluded that root development of older vegetation is constrained by the high pH and/or high levels of compaction of the residue, so that root densities are very low below 1.0 m depth (Cronin, 1995; Gianatti, 1997; Croker,1999). Thus it is unlikely that mature vegetation on residue areas built using the current practice will be able to readily exploit water from deep watertables.

5. Conclusions

- The water use of vegetation growing on residue areas can be enhanced by the presence of a watertable accessible to plant roots. This suggests that there is scope to build residue storage areas so that the depth of the capping layer and drainage conditions can be designed to optimise plant water use by vegetation and to minimise the generation of drainage water requiring treatment.
- Careful analysis of the water balance of residue areas will be required to determine the optimum depth and drainage condition of the capping layer to give the best result. This is because annual variability in rainfall and evaporation will influence the depth of the watertable generated from year to year.
- A more robust result in terms of consistency of minimising drainage generation from year to year is likely to be achieved if residue management practices more conducive to root development can be identified and adopted. Greater root densities throughout the profile of the capping layer would ensure that the watertable is accessible to plants, regardless of the seasonal climatic conditions and resulting depth of the watertable.

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