Waterlogging: a hidden constraint to crop and pasture production in southern regions of Australia

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Abstract

This paper reviews what is known about waterlogging in southern regions of Australia, with an emphasis on Western Australia. The extent and hydrology (including drainage) of waterlogging in Western Australia is relatively well known. Also there have been a number of laboratory and glasshouse experiments on the effects of waterlogging and low root 02 concentrations on growth, survival and metabolism of plants. There have been few field measurements of the effect of waterlogging on cereals and almost none on pastures. We acknowledge that laboratory and glasshouse experiments have only a limited ability to simulate field conditions.

The field data that are available show that waterlogging has a major effect on both crop and pasture production but the effect may vary considerably. This reflects the many interactions that may occur between waterlogging and other factors affecting plant growth (e.g. salinity, nutrition, temperature, flooding) and the time of the waterlogging relative to the growth stage of the plant.

In Western Australia there is an urgent need to carry out agronomic research on crops including: trials on varieties, seeding rate, time of planting, levels of nutrition and pest control such has been carried out in Victoria. There is also a need to examine the performance of mixed pasture stands subject to waterlogging and to develop recommendations regarding varieties, nutrition and grazing practices. An integrated effort is required to address the waterlogging problem.

Introduction

Waterlogging is probably one of the most important factors limiting the growth of crops and pasture in the high rainfall regions (>500 mm per annum) of southern Australia. In these areas, crops and pastures are presently achieving a fraction of their potential yield (17, 40). We believe that the exten of damage due to waterlogging is underestimated since waterlogging is a condition (see Definitions of Terms) which is not necessarily apparent at the soil surface.

Studies of plant responses to waterlogging are particularly appropriate since (a) there is economic pressure for farmers to increase production from areas susceptible to waterlogging, and (b) it is likely that more intensive land use will further decrease the structure of topsoils and subsoils, increasing the extent and intensity of waterlogging.

This paper briefly reviews what is known about waterlogging and its effects on crop and pasture production in southern regions of Australia. The examples that are used are mainly from Western Australia, which reflects the background of the authors. However, we believe that waterlogging is also a major problem on many of the duplex (texture contrast) and heavy clay soils in other states and has not been given sufficient recognition to date.

Definitions of terms

Waterlogging is a soil condition whereby excess water in the root zone inhibits gas exchange with the atmosphere.

Flooding is a condition in which free standing water occurs above the soil surface. Waterlogging usually coincides with flooding but many waterlogged areas are not flooded.

SEW30 (daily sum of excess watertable rise within 30 cm of the soil surface) is an index of waterlogging intensity and duration in the field.

Waterlogging tolerance. A plant species or tissue which grows or survives in waterlogged soils is one which shows waterlogging tolerance.

Interceptor drains are drains constructed across a hillslope to intercept subsurface water flowing down the slope. Most of the drainage effect occurs downslope of the drain.

Relief drains are drains constructed down a slope such that they receive water from both sides and have a drainage effect about equal on both sides of the drain.

Causes of waterlogging

The water responsible for waterlogging can come from water infiltrating *in situ,* from runoff, from interflow, from deep groundwater seepage and from irrigation. It is often not easy to quantify the source(s) of the water that cause a waterlogging problem. However for management purposes it is essential to know the source(s) (25).

The susceptibility of a soil to waterlogging depends principally upon its water storage and transmission properties. The water storage properties of several types of soil profiles have been simulated (20). Sand over clay soils were found to accumulate water in the profile due to the high infiltration and low evaporation properties of the sandy topsoil and the inhibited drainage of the clayey subsoil. The simulation ignored lateral water flows which can increase or decrease waterlogging depending on where the soil is in the landscape.

In Western Australia waterlogging in sloping duplex soil is negatively correlated with the saturated hydraulic conductivity of the A2 and B soil horizons, with topsoil thickness and with slope, while it is positively correlated with slope length (12). Low hydraulic conductivities in the A2 horizon ($<10^{-5}$ m/s) and low slopes (<2%) reduce lateral drainage while long slope lengths (>50 m) allow interflow waters to collect in zones of convergent flow.

The spatial distribution of waterlogging in Western Australia is very variable due to the high variability of the soil properties (particularly the permeability of the B horizon). A rise in the watertable within 30 cm of the soil surface commenced in many duplex soils when rainfall exceeded potential evaporation by as little as 50 mm after the break of the season (12). Once soil profiles are wet, small additions of water can result in a rapid rise in the watertable (Figure 1).

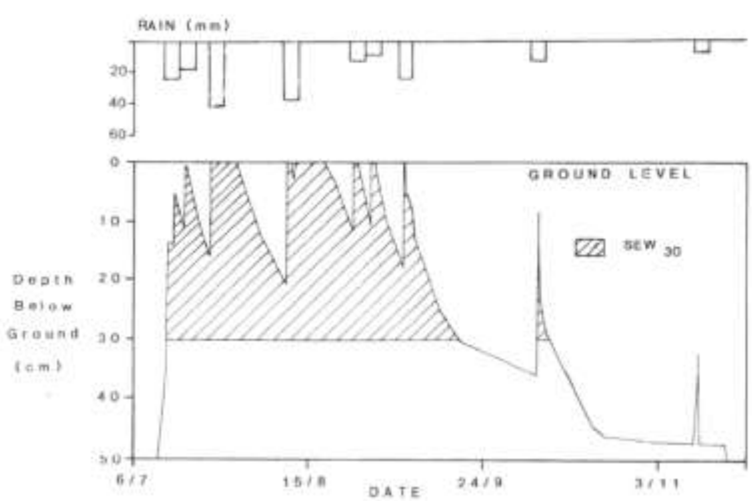

Figure 1. Perched groundwater levels in relation to time of year and rainfall; Narrogin 1987.

The location of waterlogged areas in a landscape can be predicted once topographic contours and soil properties are known (28). This is possible due to advances in digital terrain analysis on computers. While the method is a research tool at present, the increased amount of soil and topographic contour data on geographic information systems is likely to make this technique a practical tool in the near future.

Extent and economic importance of waterlogging

Measurements used to assess waterlogging

Common methods of assessing waterlogging are briefly described because the estimation of the extent of waterlogging depends on the methods used.

Air filled porosity: Wesseling and van Wijk (39) considered that soils were waterlogged if they had less than 10% air-filled porosity due to the presence of water. However, under this definition severely compacted soils would be classified as waterlogged even with little water present.

SEW30: After a review of drainage experiments in The Netherlands, Sieben (36) considered that crop yields were adversely affected when the watertable was within 30 cm of the soil surface. He introduced the term SEW30 (i.e. the sum of excess watertable rise above 30 cm) as a measure of waterlogging intensity. The SEW30 is the sum of all daily values (in cm) by which watertables are closer than 30 cm to the soil surface (units of cm.days, Figure 1). Hence if the watertable was 20 cm below the soil surface for 7 days, then at the soil surface for 2 days and afterwards more than 30 cm from the soil surface:

SEW30 = (10 x 7) + (30 x 2) = 130 cm.days

The SEW30 index assumes that the waterlogging intensity increases linearly with watertable rise above 30 cm.

There may not be a constant relationship between air-filled porosity and SEWN. In loamy soils with a structure which inhibits gas movement (e.g. an absence of long and continuous pores), it is possible to get different air-filled porosities for the same perched water levels in the profile (24).

Remote sensing: Waterlogged cereals are usually yellow or brown which suggests that coloured aerial photographs could be used to map the extent of the problem. However, there are many other crop conditions which produce the same colours. An examination of the spectra of waterlogged and non waterlogged wheat and oat crops (using a portable field spectroradiometer) showed that there is poor discrimination in the visible part of the spectrum but very good discrimination in the near infrared (27). The best discrimination using airborne multispectral scanning and Landsat TM was in the near and thermal infrared (27).

Soil and landforms susceptible to waterlogging

Waterlogging is not confined to low lying areas. For example, in Western Australia about 60% of the eastern Murray River Catchment area (1630 km^2) had a perched watertable within 30 cm of the soil surface at least once during both 1987 and 1988 (27). About three quarters of the catchment area consists of sloping duplex soils, and over 60% of these soils (approx. 440 km^2) had watertables within 30 cm of the soil surface at some time in both 1987 and 1988. Interceptor drains are effective in this landform for alleviating waterlogging. Waterlogging intensities in 1987 were up to 600 cm.days. The most susceptible landform to waterlogging was the floodplain areas around major rivers where over 90% had watertables within 30 cm of the soil surface at some time in both 1987 and 1988; drainage is very difficult in this landform due to low slopes.

Value of lost production due to waterlogging

The effect of monthly rainfall on final crop yields was examined for 162 farms in the central Upper Great Southern region of Western Australia (27). There was a strong positive correlation between yield and April and May rainfall, and a strong negative correlation with June and August rainfall (Figure 2; (27)). Early rains presumably allowed the crops to develop quickly while the soil temperatures were still warm. Rainfall in June and August presumably caused waterlogging damage diseases and nitrogen leaching. The poor correlation between July rainfall and yields may be due tc the crops being semi-dormant due to the cold conditions. Under these conditions adequate oxygen supply to the roots might occur during waterlogging via lateral and horizontal water seepage.

Estimates of the economic losses due to waterlogging can be obtained from annual production data for the major crops and the rainfall during the growing season. Using the negative correlation between crop yield and August rainfall (Figure 2) and rainfall probability data, the effect of excess August rainfall on wheat, oats and lupin production was estimated for 8 shires in the central Upper Great Southern region of Western Australia (27). For a 10 year period with wet and dry years, average annual losses from the 8 shires were estimated to be $11 million from wheat, $1.6 million from oats, and $0.5 million from lupins. This represents a loss of 14, 12 and 8% of the respective annual production of wheat, oats and lupins in these shires.

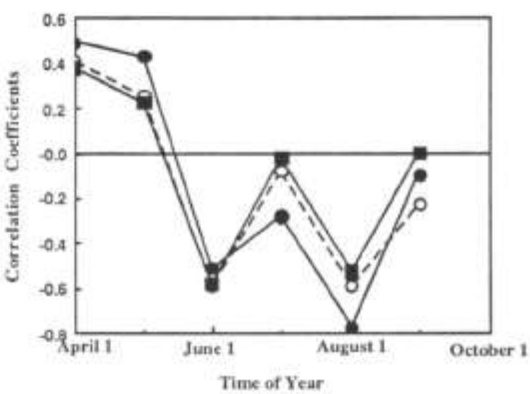

Figure 2. Correlations between crop yields and monthly rainfall for the eastern Murray River Catchment area of Western Australia. Symbols: spring wheat (closed circles), oats (open circles), lupins (closed squares).

Mapping waterlogged cereal crops

Very accurate maps of waterlogging are possible using airborne multispectral scanning due to the large number of spectral bands (>13) and their spatial resolution (ca. 5m). However, scanning data are not as readily available as satellite data. We feel that the best method for routinely mapping waterlogging in cereal crops over large areas is using Landsat TM which has a spatial resolution of 30 m for 6 of its 7 spectral bands. The best bands for discrimination are bands in the near and thermal infrared. A 27,000 ha area near Yornaning, Western Australia, was classified in 1988 using the best discriminator (27). About 30% of the area was cropped, and 32% of this area was classified as moderately waterlogged (grain yield about 19% of adjacent non waterlogged areas), and a further 6% was classified as severely waterlogged (total crop failure).

Effects of waterlogging on soils

In general gases diffuse about 10,000 times more slowly in water than in air (18). Thus even small discontinuities in the gaseous phase of the soil pores impair gas diffusion both into and out of the waterlogged part of the soil. As a consequence of waterlogging (i) 02 used for respiration of soil microorganisms and roots is usually used up and not replaced; (ii) CO2 produced in respiration and alcoholic fermentation of soil microorganisms and roots is not exhausted, so it accumulates; and (iii) other gases like the plant hormone ethylene are also produced and accumulate. The rates of these changes in soil gases depend mainly on temperature but may also be influenced by other factors including soil salinity, organic matter and pH. Decreases in 02 and increases in CO_2 and ethylene have been measured for at least 5 soils from locations prone to waterlogging in Western Australia (soils collected and analysed in the laboratory (34); field analyses (4) and own measurements).

Waterlogging has a range of additional secondary effects such as electrochemical changes and accumulation of breakdown products from organic matter which are reviewed by Ponnamperuma (30). The major factor considered to limit plant growth during waterlogging is low 02, and this is supported by similar effects in waterlogged soil relative to deoxygenated nutrient solution for some but not all plants (for exception see 21). Hence the formation of aerenchyma (continuous gas filled channels inside the root) is a major advantage for plants during waterlogging because it facilitates 02 supply to the root apices.

Effects of waterlogging on plant growth

This section contains a critical evaluation of the techniques used to impose waterlogging followed by discussions on the adverse effects of waterlogging or low root 02 on cereal and pasture production. Other crops in W.A. will not be discussed in detail because there is little published information.

Techniques

The most common method of imposing waterlogging in glasshouse experiments is to add water to pots of soil. Unfortunately in many experiments the pots contain only topsoil or they are maintained at temperatures substantially higher than in the field. Another limitation is the absence of vertical or lateral seepage. All these factors would exacerbate the effects of waterlogging.

Many workers simulate waterlogging in the glasshouse in nutrient solution culture by an immediate partial deoxygenation of nutrient solutions by bubbling with nitrogen gas (approx. 0.03 kPa 02, e.g. (2, 37)). Other workers impose even more severe conditions by bubbling with high purity nitrogen (<0.001 kPa 02, e.g. (31)). In less controlled conditions some workers impose poor aeration by exposing plants to stagnant nutrient solution which slowly becomes low in 02 due to root respiration (13, 22). The stagnant nutrient solutions have the advantages that gases and volatile compounds (e.g. ethanol and aldehydes) which may affect plant growth are retained in the root medium. However boundary layers which would form around roots due to stagnant conditions would likely induce nutrient deficiencies, and they would result in a loss of pH control in the rhizosphere relative to the waterlogged soil environment.

The major problems with studies of waterlogging in the field are that waterlogging is variable in time and location, as well as intensity. For ease of interpretation some workers regulate the watertable using lysimeters (6,10) or hydrologically-isolated plots (4). If naturally varying watertables in the field are measured then a method of integrating the levels needs to be used. One way in which this has been done is using the SEW30 index. While SEW30 may be a useful index of waterlogging, it is not high watertables *per se* which adversely affect root growth and metabolism. Therefore we would not always expect a consistent correlation between SEW30 and growth. Conditions which might substantially interact with SEW30 to affect growth include:

Temperature: For growing tissues we would normally expect demand for 02 to decrease 2 to 3 fold for every 10?C fall in temperature (8). Thus, root survival during waterlogging is likely to be substantially higher at low temperatures.

Frequency of waterlogging: A number of brief periods of waterlogging might be less damaging to root growth than a few longer periods. For example, one set of observations in a loamy sand uncle artificially waterlogged conditions in the field showed that at 15 to 20?C it takes 2 to 4 days for 02 concentrations to become highly limiting to root growth (<5 kPa (3, 4)).

Flooding: It is likely that brief periods of flooding around shoots may exacerbate the damage caused by waterlogging (see Concluding Comments). By definition SEW30 does not include flooding.

Stage of development: More adverse effects of waterlogging in the field on winter wheat occurred prior to emergence in comparison to during tillering (11). Waterlogging at 12?C for 6 days after sowing on sandy loam or clay reduced plant numbers by 88 and 97% respectively (11).

Poor nutrition: (see below).

Salinity: Salinity interactions are discussed elsewhere in these proceedings (5; see also 1).

Several of the above factors could be accounted for by using the Stress Day Index method proposed by Hiler (19). The index is the product of crop susceptibility and the degree and duration of waterlogging (e.g. SEW30) at different times of the growing period.

Cereal production

Measurements of the effect of waterlogging on cereals in southern Australia have been carried out in the glasshouse (38) and in the field under controlled (4) and uncontrolled (12, 24, 27) conditions. In addition, several investigations have been conducted in hypoxic nutrient solution cultures (2, 7, 9). In summary the data show that (i) cereals can avoid 02 deficits by producing roots with aerenchyma, (ii) even roots without aerenchyma have a substantial ability to resume growth and take up nutrients once waterlogging ceases, (iii) waterlogging may interact with poor nutrition to lower yields, and (iv) some cereals are less affected by waterlogging than others.

Formation of aerenchyma: One major adaptation of roots to waterlogging is to form aerenchyma (continuous gas filled channels inside the root) which enable 02 to diffuse internally from the base of the shoot to the root apices. An indication of aerenchyma can be obtained from porosity, however the porosity of tissues can also be affected by gas spaces in the cell walls which does not contribute substantially to 02 diffusion. Aerenchyma formation has been estimated in plants grown both in soils and nutrient solution culture. For example, root porosities were measured in several cereals and dicots grown in loam which was waterlogged or drained for 11 days (41). The best contrast in root porosities between drained and waterlogged plants was with a wheat cultivar (cv. Pato) which had 15% porosity for waterlogged plants and 6% porosity for drained plants.

Aerenchyma can also be estimated visually. The anatomy of crown roots was examined in barley after waterlogging for 14 days in a sandy loam soil (13). The cortex in crown roots from waterlogged plants had well developed aerenchyma in contrast to the small intercellular spaces in the cortex of roots from drained plants. In experiments in nutrient solution at low 02, roots with aerenchyma (observed visually) had porosities of 9 to 14% whereas those without aerenchyma had porosities as low as 3% (2,7, and own unpublished data).

The observations of higher porosities in crown than seminal roots of barley and wheat grown at low 02 (e.g. 2,7) suggested that roots may differ in their capacity to form aerenchyma. However, recent studies have shown that aerenchyma can form in both crown and seminal roots provided these are shorter than 10 to 15 cm (Thomson, Waters, Greenway and Barrett-Lennard, unpublished data). Thus we would expect prolonged waterlogging to kill the apices of any primary root axis longer than 10 to 15 cm.

Recovery from waterlogging: Evidence from both the field and glasshouse suggests that cereals grown at high levels of nutrition have a considerable ability to resist waterlogging and recover following the return to drained conditions. In an investigation at high nutrition in hydrologically-isolated plots in the field, two periods of waterlogging for 9 to 11 days separated by a 10 to 13 day period of drainage decrease total root length by 26%, 64% and 64% at the 0 to 10, 10 to 20 and 20 to 30 cm soil depths respectively (3). However, 13 to 16 days after the waterlogging ceased there were no significant differences in root length between previously waterlogged and drained plants. At the final harvest there was no significant effect on final grain weight (3).

In experiments using plants grown in nutrient solution culture in the glasshouse, 10 to 14 days of hypoxia inhibited the relative growth rates of seminal roots by more than 90%, although there was no significant effect on crown roots (2). This treatment also caused the death of the tips of seminal axes (2), and decreased rates of K, N and Cl uptake (9). However during the 4 days following the return of plants to aerated solutions there were dramatic increases in root growth (due in part to a proliferation of new lateral roots), and there was a recovery of nutrient uptake (2, 9).

Interaction with poor nutrition: Nutrient supply to roots may be achieved via (i) root growth (interception of nutrients), (ii) mass flow (via the plant transpiration stream) and (iii) diffusion (23), as well as via vertical and horizontal seepage. Waterlogging is likely to affect all of these processes in addition to affecting active uptake of nutrients itself. Uptake of mineral nutrients at the root surface may be active (requiring energy) or passive. Effects of waterlogging on active nutrient uptake and plant growth are shown by the following simplified sequence:

WATERLOGGING → low O_2 → low respiration → low energy → low nutrient uptake
↓ ↓↑ ↓↑
LOW ROOT GROWTH → **LOW SHOOT GROWTH**

Evidence for adverse effects of waterlogging on rates of nutrient uptake are found in results of glasshouse studies in which barley was grown in waterlogged soil (14) and wheat was grown in hypoxic nutrient solution (37). Waterlogging or hypoxia for 4 to 6 days decreased net rates (root weight basis) of N, P and K uptake in barley and wheat by 65 to 95% ((37) and calculated from (14)). These changes coincided with changes in concentrations of N, P and K in the shoots (14, 37).

When plants are returned to high 02 concentrations after a period of hypoxia, they appeared to retail their capacity to take up nutrients and to resume growth. In an experiment in nutrient solution culture wheat plants exposed to hypoxia for 10 days and then returned to aerated solutions subsequently took up N, P and K at net rates substantially higher than in plants grown continuously in aerated solution Furthermore, the concentrations of N, P and K in the plants which had previously been hypoxic increased within 4 days to the same levels as in plants in aerated solutions (9).

One instance in which waterlogging affected plant nutrition because of a decrease in interception of nutrients by roots was shown by Barrett-Lennard *et al. (3).* Wheat grown in hydrologically-isolates plots in the field was fertilized at the start of the season with "conventional" rates of N, P and K. A 26 day period of waterlogging during early tillering significantly decreased concentrations of N, P and K in the shoots and caused the plants to develop shallow roots (95% of total root length was <15 cm deep; no roots deeper than 30 cm). The waterlogging had little consequence for subsequent P and K nutrition of the plants since there were relatively high concentrations of P and K in the upper 15 cm of soil. When the waterlogging ceased, the concentrations of these nutrients in plants rapidly returned to those in drained plants. In contrast, there were very low concentrations of N in the upper 15 cm of the soil , and there was little or no recovery from N deficiency when waterlogging ceased. Final grain yields were reduced by 50% (3).

Differences in yield of cereals after waterlogging: The available evidence suggests that oats yield better on land which is subject to waterlogging than spring wheat. However, it is not clear whether this is because oats (i) grow better *during* waterlogging, (ii) have more plants/tillers per area that survive during and after waterlogging, and/or (iii) grow better *after* waterlogging, relative to spring wheat. Some evidence for proposition (iii) has been obtained in a glasshouse experiment in which pots of soil were continuously flooded to 1 cm above the soil surface for 42 days (38). At the end o the flooding treatment, the oats had 8 to 26% lower shoot dry weights than spring wheat; however, by the end of the season, the previously flooded oats had recovered to produce 11 to 26% and 14 to 29% higher grain and straw yields respectively than previously flooded spring wheat (38).

The effects of waterlogging in the field on oats and spring wheat vary substantially between sites and seasons (Figure 3). At Mount Barker in 1984, oat yields were unaffected by waterlogging until SEW30 exceeded about 500 cm.days (12). At Narrogin in 1985 spring wheat yields decreased by about 56 kg/ha for every 100 cm.days, and there was no evidence of a threshold before yields declined (12). There was also no threshold at Yornaning in 1987 where yields of l 'h spring wheat and oats decreased by 520 to 550 kg/ha for every 100 cm.days of waterlogging (27). The use of different cultivars and different soil and environmental conditions might account for these variations.

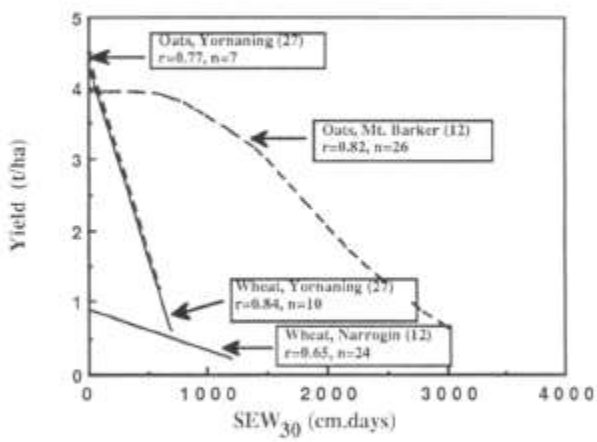

Figure 3. Effect of waterlogging (estimated by SEW30 on grain yields of crops in Western Australia.

Pasture production

There is surprisingly little information on the effects of waterlogging on the productivity of pastures of mixed species, despite the likelihood that there are effects on both productivity and species composition. In 3 of 4 sites studied in the central Upper Great Southern region of Western Australia, waterlogging reduced the growth of pasture plants by up to 19-fold in early and late winter (calculated from Figure 4A on July 2, (27)). In the coldest part of winter there was little difference between the growth rate in wet and dry areas (July 22 in Figure 4A). Compensatory growth occurred in the waterlogged areas during the spring flush in these three areas. However, the amount of pasture during the spring does not limit carrying capacity as much as does winter growth. In the driest area studied (Tutanning, Figure 4B) pasture growth was actually better in the wetter than the drier areas. This was presumably due to water deficits in well drained soils. In the three higher rainfall areas, grasses predominated over legumes in waterlogged areas, and this may have occurred due to greater development of aerenchyma in the grasses (see previous section).

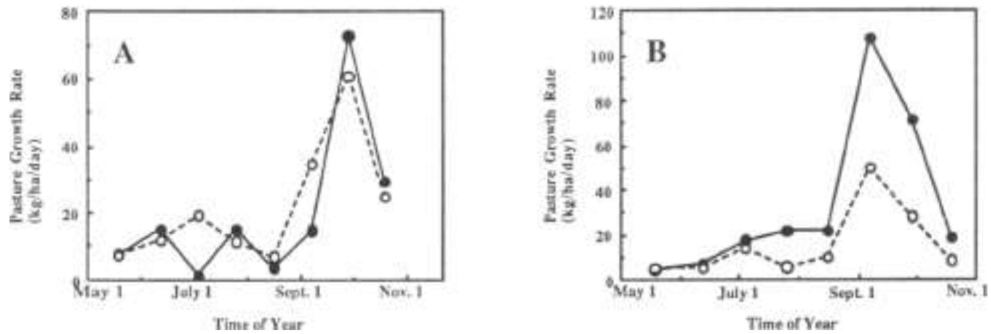

Figure 4. Growth of pasture plants in waterlogged and drained pastures at different times of the year in 1987 at Rosedale (A) and Tutanning (B) in the central Upper Great Southern of Western Australia. Results at Rosedale (A) were similar to two other locations (12). Dashed lines are SEW30 of 0 cm.days; solid line in (A) is SEW30 of 60 cm.days; solid line in (B) is SEW30 of 24 cm.days.

Some information is available on the growth of pasture legumes during waterlogging. For example, annual *Medicago* species are more susceptible to waterlogging than subterranean clover (16). The earliest maturing medics were worst affected by waterlogging. Differences in growth during waterlogging was also indicated for subterranean clovers. In one investigation of 75 cultivars the more tolerant subspecies after 21 days of waterlogging were reported as *yanninicum* > *subterraneaum* > *brachycalcinium* (15; based on dry weights of waterlogged relative to drained plants at the end of treatments). The subspecies *yanninicum* had a much higher proportion of shallow roots which may explain its greater yield in the waterlogging treatment; alternatively the growth of drained plants could have been low relative to waterlogged plants in this subspecies. There are no data in the paper to distinguish between these possibilities.

Amelioration of waterlogging

Obtaining production from areas susceptible to waterlogging is most likely to be economically achieved by using a combination of drainage and agronomic practices. In Western Australia, two types of open drains are used for controlling waterlogging: interceptor drains on sloping sites (> 2 per cent slope) and relief drains on sites with little slope (26). Interceptor drains are often very cost effective for mitigating waterlogging on sloping duplex soils (12, 32). The main factors affecting their cost effectiveness are the frequency and intensity of waterlogging, the frequency of cropping and the amount of land occupied by the drains. While design criteria are available for interceptor drains there have been few investigations of the effectiveness of relief drains in southern regions of Australia. In the south east of South Australia, 1450 km of surface drains have been effective in removing surplus water from interdunal flats, alleviating both waterlogging and salinity (33). Some overdrainage occurs beside main drains (i.e. yields are adversely affected by the drains).

Drainage can also be achieved by growing crops on raised soil beds above the watertable. Bedding drainage has been widely used throughout the world but has not been accepted in the broadacre cropping areas of Western Australia (26). In intensive cropping areas raised beds may be economic.

Concluding comments

These concluding comments focus on areas in which further work is urgently required. In summary we believe that (i) there are still major weaknesses in our understanding of waterlogging as a constrain to plant growth, and (ii) attention needs to be given to the development of integrated agronomic and hydrological research designed to cost-effectively improve productivity in waterlogged land.

Hydrology. The hydrology of waterlogged areas in Western Australia is now reasonably well known Areas for future investigation include determining the importance of zones of preferred lateral seepage on hillsides and the effect of tillage on the permeability of subsoil clays. The design of relief drains or clay flats also needs to be made quantitative, and there is an urgent need to extend our knowledge on interceptor drains because these are required for many sloping duplex soils.

Remote sensing. Remote sensing methods of mapping waterlogged areas will be continually refined a part of a three year project to map all visible forms of land degradation in south-western Australia.

Measurement of waterlogging in the field. The SEW30 has substantial limitations as a predictor of the extent to which waterlogging adversely affects growth and yield. Clearly other factors interact with high watertables to affect growth. A major evaluation is required to develop a new index (e.g. the Stress Day Index) which can be used to quantify on a broad scale (i) the severity of waterlogging and (ii) interactions with other factors which affect plant growth.

Physiological studies. An excellent start has been made in determining the effects of waterlogging on cereals under controlled conditions. However the scope of these studies now needs to be extended to other plants and to uncontrolled conditions in the field. Future research is required on the following:

- Pasture species. Little is known about the comparative tolerance of pasture species to waterlogging. Furthermore it is possible that some grasses may have proliferic aerenchyma (e.g. kikuyu; own observations) which under certain conditions may allow them to oxygenate the soil and even support growth or survival of other plants like clover which are not known to develop aerenchyma.
- Legumes and ther crops. Recent work with lupins and field peas suggests a high degree of waterlogging tolerance of some lupin cultivars, with no growth reductions of plants even after 12 days of continuous waterlogging (29). Further research is necessary to determine the mechanism(s) which enable rapid growth rates to be maintained in these cultivars.
- Flooding. There is a special need to initiate studies which examine the adverse effects of flooding. It is likely that several days of flooding will exacerbate the damage due to waterlogging. Flooding like waterlogging, results in limited gas diffusion due to the presence of water. To our knowledge there are no data on plant growth or environmental conditions in the field during flooding. This would be particularly relevant to small plants (some pasture legumes or seedlings) which could easily become submerged after periods of high rainfall and slow runoff. The importance of diffusion and interactions of gases during complete submergence of rice has been discussed in detail by Setter *et al. (35).*

Agronomy. Substantial improvements in crop production from flat waterlogged land might be achieve, by focusing on agronomic practices (e.g. early planting, higher seeding rates, maintenance of higher levels of nutrition using split fertilizer applications). There has been almost no work on this in Western Australia, although useful progress has occurred in Victoria (Gardener, this proceedings).

Breeding. One of the cheapest ways of improving production from waterlogged soils may be to select and breed cultivars with improved waterlogging resistance. Research could initially focus on the identification of selectible variation within the required physiological characteristics, and subsequently on the transfer of genes for these characters into commercial types. In some cases improved yields might be achieved by selection of long season cultivars which have slow growth rates during the waterlogging period.

References

1. Barrett-Lennard, E.G. 1986. Reclam. Reveg. Res. 5: 245-261.

2. Barrett-Lennard, E.G., Leighton, P.D., Buwalda, F., Gibbs, J., Armstrong, W., Thomson, C.J. and Greenway, H. 1988. Aust. J. Plant Physiol. 15: 585-598.

3. Barrett-Lennard, E.G., Leighton, P.D., Greenway, H. and McPharlin, I.R. 1987. Final report to the Wheat Industry Research Committee of WA.

4. Barrett-Lennard, E.G., Leighton, P.D., McPharlin, I.R., Setter, T. and Greenway, H. 1986. Aust. J. Soil Res. 24: 477-483.

5. Barrett-Lennard, E.G. and Nulsen, R.A. 1989. Proc. 5th Aust. Agronomy Conf. (Perth)

6. Belford, R.K. 1979. J. Soil Sci. 30: 363-373.

7. Benjamin, L.R. and Greenway, H. 1979. Ann. Bot. 43: 383-391.

8. Bidwell, R.G.S. 1979. Plant Physiology. Macmillan Publ. Co., New York, Second Ed. 726 pp.

9. Buwalda, F., Barrett-Lennard, E.G., Greenway, H. and Davies, B.A. 1988. Aust. J. Plant Physiol. 15 599-612.

10. Cannell, R.Q., Belford, R.J., Gales, K. and Dennis, C.W. 1980. J. Sci. Food. Agric. 31: 105-116.

11. Cannell, R.Q., Belford, R.J., Gales, K., Dennis, C.W. and Prew, R.D. 1980. J. Sci. Food Agric. 31: 117-132.

12. Cox, J.W. 1988. PhD Thesis, University of Western Australia.

13. Drew, M.C., Jackson, M.B., Giffard, S.C. and Campbell, R. 1981. Planta 153: 217-224.

14. Drew, M.C. and Sisworo, E.J. 1979. New Phytologist 82: 301-314.

15. Francis, C.M. and Devitt, A.C. 1969. Aust. J. Agric. Res. 20: 819-825.

16. Francis, C.M. and Poole, M.L. 1973. Aust. J. Exper. Agric. Anim. Husb. 13: 711-713.

17. Gardner, W.K., Velthuis, R.G. and Amor, R.L. 1983. J. Aust. Inst. Agric. Sci. 49: 60-70.

18. Grable A.R. 1966. Adv. Agron. 18: 57-106.

19. Hiler, E.A. 1969. Trans. A.S.A.E. 12: 499-505.

20. Hillel, D. and Talpaz, H. 1977. Soil Sci. 123: 54-62.

21. Jackson, M.B. 1979. J. Sci. Food Agric. 30: 143-152.

22. Konings, H. 1982. Physiol. Plant. 54: 119-124..

23. Marschner, H. 1986. In: Mineral Nutrition of Higher Plants. Academic Press. 674 pp.

24. McDonald, G.K. and Gardner, W.K. 1987. Aust. J. Exp. Agric. 27: 661-670

25. McFarlane, D.J. 1985. J. Agric. W. Aust. 26: 119-121.

26. McFarlane, D.J., Negus, T.R. and Cox, J.W. 1985. J. Agric. W. Aust. 26: 122-125.

27. McFarlane, D.J., Wheaton, G.A., Wallace, J. and Negus, T.R. 1989. Final report to the Wheat Industry Research Committee of W.A.

28. O'Loughlin, E.M. 1985. Wat. Resour. Res. 2: 794-804.

29. Phuphak, S. and Setter, T.L. 1989. Proc. 5th Aust. Agron. Conf. (Perth).

30. Ponnamperuma, F.N. 1972. Adv. Agron. 24: 19-96.

31. Reggiani, R., Brambilla, I., and Bertani, A. 1985. J. Exp. Bot. 36: 1698-1704.

32. Salerian, J.S. and McFarlane, D.J. 1987. DRM Tech. Report No. 54, W. Aust. Dept. Agric.

33. Schale, G., Cramer, S.R. and Lewis, D.C. 1987. Tech. Report. No. 122. S. Aust. Dept. Agric.

34. Setter, T.L. and Bywaters, T. 1989. Proc. 5th Aust. Agronomy Conf. (Perth)

35. Setter, T.L., Waters, I., Wallace, I., Bhekasut, P. and Greenway, H. 1989. Aust. J. Plant Physiol. 16: (In Press).

36. Sieben, W.H. 1964. Van Zee tot Lod. 40, The Netherlands.

37. Trought, M.C.T. and Drew, M.C. 1980. J. Exp. Bot. 31: 1573-1585.

38. Watson, E.R., Lapins, P. and Barron, R.J.W. 1976. Aust. J. Exper. Agric. Anim. Husb. 16: 114-122.

39. Wesseling, J. and van Wijk, W.R. 1957. In: Luthin, J.N. (ed.) Drainage of Agricultural Lands. Am. Soc. Agron.

40. Whan, B.R., and Anderson, W.K. 1986. Proceedings of the Standing Committee of Agriculture Workshop, 12-13 August, Horsham.

41. Yu, P.T., Stolzy, L.H. and Letey, J. 1969. Agron. J. 60: 844-847.