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No. 82

J.M. Aldrick, A.J. Clarke, P.W. Moody, M.H.R. van Cuylenburg and B.A. Wren

Cover photograph: The Frank Wise Institute for Tropical Agricultural Research (formerly the Kimberley Research Station) on the east bank of the Ord River at Kununurra.

Soils of the Ivanhoe Plain, East Kimberley, Western Australia

By: J.M. Aldrick, A.J. Clarke, P.W. Moody, M.H.R. van Cuylenburg and B.A. Wren
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Summary

The Ord River Project was approved by the Commonwealth Government in 1959 and the first five farms were released in 1962.

Early soil surveys were unable to explain considerable variation in crop performance. A more detailed soil survey of the Ivanhoe Plain was commissioned by the Western Australian Department of Agriculture and this was undertaken during the dry season of 1977.

As a result of the survey, the Ivanhoe Plain was divided into two geomorphic provinces. The soils within these two provinces are developed on similar parent materials in similar pedogenetic environments. The principal difference between the provinces is the time during which pedogenesis occurred. The cracking clay soils of the northern province are generally more highly leached than their younger counterparts in the southern province.

Sixteen land units are identified as distinct from soil units. These units give cognizance to vegetation and topographical features as well as soils.

The suitability of the various land units is considered given the expected land use of irrigated agriculture. Of the 17,851 hectares surveyed, about 50% is considered to have good potential for irrigated agriculture. The remaining 50% has numerous limitations with varying degrees of severity. Care will be required in farming these units.

A common map key is proposed for use in future surveys on the Ivanhoe, Weaber and Keep River Plains.

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Introduction

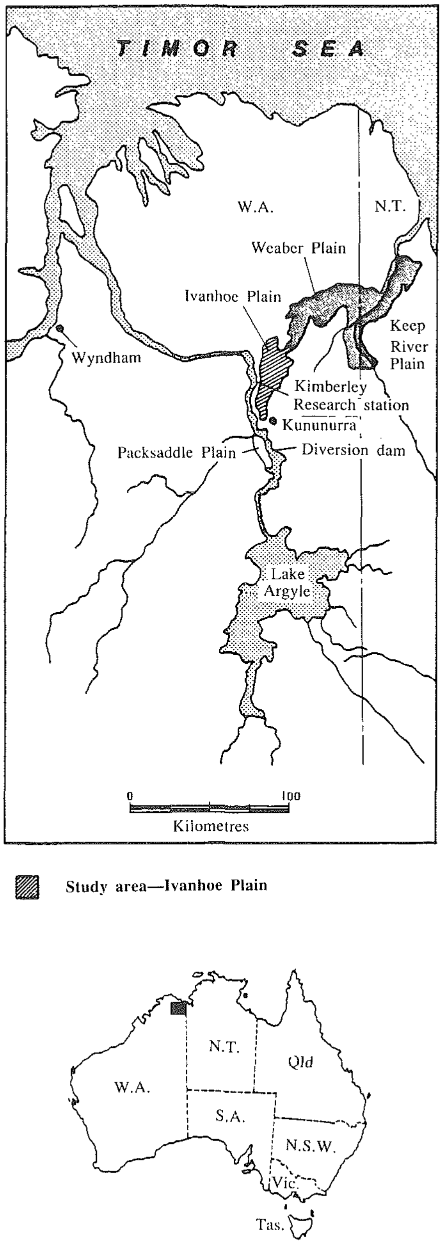


Figure 1. Location of the Ivanhoe Plain in the Ord River Irrigation Area, Western Australia.

Location

The Ivanhoe Plain is part of a series of alluvial plains formed by the Ord and Keep Rivers and is on both sides of the Western Australia -Northern Territory border. It is in the extreme north-eastern corner of Western Australia, in the east Kimberley, and extends north from Kununurra along the eastern side of the Ord River (Figure 1).

The Ord River Dam, 50 km upstream from Kununurra which formed Lake Argyle, has the capacity to supply sufficient water for all areas with irrigation potential lying downstream from it on either side of the State border.

Climate

The region is semi-arid with summer monsoonal rains. Average rainfall for Kununurra is 740 mm, most of which falls in the four months from December to March, with the rest of the year a virtual drought. The mean maximum temperatures range from 30.4°C in July to 39°C in October and mean minima range from 14.3°C in July to 24.4°C in November. The area is virtually frost-free.

History of development

The pastoral industry started in the Kimberley in the early 1880s. Alexander Forrest led an expedition across the Kimberley in 1879 and his glowing reports of the country attracted pastoralists from Queensland and New South Wales (Teakle 1944).

The discovery of gold at Hall's Creek in 1884 provided a market for beef, but the gold rush did not last long and live-cattle exports commenced from Wyndham. This ended after a meatworks was opened in Wyndham in 1918 (Stewart *et. al.* 1970).

The cattle industry changed little from 1920 onwards, but interest in irrigation development arose in the late 1930s. During the World War of 1939-1945, this intensified with government concern for post-war reconstruction and for the vulnerability of northern Australia to foreign invasion (Department of Natural Resources 1976). Proposals were also made for a Jewish refugee settlement (Melville and Steinberg 1943).

A Royal Commission in 1940 recommended the identification of land suitable for irrigation along the Ord River for 160 km from Wyndham (G.H. Burvill 1945, unpublished). In the following year a group of engineers and scientists indicated several sites where the Ord River could be dammed 100 - 150 km from Wyndham to command land suitable for irrigation downstream. In 1941 also, an agricultural experiment station of 5 ha was established on the levee soils near the present site of the main pumping station on Lake Kununurra. Investigations of dam sites, contour surveys and access roads continued in subsequent years.

In 1944, Burvill carried out a reconnaissance of 300,000 ha between Wyndham and the Western Australian border and the first detailed soil surveys in the area. The objects of the surveys were to assess the areas of potentially irrigable land and to define and map the soil types, the maps being intended as a basis for possible subdivision of the areas into farms. The main areas surveyed were the Ivanhoe Plain (then called the Carlton Reach Plain) and the Mantinea Flats - Goose Hill area further downstream. The extent of the dark cracking clay plains was delineated (G.H. Burvill 1945, unpublished).

In 1945, the Rural Reconstruction Commission recommended that extensive agricultural investigations should proceed and in late 1945 the small experiment station was replaced by the Kimberley Research Station at a site about 16 km downstream.

The site included large areas of cracking clay soils considered to represent the bulk of the soils of the Ivanhoe Plain. The research station was set up as a joint Federal-State venture to determine the feasibility of irrigated agriculture in the area and identify the most suitable crops and farming techniques.

In following years, investigations of potential dam-sites and channel routes continued. By 1958 these investigations had shown that it was possible to store more than enough water to irrigate all the irrigable soils that could be commanded both in Western Australia and the Northern Territory. Work at the Kimberley Research Station had shown that several crops could grow well there under irrigation.

Ord River Project

The Ord River Project was envisaged as a scheme to be developed in various stages. The basic points were the construction of a diversion dam near Kununurra, a main storage dam to be constructed at its present site, an irrigation area of up to 80,000 ha and the generation of hydroelectricity at the main dam (Anon. 1961).

Approval was granted for Stage 1 by the Australian Government in 1959 and construction commenced the following year. This stage concerned the building of the diversion dam at Bandicoot Bar and the development of about 6,000 ha of irrigated land watered from the diversion dam. Building of the diversion dam was completed in 1963 and the storage lake of 9.74 million m^3 capacity was called Lake Kununurra.

In 1960, the State Government agreed with Northern Developments Pty Ltd to the development of a pilot farm on almost 1,000 ha. It was intended to determine farm scale problems and establish the economic size of individual farms ready for Stage 1 development.

The first five farms in the irrigation area were released in 1962. Others were released progressively up to a total of 30, until by 1967, the total irrigated area was 5,540 ha, most of which was under cotton.

In 1969, construction of the main Ord River Dam commenced and it was officially opened in 1972. Its full storage capacity is 5,720 million m^3, although it is capable of six times this volume at full flood level. Water from the main dam maintains the full storage level in Lake Kununurra, enabling water to be released to irrigation farms by gravity flow.

Previous surveys

The first soil survey of the area was that of Burvill in 1944. A reconnaissance of about 300,000 ha between Wyndham and the Western Australian border was carried out, as well as more detailed soil surveys of the areas most promising for irrigation. These were the Ivanhoe Plain (22,000 ha) and the Mantinea Flats - Goose Hill area (12,000 ha). This represented work of considerable detail and information and it was achieved in primitive and difficult conditions when compared with present-day surveys.

The soils of the levees along the Ord River were mapped in detail. The bulk of the Ivanhoe Plain was classified as one type, Cununurra clay 'normal' phase, with areas of 'flooded' and 'eroded' phases around its edge.

Stewart *et. al.* (1970), has reported in "Lands of the Ord - Victoria Area", on land system surveys carried out in 1949 and 1952. These

provided an overall description of the geology, soils and vegetation of the Ord -Victoria region and the report included statements on the agricultural potential of the different land systems.

The Western Australian Department of Agriculture (T.C. Stoneman, unpublished) carried out surveys of the potentially irrigable soils in 1963 and prepared maps delineating the extent of the cracking clay soils on the Weaber and Keep River plains extending into the Northern Territory. These soils were regarded as being generally similar to the Cununurra clay described by Burvill in 1945. The surveys showed there were slight variations, but it was not feasible to map them separately at that time.

Sampling on a 1.6 km grid to a depth of 2 m was carried out to test for salinity. Some samples were analysed in more detail. Also in 1963, the extent of the clay plains was mapped on Packsaddle, Nigger Hill and Ivanhoe Station plains.

In 1965, the Carlton Plain was soil surveyed to show the extent of the clay plain and to identify several levee soils (T.C. Stoneman, unpublished). This and the 1963 surveys indicated that a total of about 75,000 ha of land was potentially irrigable, including 9,000 ha of levee soils.

Trial work on Kimberley Research Station had shown variations that appeared to be related to soil differences. To resolve this problem Gunn (1969) made a semi-detailed soil-survey of Kimberley Research Station and mapped out soil types which were significantly distinct from Cununurra clay and had undesirable chemical properties. It became evident that a survey of the entire Ivanhoe Plain was required.

The Northern Territory Administration conducted a reconnaissance inspection of the Keep River/Legune area in late 1969 (Aldrick 1969, unpublished) and this was followed by soil surveys of the Keep and Lower Weaber Plains in 1971 and 1972 (Aldrick and Moody 1977). Several distinct soils were found within the cracking clay plains.

This evidence, and the experience of farmers on the Ivanhoe Plain irrigation area who had found important soil variations that affected their activities, indicated that a more detailed soil survey of the Ivanhoe Plain was required. The Department of the Northern Territory (formerly the Northern Territory Administration) agreed to co-operate on this work so that the Western Australian Department of Agriculture could benefit from their experience gained on the Keep and lower Weaber Plain surveys. In this way a more co-ordinated approach could be made to the study of the soils of the Ivanhoe Plain.

The methods used are as described in Appendix 1.

Origin of the Ivanhoe Plain and formation of the soils

J.M. Aldrick

The source of the alluvium

The Ord River catchment lies to the south of the Ivanhoe Plain, astride the Northern Territory -Western Australian border. The geology of the area has been mapped and described by Sweet *et. al.* (1971) and Mendum (1972), and a short summary relating specifically to the Northern Territory section of the catchment has been extracted from their work by Aldrick, Howe and Dunlop (1978).

In Tertiary times most of the catchment was probably an ancient lateritic peneplain, with the Ord River meandering gently across it. A long period of erosion removed most of the lateritic material and etched out the underlying Proterozoic and Cambrian rocks. The most recent contributions of alluvium to the plains in the Ord Valley have been derived mainly from these older rocks.

Volcanic rock formations of the Antrim Plateau Volcanics are now exposed over a large proportion of the catchment, and these would have been a signficant source of basic primary minerals. The Hardman Basin is also of significant extent, and is composed mostly of soft calcareous and micaceous shales, and limestones. Proterozoic dolomites also occur and magnesium would have been contributed to the alluvium. Abundant chert and other siliceous materials occur in the catchment and these have contributed to gravelly stream bed-loads. Various other rocks including sandstones and siltstones also occur in the catchment.

The alluvium has been derived from a variety of mainly argillaceous sources and is rich in basic primary minerals, calcium and magnesium carbonates, micaceous particles, and siliceous gravels.

Formation of the Ivanhoe Plain

Because of the great uniformity of the upper 120 to 150 cm of the clay soils over a large area it was suggested by G.H. Burvill (1945, unpublished) that the plains consisted of lacustrine materials deposited in a deeply indented narrow bay which opened onto the northern coastline. Gunn (1969) and Aldrick and Moody (1977) have shown that the plains are more likely to be of riverine origin. They considered that the overall fall along the plains is too great for them to be lacustrine, and also that soil textures are too coarse and subsoil colours too reddish to be consistent with lake deposits. They have also recognized old river meanders and remnant channels and levees, and have identified river gravels on the plains. Similar evidence from this survey supports the hypothesis that the Ivanhoe Plain is of riverine origin.

The depth of the clay soils is not thought to be regulated by the thickness of a particular upper layer of fine alluvium. An inspection of the reddish material underlying the soils shows it to be a generally suitable substrate for the formation of cracking clay soils. I believe that the soils are uniformly 120 - 150 cm deep because that represents the depth to which incident rainfall normally percolates, thus allowing pedogenesis to occur.

From Landsat and aerial photography data it seems likely that the Ord River has been superimposed on the rocks it now traverses, following removal by erosion of the ancient land surface it previously drained. Carroll (1947) showed that originally the Ord River flowed north-east from Kununura, probably along the course of Eight Mile Creek. As superimposition progressed the course of the Ord was probably successively modified. G.H. Burvill (1945, unpublished) considered that eventually the Ord was captured by a westward-flowing stream and thus entered its present tract to Cambridge Gulf. Gunn (1969) has suggested that the river may once have flowed through the narrow gap west of Cave Spring Range. Evidence from this survey supports Gunn's contention, and suggests that the route through Cave Spring Gap was probably the one followed immediately before the capture of the river and its diversion to the west.

Local opinion and the geomorphic evidence indicate that flooding of the Ivanhoe Plain by water overflowing from the Ord River no longer occurs. G.H.Burvill (1945, unpublished) reached a similar conclusion. Today, the Ord is entrenched in its own alluvium, and the Ivanhoe Plain is relict.

The geomorphic provinces

The westward-flowing stream that captured the Ord probably intercepted the river at a point between the Kimberley Research Station and Buttons Crossing. Following its capture and diversion, the river would have eventually ceased to meander across the northern part of the Ivanhoe Plain. However, upstream of the site of capture (i.e. to the south) normal re-working of the alluvial plain would have continued to occur until more recently. As a consequence, the alluvium in the north has been exposed to weathering and pedogenesis for longer than the alluvium south of the site of capture. This has been the basis of a subdivision of the Ivanhoe Plain into a southern (younger) province and a northern (older) province. An approximate line separating these provinces is shown in Figure 2. Diagrammatic cross sections of the provinces are shown in Figures 3 and 4.

The northern (older) province

Because of their longer exposure to pedogenetic influences the clay soils in this province show evidence of greater maturity than the clay soils of the southern (younger) province. In the north, the soils are more leached, greyer, less well drained and have a coarser structure than the soils of the southern (younger) province. The chief differences between the soils of the two provinces are outlined in Table 2.

Slopes are relatively low in this province with gradients of 1:2500 to 1:3500 being common. Parts of Green and Martin's Swamps are almost flat. Areas with steeper slopes occur in this province and some of these correspond with the probable location of old river levees and point-bar systems that were present before the capture of the Ord. Adjacent to some of these steeper areas, relict river courses are clearly visible on aerial photographs and they have a similar width and radius of curvature at bends to those of the present-day Ord River (Figure 2).

Following capture, slow erosion of the plain has led to the filling of the vacant river channels with clay and to the removal of most of the levees and point bars that flanked them.

Obscure remnants of the sandy alluvial flanks still persist in some areas as relict levees, point bars, and meander cores, and these are mapped in land units 2c, 2e, 10a, and 10b.

A drill hole to 5 m depth in an area of land unit 10a intersected various layers of sandy loam, coarse sand and river gravels below 2 m. These materials are typical of point-bar deposits. The sandy remnants occur on steeper slopes because they originally occupied an area between two successively lower parts of the Ord River, i.e. between the two arms of a bend.

It is likely that some of the interdune corridors between the sandy remnants of the old point bar systems had clay floors and that carbonates leached from the nearby point bars and present in retained floodwaters would have accumulated in them. Land unit 4c, which occurs commonly in these areas, has calcareous clay soils with large pedogenetic calcrete nodules (Keep family) and probably represents relics of these old calcareous interdune areas.

The situation south-west of Martin's Swamp (Figure 2) is of note. A relict river course and associated ancient levees and point bars are located there and coarse sand was found in the soils (and immediately below one of them) where the old point bars were once located. A similar, though less obvious ancient river course with associated coarser deposits occurs on and just north-east of part of Kimberley Research Station (Figure 2). On a relatively steep area between these levee remnants and the relict stream channel R.H.Gunn (personal communication) found a lighter than usual texture in the reddish material underlying the clay soils. This area may also have been a levee or point bar deposit. The pattern of ancient riverine land forms persisting in these areas closely resembles the pattern of bends and point bars now located on the modern Ord River about 6 km north of the diversion dam.

In Cave Springs Gap another ancient river channel is evident on aerial photographs. It too has been filled with clay and it is still flanked in places by remnant sandy levee areas (mapped as land unit 10b) occurring on relatively steeper slopes. Indistinct patterns on aerial photographs show this channel passing down the narrow gap (Figure 2).

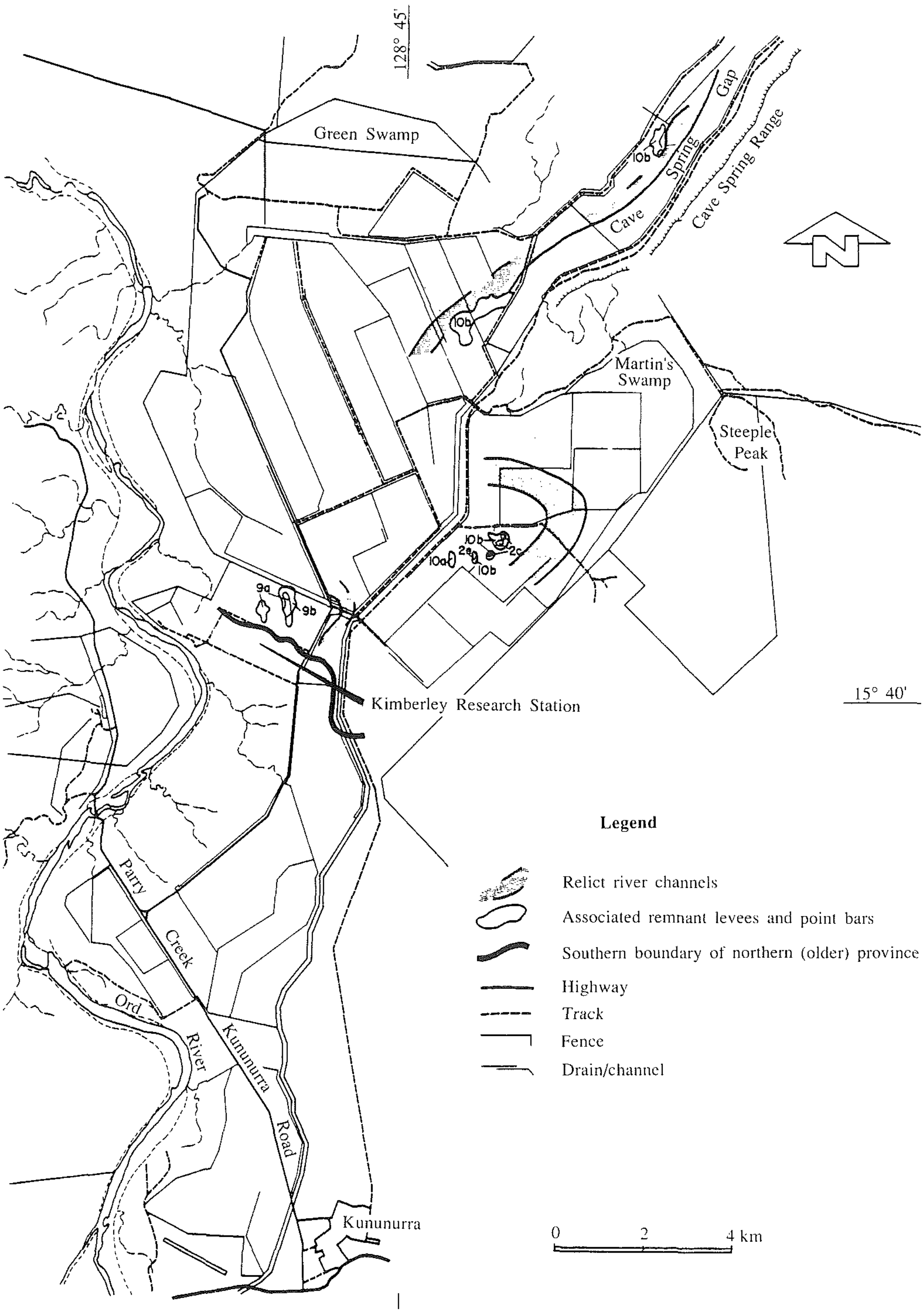


Figure 2. Location of relict fluviatile landforms

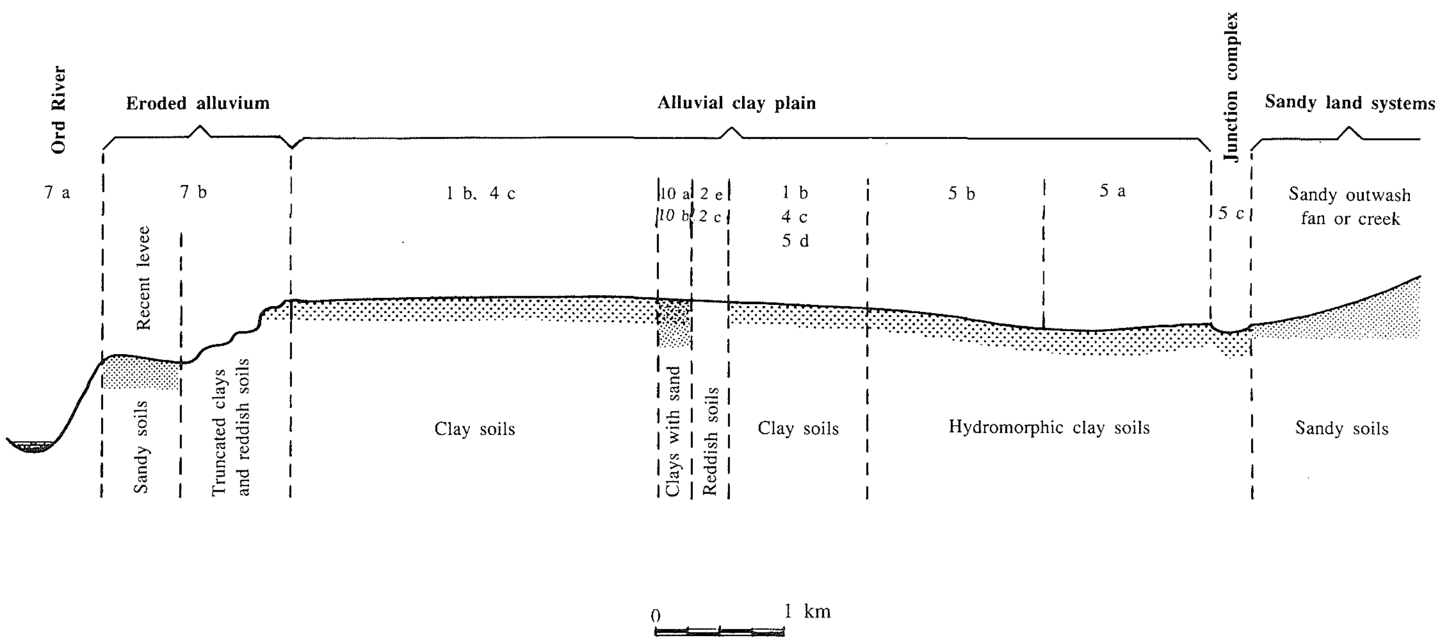


Figure 3. Diagrammatic cross-section of the northern (older) province

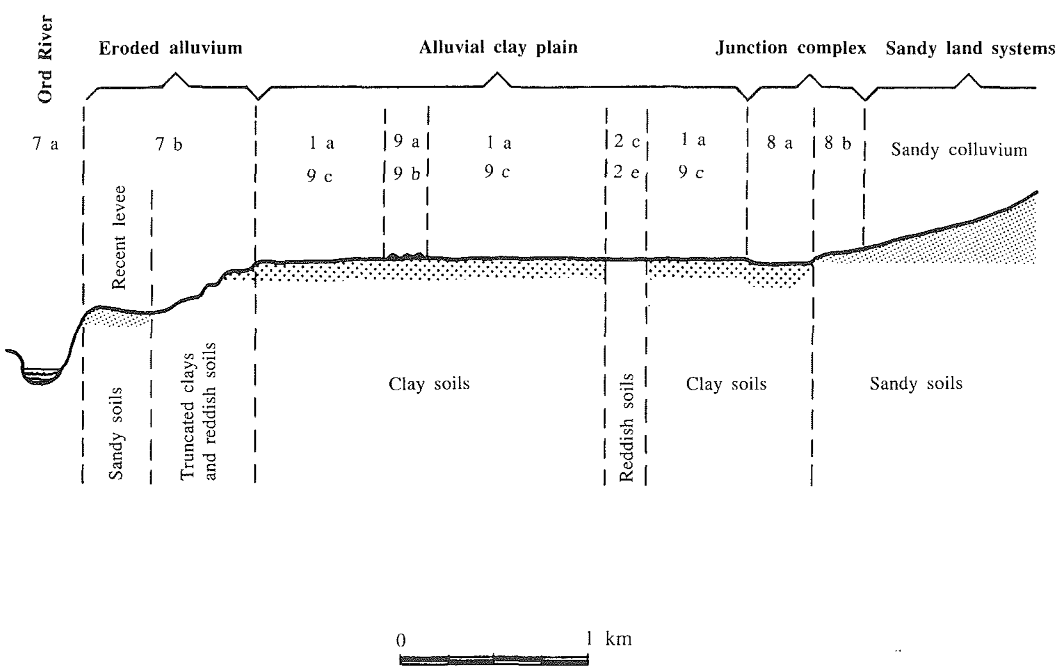


Figure 4. Diagrammatic cross-section of the southern (younger) province

The southern (younger) province

The alluvium in this province is younger and, because of the relatively short period of exposure to pedogenetic influences, the clay soils are less mature. The parent alluvium is high in carbonates and because of the lesser degree of leaching these have persisted in the soils. The clays are browner, more alkaline, better drained and have a finer structure than those of the northern (older) province. Figures provided by T.C. Stoneman (personal communication), Gunn (1969) and from this survey, show that both total and available phosphorus contents of the soils are lower than for the northern (older) province and clay contents are lower. These differences are represented in Figures 5 and 6. The mean profile clay contents and mean total and available phosphorus contents for all sites analysed are represented in these figures. They have been arranged in a numerical hierarchy for convenience and no spatial relationship is implied within each group.

Slopes in this province are greater than in the north, with gradients of 1:1500 to 1:2000 being common. Many of the slopes here are equally as steep as those exhibiting evidence of relict river courses in the northern (older) province, but no such relict stream courses are evident in the south. As this province occurs upstream of the site of capture of the Ord the stream course was at no time abandoned and back-filling of the stream channels has continued to occur in the ordinary course of the progression of river meanders across the plain.

A significant feature of the southern (younger) province is the presence of low gravelly rises and linear belts of highly calcareous soils (Walyara family) and lag river gravels. These occur most commonly on and near Kimberley Research Station and were thought by Gunn (1969) to be almost certainly remnants of old levees and channels. However, these remnants are probably not related to the massive relict features found in the northern (older) province as a result of the Ord vacating its bed completely.

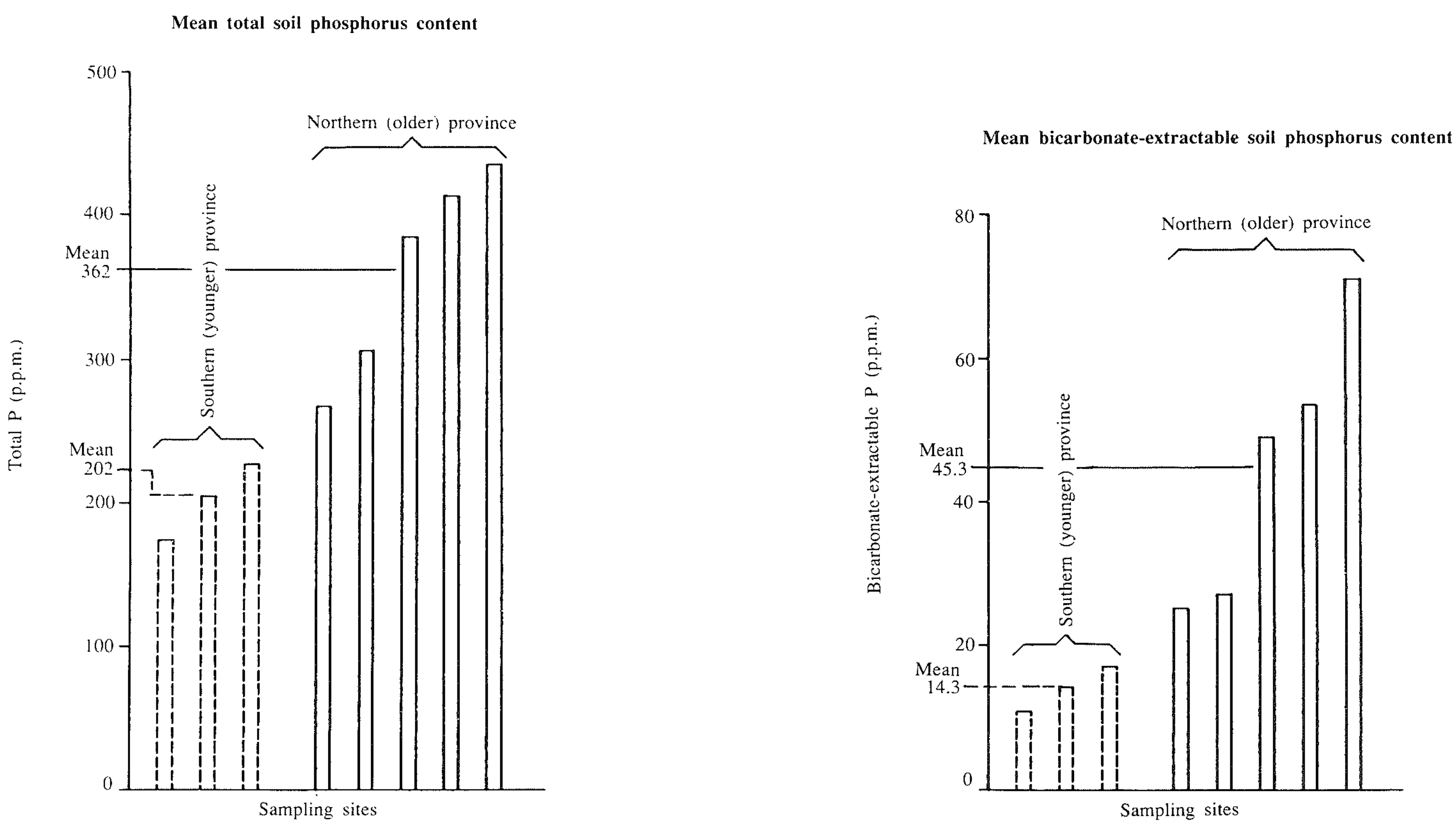


Figure 5. Mean phosphorus content of soils in the two provinces

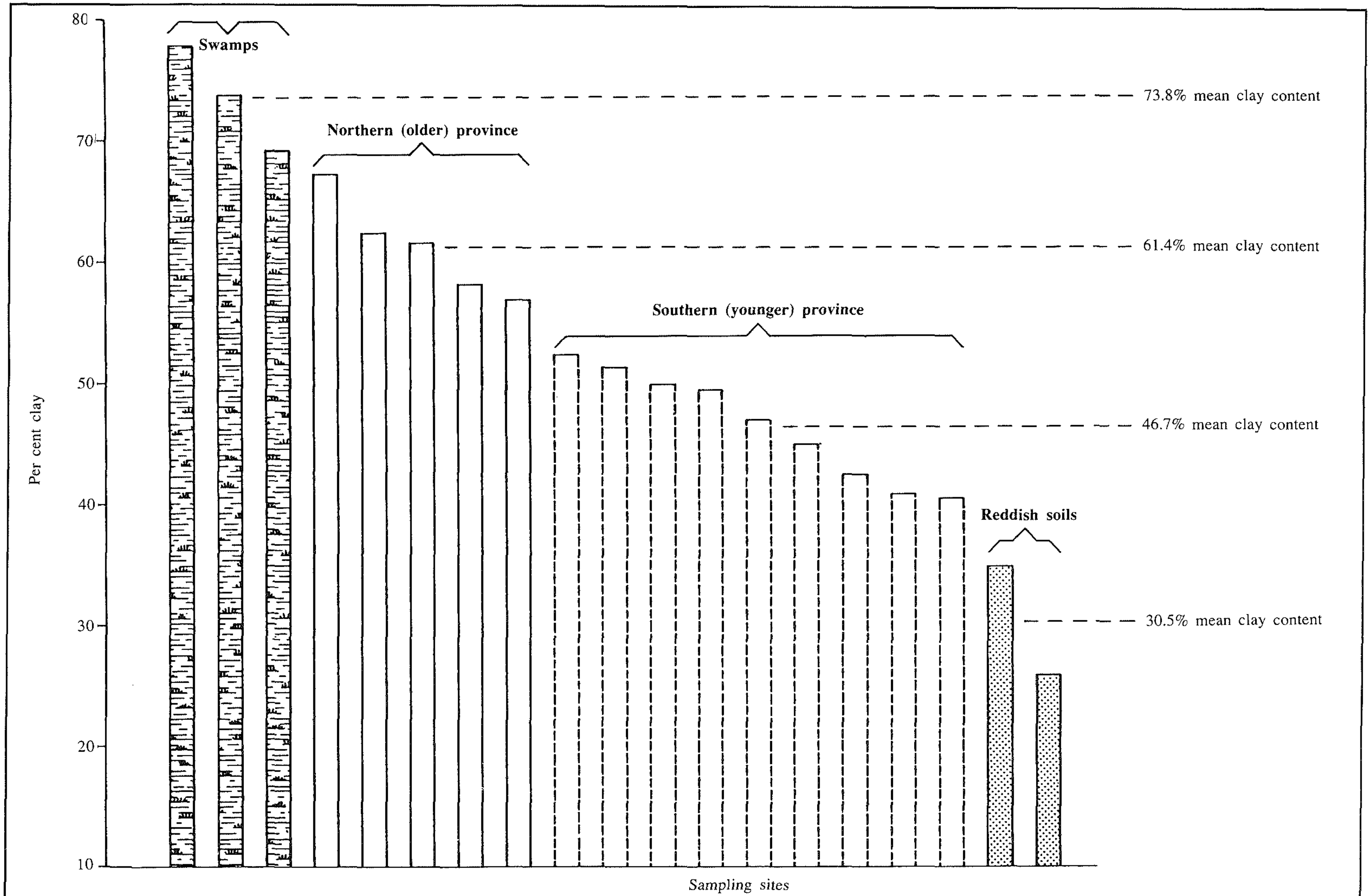


Figure 6. Mean clay content of four groups of soils

Development of the cracking clay soils

The greater part of the Ivanhoe Plain is now covered by cracking clay soils. These soils belong to a distinctive group occurring in all five continents in the tropical, sub-tropical and warm-temperature zones (Dudal 1965). Complex pedological processes are involved in their formation and particular conditions of climate and parent materials are pre-requisites for their development (Buringh 1968). Long periods, of the order of 5,000 to 10,000 years are required for these soils to mature.

Climate

Evidence suggests that the climate across northern Australia has remained similar for several thousand years. White and Peterson (1969) using evidence from investigations of the pre-history of western Arnhem Land, have suggested that the climate near Oenpelli has remained broadly similar throughout the last 7,000 years. Indirect evidence from the distribution of jungle-fowl mounds near relict areas of monsoon forest on Melville Island (Stocker 1971) suggests that the climate there has been relatively stable for the last 8,000 years. Investigations of chenier systems in Queensland have shown that sea level changes in the last 5,000 years have been no more than ± 1 m (Cook and Polach 1973), and this would imply general climatic stability.

It is probable then that the climate of the survey area has also remained similar for several thousand years. Today, the climate near Kununurra has alternating wet and dry seasons, an average annual rainfall of about 740 mm and mean temperatures varying between 20° and 35°C (Department of Natural Resources 1976). These conditions satisfy the climatic requirements for cracking clay soil formation.

Parent material

The most recent deposits of alluvium in the Ord Valley have been fine in texture and rich in basic primary minerals. Magnesium and calcium are abundantly available as their carbonates, a form that allows ready release of these elements with weathering and maintains a high pH. These chemical conditions are ideally suitable for the formation of montmorillonitic clays (Dudal, 1965; Buringh, 1968).

The parent alluvium has, for most of the area, been of sufficiently low permeability to restrict removal of the alkaline earths by leaching. The topography has been relatively flat and natural rates of erosion have been low, so that long periods were available for pedogenesis to occur and cracking clay soils were able to develop.

Soils of the seasonal swamps

Seasonal swamps occur both as a "junction complex" where the Ivanhoe Plain adjoins the sandy land systems to the east and in broad land-locked plains in the north. The chief areas occur in Green and Martin's Swamps and along Cave Spring Gap in the northern (older) province (Figure 2).

It is likely that some aggradation has occurred in these swamps because of influx of materials contributed from two sources. Firstly, slow erosion because of normal run-off from the main body of the clay plains would carry some suspended clay and secondly, contributions of run-off from the adjoining sandy land systems would also contain suspended materials. Some of the creeks discharging into the swamps carry considerable volumes of water when in flood. These have deposited significant sandy outwash fans at the edge of the plains. The suspended and dissolved materials contributed by each creek would vary with their specific source and it is likely that minor variations in the pedological character of each of the swamps occurs as a result.

Because of the annual inundation, leaching has been intense in the swamps. Whilst incident rainwater alone has been responsible for leaching over the bulk of the Ivanhoe Plain, in the swamps the large contributions of run-off water have also had an effect. These waters would almost certainly carry dissolved compounds which, if they were able to accumulate, would tend to increase the salinity of the soils. Analyses show that salts have not built up significantly in the swamp soils, probably because sufficient of the ponded water has been able to infiltrate to leach the salts down through the soil. However, the subsoils show an increased exchangeable sodium percentage.

Partly because of the influx of suspended clay and probably to increased weathering under these hydromorphic conditions, clay contents of the swamp soils are very high (≅70%) and permeability is very low. The potential problems that are likely to arise if these areas are irrigated are outlined later.

The reddish soil inclusions

Areas of coarser alluvium than usual occur in some parts of the Ivanhoe Plain, and reddish soils have formed in them. These areas of alluvium could be coarser for a number of reasons. Generally, they represent areas where water velocities were higher and competence greater during deposition of the alluvium. This would have occurred for example where levees and point bar deposits were laid down. Residues of these formations have persisted in some areas and those with reddish soils are mapped in land units 2c and 2e.

Some minor areas of coarser alluvium also occur close to the sandy land systems and even in the "junction complex". These may have received a contribution of sand from small local creeks originating in nearby formations. Reddish soils have also formed in these materials.

Because of their initial coarseness, these areas of alluvium were more permeable and have been more effectively leached than the rest of the alluvium. As a result, they have been depleted of sparingly soluble bases such as calcium and magnesium carbonates and their pH has been significantly lowered. The parent materials so formed were not suitable for the formation of montmorillonitic clays and cracking clay soils could not form in them. Pedogenesis of a lateritic nature proceeded instead and red earth soils were developed.

Texture and degree of leaching (and thus pH profile) vary from one occurrence of the reddish soils to another, depending on the specific nature of the parent alluvium at any point. In general, these soils could be assembled into two groups and a sandy phase and a heavier-textured phase have been described.

The areas of coarser alluvium with reddish soils that occur on most of the clay plains are now isolated from the original stream they evolved from and are thus relict. However, the areas described by Stoneman (1972) on the Packsaddle Plain still occur close to their parent stream (the Ord River) and are likely to be younger. Stoneman describes them as being slightly micaceous below 60 cm and this may also indicate relative youth.

In his 1945 report, Burvill described a group of reddish soils that formed in coarser areas of alluvium (Meruin family). In his description he noted that these soils mostly occurred between the clay plain and the Ord River, on older areas of alluvium that had been exposed following removal of the overlying materials by erosion. However, he extended the grouping to include those reddish soils that occurred as "islands" and more extensive areas in the main body of the clay plains. The implied assumption is that the reddish soil areas found on the plains represent "windows" in the younger alluvium where the older materials are exposed. This hypothesis is not supported here and the alluvia that both the cracking clays and the reddish soils have formed in are regarded as contemporaneous.

In the Keep River and lower Weaber survey, Aldrick considered that the occurrences of reddish soils found there were remnants of a former landscape that was previously more extensive, and had been encroached upon and largely re-worked by a river (Aldrick and Moody, 1977). A re-inspection of the evidence now indicates that the situation may be somewhat more complex.

It seems likely that the areas of reddish soils in the Keep River area originally formed on coarser alluvium that was deposited by the Ord River before it was captured, when the Keep River was one of its tributaries. Following the diversion of the Ord these areas would have become relict, but the Keep River would have continued to transgress the alluvium. It is probable that it subsequently dissected some of the reddish soil areas, so providing evidence of the "older" nature of those areas.

Thus, these reddish soils had indeed formed on a "prior" landscape, in relation to the later movements of the Keep River, but the chronological separation between them and the more modern fluviatile landforms would be small. The reddish soils of the Keep River area are now regarded as being contemporaneous with those of the Ivanhoe and other plains.

Description of the soils

J.M. Aldrick, A.J. Clarke and M.H.R. van Cuylenberg

Generalized and simplified descriptions of the soils are given below. Detailed profile descriptions are given in Appendix 2.

Cununurra family

Soil pH profile proved to be an important factor in the classification of Cununurra soils. In this area, virgin soil pH is thought to vary mainly with degree of leaching, which depends in turn upon the age of the soil concerned and its position in the landscape. Thus a relatively young but regularly inundated soil may be as leached as a much older one exposed only to incident rainfall. Because of this relationship, particular soil pH profiles are characteristic of areas having different geomorphic histories. For example, soils formed on the more recently re-worked deposits near Kimberley Research Station have a moderately uniform pH profile with only slightly depressed topsoil pH values, but the older soils further north have markedly lower topsoil pH values with a tendency for pH to increase down the profile.

Soil pH profiles were also found to vary to a high degree with factors of agronomic significance such as tilth, texture, and drainage rating, and other factors such as colour, gilgai and native vegetation. These varying factors, were used to separate the family into phases.

The most important phases of the Cununurra family are the normal, alkaline, and leached phases. Distinct pedological differences were observed between these phases. The chief differences are tabulated in Table 1. Further details are given in the text and in Appendix 2.

Normal phase

The normal phase of Cununurra clay has been described by Aldrick and Moody (1977) in their report on the soils of the Keep River area. There, it was the most common soil on the plains, but it was found only occasionally on the Ivanhoe Plain.

Typically these soils have mild gilgai microrelief (20 - 25 cm amplitude) and are about 120 - 150 cm deep over reddish parent alluvium. No morphological or chemical differences were detected between mounds and depressions of gilgai, indicating that land-levelling should not create significant soil problems.

A simplied profile of the normal phase is:

A11 (0 - 5 cm)	Dark greyish-brown 'self-mulching' clay, pH 7.5.
A12 (5 - 25 cm)	Dark greyish-brown medium to heavy clay, very hard, strongly structured, some carbonates, pH 8.5.
A13 (25 - 125 cm)	Dark greyish heavy clay, extremely hard, strongly structured, some carbonates, pH 8.5.
Transition (125 - 140 cm)	Brownish medium to heavy clay, weakly structured, increasing carbonates, pH 8.6.
AC (140 - 160 cm +)	Reddish medium clay, micaceous, with abundant carbonate nodules, pH 8.5.

Alkaline phase

These soils occupy a large proportion of the Ivanhoe Plain and are generally restricted to the area last re-worked by the Ord River. These areas occur generally south of the centre of Kimberley Research Station. The northern boundary of the occurrence of these soils is shown clearly on the map. They are 'brown' clays.

Table 1. Comparison of three main phases of Cununurra clay

Phase	Normal	Alkaline	Leached
Found	Chiefly Keep River area	Ivanhoe Plain south of K.R.S.*	Ivanhoe Plain north and east of K.R.S.
Principal profile form	Ug 5.15	Ug 5.34	Ug 5.25
Colour main horizon (A13)	Dark V/C = 1	Brown V/C = 5	Grey V/C = 2
Topsoil tilth	Medium	Fine	Coarse and cloddy
Virgin topsoil pH (0-25 cm)	Medium 7.5-8.0	Higher 7.8-8.5	Lower 6.8-7.8
Visible carbonates in profile	Some small nodules, more lower in profile	Nodules clearly present throughout, sometimes amorphous carbonates	None commonly visible except lower in profile
Drainage rating	Poor	Imperfect to poor	Poor to very poor
Associated soils	None common	Walyara and intergrades	Cununurra wetter phase

* K.R.S. - Kimberley Research Station

'Brown' clays have been recorded on the Ivanhoe Plain near Kimberley Research Station in previous reports by G.H. Burvill (1945, unpublished), Gunn (1969), and Aldrick and Moody (1977). Aldrick noted that these seemed to be different from the most common soil on the Keep Plain, which was a 'dark' clay, and advocated that the taxonomic discrepancy be investigated.

Pedologically, alkaline phase soils show evidence of minimal leaching. They have a relatively high carbonate content and are sometimes calcareous almost to the soil surface, with pH readings (virgin soil) of 7.5 or 8 at shallow depths. In some areas, probably in old levee situations (Gunn 1969), even more calcareous soils occur (Walyara family). Some carbonate nodules and fine amorphous carbonates are visible in the topsoil of many of the alkaline phase soils and small patches of calcareous intergrades with Walyara soils frequently occur. Soil structure is strong and fine and on cultivation the soil breaks down readily to a fine tilth.

These soils were claimed by some cotton growers to be more productive than soils of the leached phase in wet years and this could be a result of better internal drainage. Zinc deficiencies have been reported in rice grown on the highly calcareous Walyara soils and it seems likely that the high pH of the alkaline phase, especially the intergrades with Walyara soils, could also lead to an induced zinc deficiency.

A simplified profile of the alkaline phase is:

A11 (0 - 10 cm)	Dark brownish 'self-mulching' clay with a fine tilth. Some small carbonate nodules, pH 7.8.
A12 (10 - 35 cm)	Dark brownish medium to heavy clay, very hard and strongly structured. Some carbonate nodules, pH 8.4.
A13 (35 - 135 cm)	Dark brownish medium to heavy clay, very firm and strongly structured. Moderate amounts of carbonate nodules, pH 8.7.
Transition (135 -145 cm)	Brownish medium clay, increasing carbonate content (mainly nodules), pH 8.7.
AC (145 - 160 cm+)	Reddish light to medium clay with abundant carbonate nodules, pH 8.5. Some micaceous material.

Leached phase

Soils of this phase occur commonly in the pedologically older areas of the Ivanhoe Plain north of the elbow of capture of the Ord River. These areas lie roughly north and east of the centre of Kimberley Research Station. The approximate southern boundary of occurrence of these soils is shown on the map.

Pedologically, leached phase soils show evidence of being more strongly leached than members of either the normal phase or the alkaline phase. Free carbonates are only rarely visible in the top 100 cm or so of soil material and soil pH readings are lower at shallow depths than those of either the alkaline phase or the normal phase. In many cultivated and irrigated topsoils where soil pH is artificially raised compared with virgin profiles, it is noticeable that pH drops to more usual levels immediately below the disturbed zone.

Soil colour is distinctly greyer than the alkaline phase and marginally greyer than the normal phase; However, the differences are minor and difficult to detect without careful standardization. Soil structure is coarser than in the alkaline phase, especially in the upper parts of the profile and on cultivation these soils tend to produce a coarse cloddy tilth, less desirable than the fine tilth of soils of the alkaline phase.

Clay contents are also higher than for soils of the alkaline phase. Some cotton farmers claimed that these soils were inferior to soils of the alkaline phase in wet years and this could be because of their poorer drainage.

Small patches of calcareous soil comparable with those found amongst the alkaline phase soils do not occur in the main areas of these soils. Relatively large and individually mappable areas of other calcareous high pH soils do occur and these have been mapped separately in land unit 9C.

In a number of instances relatively poorly drained areas of soil (Cununurra wetter phase) were found amongst the leached phase soils. The worst areas of these have been mapped separately in land unit 5d.

A simplified profile of the leached phase is:

A11 (0 - 5 cm)	Dark greyish 'self-mulching' clay, pH 7.0.
A12 (5 - 25 cm)	Dark greyish heavy clay, extremely hard and strongly structured, pH 7.6.
A13 (25 - 130 cm)	Dark greyish heavy clay, very firm and strongly structured, traces of carbonates, pH 8.5.
Transition (130 - 145 cm)	Dark yellowish-brown heavy clay, traces of carbonates, pH 8.8.
AC (145 - 160 cm+)	Dark brown medium to heavy clay, small amounts of carbonate nodules, pH 8.9.

Wetter phase

In the Keep River area Aldrick and Moody (1977) found Cununurra soils with worse drainage than usual amongst the normal ones and these had vegetation associations indicative of wetter conditions than usual. They often occurred around the margins of swampy areas. They had paler colours than normal in the upper 30 cm or so of the profile, but the lower part of the soil was similar to that of the normal phase.

On the Ivanhoe Plain more poorly drained soils were also found and these graded into the 'greyish' phase of Aquitaine soils. Some were found around the margins of swampy areas and these were similar to the wetter phase soils found in the Keep River area. Others occurred on broad, relatively flat interfluve areas amongst Cununurra soils of the leached phase and these were a little different. They had greyish topsoils similar in colour to soils of the leached phase and slightly paler, stickier subsoils with an almost massive appearance. This latter group has been classified with the other wetter phase soils for convenience and simplicity. It is expected that agronomically the two soils found in the wetter phase will behave similarly. They have been mapped in land unit 5d.

Aquitaine family

Soils in this family have very evident hydromorphic characteristics. They were probably the most common soil included in the 'flooded' phase of Cununurra clay by G.H. Burvill (1945, unpublished). However, they have marked differences from the Cununurra soils particularly in the main horizon (the A13 horizon) and so cannot be considered as a phase of that family.

Aquitaine soils occur in depressed, contained areas such as swamps and 'junction complex' areas, around the margins of the plains, where annual inundation is a significant feature. The inundation is because of local run-off from both the adjoining sandy country and the clay plain itself. Both local opinion and the geomorphic evidence indicate that river water does not contribute to the inundation.

In the Keep River area one phase of Aquitaine soils was described (Aldrick and Moody 1977), but because of the greater diversity of profile morphologies related to varying degrees of seasonal inundation that occur on the Ivanhoe Plain, it has become necessary to divide the family into three phases. Soil colour is the most obvious variable and as it varies with other features of the soils it has been used as a basis for the subdivision.

'Bluish' phase

These soils have a distinctive colour when dry and are referred to locally as 'blue' clays. The colour is particularly pronounced along earth roads and tracks in the dry season. Soils in this phase are more deeply inundated and have more hydromorphic profile attributes than soils of the other two phases.

Because of the inundation, leaching has been more pronounced and soil pH is lower in the upper profile than for Cununurra clays. Free carbonates are not common except in the transitional zone below the profile. The underlying 'reddish' parent material is distinctly paler or more yellow than that under Cununurra soils and contains a few mottles.

Most of the soils are mapped in land units 5a and 5c. In land unit 5c adjacent to the sandy country bordering the plains, inclusions and surface accumulations of sand, gravel, stone and rock are common and a 'debil-debil' microrelief has developed (see land unit description for 5c).

Native tree species grow particularly densely on soils of the 'bluish' phase. These are usually *Eucalyptus microtheca* and *Excoecaria parvifolia*. However, soils in land unit 5c are treeless.

A simplified profile of the 'bluish' phase is:

A11 (0 - 8 cm)	Greyish ('bluish' when disturbed) structured medium clay, weakly 'self-mulching', pH 6.0 to 7.0.
A12 (8 - 30 cm)	Grey ('bluish' when disturbed) medium to heavy clay, extremely hard, structured, and sometimes mottled, pH 6.5 to 7.5.
A13 (30 - 135 cm)	Grey or olive-grey medium to heavy clay, weakly structured, very firm, usually distinctly mottled, pH 7.5 to 8.0. Some carbonate nodules and sand lenses.
AC (135 - 150 cm+)	Brownish or yellowish medium clay, some mottles, some carbonate nodules, pH 8.5 to 9.0.

'Greyish' phase

Soils in this phase are greyish. They are inundated to a lesser depth and for a shorter time than soils of the 'bluish' phase. 'Greyish' Aquitaine soils occur mainly in swamps and some parts of the 'junction complex'. Towards the main body of the plains they merge with soils of the wetter phase of Cununurra clay.

These are distinctly hydromorphic swamp soils and have many features in common with soils of the 'bluish' phase. They support a less dense tree cover, although the same species are present. Subsoils are not as pale or as mottled as those of the 'bluish' phase. The 'greyish' phase soils are mapped in land units 5b and 8.

A simplied profile of the 'greyish' phase is:

A11 (0 - 8 cm)	Dark grey structured medium clay, weakly 'self-mulching', pH 6.5 to 7.5.
A12 (8 - 30 cm)	Dark grey medium to heavy clay, extremely hard, coarsely structured, pH 7.5 to 7.8.
A13 (30 - 130 cm)	Dark grey heavy clay, very firm, weakly structured, distinctly mottled, pH 8.0 to 8.5. Some carbonate nodules and sand lenses.
AC (130 - 150 cm+)	Brownish or reddish medium to heavy clay, some mottles and some carbonate nodules, pH 8.5 to 9.0.

'Olive-yellow' phase

These soils occur near the 'junction complex' along the eastern margin of the Ivanhoe Plain. They have a distinct 'yellowish' or 'olive' colour when dry, although these colours were not always substantiated by moist Munsell colour readings.

It is likely that the particular colouration is because of an influence of run-on water from the nearby sandier country. These soils occur opposite outwash fans in the adjoining sandy country and several of them were found to contain more sand than usual in their profiles.

Morphologically they are similar to soils of the 'greyish' phase (apart from their colour) and they are subjected to a similar degree of seasonal waterlogging. They have been mapped in land units 5b and 5d, but they also occur in the 'junction complex' (land unit 8). They are not common soils.

Soil profiles are similar to those described above for the 'greyish' phase, but colours are dark greyish-brown (Munsell), and some fine sand occurs in some profiles. Carbonate levels and pH are also slightly higher in the upper parts of the profile.

Keep family

Keep family soils have a long history of pedogenetic development. On the Ivanhoe Plain they have probably developed from calcareous clay deposits in the inter-dune corridor areas of ancient point bar systems. They all occur in the northern (older) province. Large pedogenetic calcrete nodules are a feature of these soils and, although these probably formed initially in the lower layers of the soils, they are now exposed on the gilgai mounds. The gilgai have a relatively large amplitude of relief and the depressions retain ponded rainwater during the wet season. Capillary movement of this water up into the mounds tends to occur especially on hot dry days and small quantities of dissolved carbonates are carried with it. These re-precipitate in the soil of the mounds and secondary accumulations of finely divided carbonates have occurred. The topsoils of the mounds have a high pH.

The situation is somewhat simpler in the pedogenetically younger soils of Walyara and Cununurra (alkaline phase) families and their intergrades. The parent alluvium of these soils was initially calcareous and, as the original carbonates have not been fully removed by leaching, the topsoils have retained a high pH. Secondary accumulations seem to be less significant.

In their Keep River report Aldrick and Moody (1977) noted that the strongly alkaline dark brown cracking clay soils found by Gunn (1969) on Kimberley Research Station in association with Walyara soils may correspond with soils of Keep family (normal phase). During this survey of the Ivanhoe Plain the strongly alkaline cracking clay soils referred to by Gunn were described on several occasions and are referred to here as intergrades between Cununurra (alkaline phase) and Walyara families. However, these intergrades are not similar to Keep family soils and the chief differences are given in Table 2.

Normal phase

Keep normal phase soils are not common on the Ivanhoe Plain. All of them occur downstream of the elbow of capture of the Ord River in the area where land unit 1b occurs. They are mapped in land unit 9c.

The soils have a gilgaied microrelief and a distinctive colour, termed 'mustard coloured' by Aldrick and Moody (1977). The soil is self mulching and surface textures may be as low as light clay. Large pedogenetic calcrete nodules appear on the surface of the gilgai mounds and are abundant throughout the profile. Soil pH values are high throughout with readings of 8.0 at the surface being common. Secondary accumulations of sparingly soluble materials have occurred and most profiles are calcareous, at least in the A13 horizon. Leaching conditions are minimal in these soils.

Levelling of areas of Keep normal phase soils would expose calcareous high pH soil material from the gilgai mounds and plant-growth problems would be likely to develop on those areas.

A simplified profile of the normal phase is:

A11 (0 - 5 cm)	Dark brown 'self-mulching' clay with some carbonate nodules, pH 8.0. A surface strew of about 5 - 10% carbonate nodules up to 2 cm in diameter is common.
A12 (5 - 35 cm)	Dark brownish medium to heavy clay, very hard, strong fine structure, 5% carbonate nodules, pH 8.3.

Table 2. Differences between Cununurra/Walyara intergrades and Keep family soils

Factor	Cununurra (alkaline phase) Walyara intergrades	Keep (normal phase) soils
Gravel on soil surface	Inherited siliceous gravel and stone	Pedogenetic calcareous nodules
Position occupied in microrelief	Found on both gilgai mounds and depressions	Usually found on gilgai mound only
Amplitude of microrelief	Usually < 20 cm	About 30 cm, sometimes more
Seasonal inundation	No appreciable period of inundation	Gilgai depressions inundated for prolonged periods
Primary profile form (Northcote 1971)	Ug, or Ug/Uf integrades	Always Ug

A13 (35 - 110 cm)	Dark brownish heavy clay, extremely hard, strongly structured, 10% carbonates, pH 8.6. Calcareous.
AC (110 - 160 cm+)	Dark yellowish medium to heavy clay, calcareous, with 10% carbonate nodules, pH 8.8.

Flooded phase

Soils of Keep flooded phase were originally recorded on the Keep River plain (Aldrick and Moody 1977), but they were not common and a detailed description was not given. They occurred in small locally depressed swamps.

During this survey similar soils were found in parts of Green Swamp. They appeared brownish or reddish when dry and usually had a value/chroma rating of 5 and a principal profile form of Ug 5.34. However, moist Munsell colours often indicated a value/chroma rating of 2 and thus a principal profile form of Ug 5.25.

Pronounced microrelief is characteristic of this phase with large amplitudes of relief in the gilgai, up to 60 cm. Profiles are alkaline and often calcareous to the soil surface and a strew of carbonate nodules is common, particularly on the mounds of the gilgai. It is probable that because of the relatively great microrelief the mounds of the gilgai are not regularly inundated and suffer only minimal leaching. They are thus able to retain and allow precipitation of sparingly soluble compounds, such as carbonates.

Native vegetation varies on these soils, but *Excoecaria parvifolia* is well represented.

Because they presented a similar aerial-photo pattern to the Aquitaine family soils they occur in association with, these soils were not mapped separately. They have some similar characteristics to soils of the Aquitaine family, but if they were to be used agriculturally their high pH and relatively great microrelief would render them significantly different and an attempt would need to be made to map them. At present they occur in land unit 5a.

A simplified profile of the flooded phase is:

A11 (0 - 8 cm)	Brownish 'self-mulching' medium clay with carbonate nodules on and in the soil, pH 8.0.
A12 (8 - 25 cm)	Brownish or yellowish-brown medium clay, extremely hard, strongly structured, 2 - 5% carbonates, pH 8.0.
A13 (25 - 120 cm)	Brown or yellowish-brown medium or heavy clay, very firm, strongly structured, with 5% carbonate nodules, pH 8.5. The soil material is faintly mottled and calcareous.

AC (120 - 150 cm+)	Dark brownish or yellowish medium to heavy clay, extremely firm, weakly structured, pH 9.0. Five to 10% carbonate nodules. The soil material is mottled and calcareous.

Weaber family

Reddish soils have been recorded throughout the plains of the Ord Scheme by at least three different authors. G.H. Burvill (1945, unpublished) originally described the Meruin family as forming in older, coarser alluvial deposits than those in which the cracking clays had formed. Most Meruin family soils occurred between the clay plain and the Ord River where erosion had cut into and exposed the underlying older alluvium. Burvill also referred to the reddish soils that occur on the clay plain itself as Meruin family, but that extrapolation is not favoured here.

In their survey of the Keep and lower Weaber plains Aldrick and Moody (1977) identified Weaber family soils and these are similar to the Weaber normal phase soils described below. A heavier-textured phase of Weaber soils has also been identified during this survey of the Ivanhoe Plain. On the Packsaddle Plain Stoneman (1972) described a somewhat sandier though basically similar soil as Packsaddle sandy loam.

The genesis and geomorphic relationships of these soils were discussed earlier.

Normal phase

These soils are well to moderately-well drained gradational-textured red earths. Their surface horizons are sandy or loamy, usually sandy clay loam or clay loam. Subsoils are reddish and heavier in texture and the whole profile is porous and massive.

They occur in small areas of alluvium that are coarser in texture than usual and thus have greater permeability. The increased leaching occurring as a consequence would probably have removed sparingly soluble bases from the soil material and lowered the pH to an extent sufficient to preclude development of cracking clay soils.

Agronomically, these soils differ significantly from the cracking clays, probably because of their different hydrological performance. They tend to dry out sooner than adjacent cracking clays after an irrigation and allow crops to wilt earlier. Applied nutrients may also behave differently in these soils. As a result, crops such as cotton perform very badly and weeds are able to encroach. However, with management tailored specifically for these soils they could produce good crops. Because of their sandier topsoil texture they may be suited to peanut production, especially where topsoil consistence is low.

A simplified profile of the normal phase is:

A1 (0 - 10 cm)	Dark reddish-brown sandy clay loam, porous, pH 6.5.
A3/B1 (10 - 45 cm)	Dark reddish light clay, porous and massive, ph 6.5.
B2 (45 - 160 cm)	Dark reddish light to medium clay, very hard, pH 6.5 to 7.0.

Heavier phase

The heavier phase occurs unpredictably on some of the inclusions of red earths in the plain. These soils are less common than soils of the normal phase. The chief morphological difference is one of texture and the heavier phase has uniform-textured profiles with topsoil textures of light to medium clay. Textures also tend to be finer throughout the profile with less coarse sand than soils of the normal phase. Development of structure is also a feature of the B horizons, particularly in the heavier-textured members.

The genesis of soils of the heavier phase was probably similar to that for the normal phase and the textural difference could probably be related to an initially finer parent material. However, permeability of this finer material would still have been greater than for the material on which the cracking clays formed.

Agronomically these soils seem to differ only to a minor extent from the cracking clays. Their heavier texture and reduced porosity would give them water infiltration and retention characteristics more simlar to those of the clays. It was observed that cotton crops growing on them were not noticeably different from crops on the adjacent clays.

A simplified profile of the heavier phase is:

A1 (0 - 20 cm)	Dark reddish-brown light to medium clay, very hard, massive and porous, pH 6.5.

B1 (20 - 70 cm)	Reddish medium clay, extremely hard, massive and porous or weakly structured, pH 7.0.
B2 (70 - 150 cm+)	Reddish medium clay, very firm, massive or structured, pH 7.5. Some grit or sand evident.

Walyara family

Originally, Walyara soils were described by Gunn (1969) on Kimberley Research Station. Essentially, they had gradational-textured profiles and were calcareous throughout. They occur on low gravelly rises and in linear belts which Gunn thought to be almost certainly remnants of old levees and channels.

Soils of this family were also recorded by Aldrick and Moody (1977) in the Keep Plains area, mainly on small flat raised areas. Aldrick indicated that the Walyara soils probably formed in these areas because of the particular hydrological regime operating there, that is, adjacent to a low periodically inundated area so that water could move upwards into the Walyara soil by capillary action. These are conditions of minimal leaching.

Most of the Walyara soils found on the Ivanhoe Plain occur on or near Kimberley Research Station and most are mapped in the complex land units 9a, 9b and 9c. Some small occurrences were also recorded in the alkaline phase of Cununurra clay in land unit 1a, but these were too small to map separately.

Crop responses on these soils have been unfavourable in the past and various chemical factors have been cited as possible causes. Amongst these have been toxicity, nutrient imbalances, high pH (Gunn, 1969) and zinc deficiency (D.A.Woolley and A.L. Chapman, 1972, unpublished).

A characteristic black curled crust and a siliceous gravel strew form on these soils over a soft to hard 'mustard coloured' A horizon. Textures are gradational in trend and rise from clay loam at the surface to medium or heavy clay. The soils are calcareous throughout and free carbonates are visible throughout the profile. Characteristically, these soils support *Carissa lanceolata*.

A simplified profile of Walyara family is:

A1 (0 - 10 cm)	Dark brown clay loam with a thin curled crust, and surface siliceous gravel. pH 8.0. Calcareous.
A3 (10 - 20 cm)	Dark brown light clay, very hard, some finely divided carbonates, pH 8.5. Calcareous.
B1 (20 - 100 cm)	Dark brown medium clay, extremely hard, with weak structure and 20% finely divided carbonates. pH 8.8. Calcareous.
B2 (100 - 160 cm+)	Dark yellowish medium to heavy clay, extremely firm, weakly structured, some finely divided carbonates. pH 8.8. Calcareous.

Other soils

These soils are not of agricultural significance in the survey area, but are included here to record their presence. A number of additional soils not described below are also thought to occur in the 'junction complex' (land unit 8) and along the river and creek banks (land unit 7b), but as these are not considered to be generally usable areas the soils concerned have not been investigated.

Cununurra darker phase

These are adequately described in the report on the Keep River area (Aldrick and Moody 1977). They are similar to soils of the normal phase but darker in colour. Very few were observed on the Ivanhoe Plain and these were mostly in land unit 8.

Cununurra eroded phase

Profiles of these soils are also basically similar to those of the normal phase, but they tend to be browner and better drained. As in the Keep River area (Aldrick and Moody 1977) they are severely gully-eroded and truncated to various degrees. All occurrences were in land unit 7b.

Milligan family

These are also adequately described in the report on the Keep River area (Aldrick and Moody 1977). Essentially, they are uniform fine-textured soils with significant inclusions of ferruginous gravel and sand from the sandy country adjacent to where they occur (in land unit 8). They are not gilgaied soils, although they exhibit some cracking. They usually occur on low mounds in association with the mottled clays described below.

Mottled clays

This group is of minor importance and has not been allocated family status. The soils are dark cracking clays with significant profile mottling especially in the upper parts, because of organic decomposition. They occur in land unit 8 in association with soils of the Milligan family. Mottled clay soils occupy seasonally inundated depressions between areas of Milligan soils.

The mapping units

J.M. Aldrick and A.J. Clarke

The distinction between a soil taxonomic unit and a mapping unit is important. The soil taxonomic units used in this report are soil families and phases. They relate to soil profiles inspected at particular points and described in pedological terms.

The mapping units, however, are termed "land units" and vegetation, landform and factors such as flooding, stoniness and the capacity to be eroded are all taken into account, as well as soil, in determining their boundaries. The final land unit is an almost uniform area of land sufficiently large to delineate on a map at a particular scale. It may contain only one soil or several different soils, but because it is designed to reflect potential for land use, the land unit must have an almost uniform set of factors relating to its capability.

The land units described here may not have consecutive numerical designations. This is because they belong to a common map key constructed to relate to all of the maps produced for the clay plains surveyed so far. Further details about the common map key are given later and in Appendix 5.

Each land unit description is in two parts; a factual description of the main tangible characteristics of the unit and an interpretive statement on the possible significance of these facts for potential users of the land. The key on the accompanying maps (sheet 1, 2 and 3) consists of an abbreviated version of these factual descriptions. The map key is in Appendix 4.

The description of the main characteristics of each unit includes references to soil families and phases. Detailed information on each of the soils has been given and further information is in Appendix 2. As most of the Ivanhoe Plain had been cleared and native vegetation could not be described, little significance could be attached to it. However, brief references have been made to native vegetation in some cases and these are based on field descriptions in uncleared areas (e.g. Green Swamp) and field descriptions plus aerial photograph interpretation in other parts of the plain.

More detailed notes on the flora of another part of the area having similarities to the Ivanhoe Plain are provided in the report on the land units of the Keep and lower Weaber plains by Aldrick and Moody (1977).

In recording the significance of the main characteristics of the units emphasis is placed on assessments of land capability, especially irrigation potential. A number of factors that may affect the use of the land have been considered, including permeability, drainage, moisture retention characteristics, seasonal inundation, erosion, pH, exchangeable sodium percentage, tilth after cultivation, microrelief and native timber cover. These factors may have a favourable or an unfavourable expression, depending on the particular use proposed for the land. For example, poor drainage and a tendency to be seasonally inundated may be adverse factors for cotton growing and require amelioration or elimination, but for rice growing or fish farming these factors may be considered favourable.

The individual land unit capability and other data are used later to provide an integrated overall view of the suitability of the Ivanhoe Plain for irrigated agriculture.

Description of land units

Land unit 1a

Land unit 1a occurs in the southern (younger) province (i.e. south of the centre of Kimberley Research Station), where the soils have formed on relatively youthful, recently re-worked alluvium. The soils are mainly brownish cracking clays with finely structured, high pH topsoils (Cununurra, alkaline phase). Small patches of calcareous Walyara soils and intergrades between Cununurra and Walyara soils frequently occur within this land unit, but are difficult to detect after cultivation. More information on the calcareous soils is given in the notes on land unit 9a.

Aerial photography pattern extrapolations indicate that the native vegetation before clearing probably included abundant large *Lysiphyllum cunninghamii* (Bauhinia) and occasional *Carissa lanceolata* (Conkerberry).

Land unit 1b

This occurs in the northern (older) province (i.e. north and east of the centre of Kimberley Research Station) where the soils have formed on relatively old (now relict) alluvium. Because of their greater age, the soils here are more strongly leached than the soils of land unit 1a. They are mainly greyish clays with coarsely structured almost neutral pH topsoils (Cununurra leached phase). Subsoil pH frequently rises to 9.0. Small patches of less well drained soils (Cununurra wetter phase) occur within this land unit. Aerial photographs indicate that the bulk of this land unit was relatively open and treeless before development.

Land unit 2c

These land units occur as 'islands' within the main areas of cracking clay soils. Their distribution is probably related to the existence of more turbulent or higher velocity areas in the floodwaters from the Ord River when the alluvial materials of the plain were originally laid down. The alluvium is coarser than usual in these 'islands' and reddish, relatively sandy soils (Weaber, normal phase) have formed in them. These soils are massive and porous with neutral pH trends and sandy topsoils. In uncleared areas, a range of eucalypts occur in these land units.

Land unit 2e

These areas have many characteristics in common with areas of land unit 2c. They occur as 'islands' of reddish soils having a similar origin, being formed in coarser areas of alluvium that were originally deposited from higher velocity or more turbulent areas of floodwater. However, the original alluvium was not as coarse as for land unit 2c and the reddish soils formed here are heavier in texture, especially topsoil texture, than for land unit 2c (Weaber heavier phase). Textures are light to medium clays throughout, although some fine sand is generally evident in the soil. Soil pH trends are neutral. A range of eucalypts probably occurred on these areas before clearing.

Land unit 4c

This land unit only occurs in the northern (older) province in the area where land unit 1b occurs. It is similar to land unit 9c, but has different soils. Land unit 4c is distinctly gilgaied, with Keep normal phase soils over most of the area. Some Cununurra soils also occur. Surface carbonate nodules and a brownish, 'mustard-coloured' hue are characteristic of Keep soils. The pedological differences between the Keep normal phase soils of this land unit and the Walyara/ Cununurra intergrades of land unit 9c are summarized in Table2.

Land unit 4f

These land units occur in concentric belts around areas of land units 2c and 2e and sometimes separately. They all occur in the southern (younger) province. They contain a mixture of Cununurra and Weaber family soils and intergrades between them. Microrelief could not be measured as every occurrence of land unit 4f had been levelled, but similar units on the Keep River plains (land units 4a, 4b, Aldrick and Moody 1977) were found to have relatively great amplitudes of microrelief. If this was the case here, inundation of the depressions would have been a regular seasonal occurrence.

Land unit 5a

These are almost flat low-lying seasonal swamps, inundated annually to significant depths. The largest areas occur in Green and Martin's swamps. The inundation is because of water originating partly as run-off from the clay plain and partly as run-off and seepage from the sandy land systems that adjoin most of these areas. The soils are mostly Aquitaine 'bluish' phase and Keep flooded phase. Minor areas of Aquitaine 'greyish' and 'olive-yellow' phases also occur. Except for Keep flooded phase these are all well leached soils, because of their regular inundation. Analyses indicate that they have exchangeable sodium percentages well in excess of 15% and soil pH readings > 9.0 in their subsoils.

Native vegetation includes a dense woodland of *Eucalyptus microtheca* and *Excoecaria parvifolia*.

Land unit 5b

Land unit 5b occurs mainly in Green and Martin's swamps adjacent to land unit 5a, but nearer the main body of the plains. These are seasonally inundated areas, but depths of water are less than for unit 5a. Duration of the inundation is also less and in years of lower than usual rainfall inundation may not occur at all. Soils are mainly Aquitaine 'greyish' phase, but where this land unit occurs adjacent to the 'junction complex' (land unit 8) Aquitaine 'olive-yellow' phase soils also occur.

These soils are well leached because of their regular inundation. Analyses indicate that they have exchangeable sodium percentages > 15% and soil pH readings of 9.0 or more in the subsoils. Native vegetation includes a woodland of *Eucalyptus microtheca* and *Excoecaria parvifolia*, but not as dense as for land unit 5a.

Land unit 5c

This land unit occurs as a narrow linear belt around the edge of the clay plain between the sandy land systems and land units 5a or 8. Land unit 5c is a slightly depressed area and when seasonally inundated, water is deeper here than in any other land unit. The soils are Aquitaine 'bluish' phase with very hydromorphic characteristics. A particular microrelief occurs here known as 'debil-debil', consisting of small steep-sided mounds about 2 m apart, up to 20 cm high and 40 cm across, in a relatively flat matrix. Inclusions and surface accumulations of sand, gravel, stone and rock from the adjoining sandy land systems are common. Land unit 5c is characteristically treeless.

Land unit 5d

These land units occur on broad interfluves in locally poorly drained areas of the main body of the plains. They only occur in the northern (older) province, where land unit 1b predominates. The most common soil is Cununurra wetter phase, but the less well drained members of Cununurra leached phase also occur. Aerial photographs indicate that these areas were originally treeless.

Land unit 7a

These are the rivers and major creeks and associated steep banks. Permanent water, bedloads of sand, gravel and stone, and rock bars are common in the Ord River. Native animals, particularly birds, are abundant in the frontage areas. Vegetation along the banks of the Ord includes some areas of tall *Eucalyptus* and *Melaleuca* species and a great variety of shrubs and grasses. Severe erosion is a feature of the banks of the major tributary creeks.

Land unit 7b

These areas are the eroded, sloping margins of the plain adjacent to the rivers and major creeks of land unit 7a. The stream beds are incised and natural erosion has been severe. Gullies, rills, scalds and wash areas are common.

Some depositional areas occur and levees, swamps and point bars have formed in them. Soils vary considerably and include truncated cracking clays (Cununurra eroded phase) and sandy alluvial soils. Exposures of the reddish alluvium that normally underlies Cununurra clay soils are common. Vegetation is complex, but includes moderately dense stands of *Eucalyptus* species and *Lysiphyllum cunninghamii*. These areas have been mapped in considerable detail by G.H. Burvill (1945, unpublished).

Land unit 8a

Land unit 8a occurs as a narrow low-lying strip along the edge of the clay plain adjacent to the sandy land systems. It is part of what was termed the "junction complex" by G.H. Burvill (1945, unpublished). This area receives run-off and seepage water from both the clay plain and the sandy areas and depressions within it are inundated seasonally. Soils vary enormously, but most are heavy clays such as Aquitaine, Milligan and Mottled clays. Contributed sand and lateritic gravel are common constituents of the soils.

Microrelief is pronounced, with amplitudes up to 40 or 50 cm. Vegetation is very varible but *Eucalyptus microtheca* and *Excoecaria parvifolia* commonly occur.

Land unit 8b

Land unit 8b occurs between land unit 8a and the sandy land systems. It is part of what was termed the "junction complex" by G.H. Burvill (1945, unpublished) and is itself considerably complex. This unit receives water mainly from the sandy areas and represents the outwash of material carried by streams from these areas and adjacent hills. Soils are variable and mostly gradational textured with sandy loam to sandy clay surface textures. There are also duplex soils and areas of heavy clays. Vegetation is extremely variable with *Eucalyptus polycarpa* and *E. microtheca* common.

Land unit 9a

Land unit 9a occurs mainly in the southern (younger) province in the area where land unit 1a occurs. Most occurrences are on or near Kimberley Research Station. A complex association of soils occurs in land unit 9a with Cununurra alkaline phase, Walyara, and intergrades between them being the most common. In regard to the Walyara soils, Gunn (1969) has indicated that "These soils are found on low gravelly rises and in linear belts

which are almost certainly remnants of old levees and channels''. After clearing, levelling and cultivation, areas of Walyara soils and the intergrades are difficult to detect. The Walyara soils are calcareous, have a high pH, and subsoil exchangeable sodium percentages significantly > 15%.

In land unit 9a a high proportion of Walyara soils occur - about 40% of the area and individual occurrences of it are up to 20 m across. Native vegetation includes large dense *Lysiphyllum cunninghamii* and *Carissa lanceolata*. *Eucalyptus clavigera* grows only on occurrences of this land unit in the northern (older) province.

Land unit 9b

Land unit 9b is similar in many respects to land unit 9a. It also occurs mainly in the southern (younger) province, particularly on and near Kimberley Research Station. It contains an association of the same soils as for land unit 9a - Cununurra alkaline phase, Walyara and intergrades between them. However, in this land unit the proportion of Walyara soils is reduced to about 20% of the area. Individual occurrences of these soils tend to be of linear orientation with dimensions up to 3 m by 6 m. Eucalypts do not usually occur in land unit 9b, but *Lysiphyllum cunninghamii* and *Carissa lanceolata* are common. Other characteristics are as for land unit 9a.

Land unit 9c

Land unit 9c occurs in small patches in the southern (younger) province, in the area where land unit 1a occurs. It is very similar to land unit 4c, but has different soils. It consists of a weakly gilgaied pattern of soils, with Cununurra alkaline phase soils in depressions and intergrades with Walyara soils on the mounds. Occasionally the mounds are extended slightly and Walyara soils occur on them. However, the proportion of Walyara soils is only about 2% of the area; much less than for land units 9a or 9b. The pedological differences between the Walyara/Cununurra intergrades of this land unit and the Keep normal phase soils of land unit 4c are summarized in Table 2.

Land unit 10a

Land unit 10a is a rarity, but quite distinctive. Only one occurrence was mapped, between Kimberley Research Station and Martin's Swamp. Evidence from aerial photographs and deep drilling indicates that it is probably an eroded remnant of an ancient point bar system. The soil is basically Cununurra leached phase, but in this area it contains abundant coarse whitish sand grains throughout and has a surface veneer of up to 80% siliceous sand and gravel. Soil pH values were below 7.0 for the top 20 cm, except where pH had been raised by irrigated use. This soil had a brittle, light-weight character when dry and seemed to have a lower than usual capacity to store moisture. It was underlain by coarse sand.

Land unit 10b

This land unit is similar in many respects to land unit 10a, but it contains less sand and occurs more frequently. All occurrences are in the northern (older) province in the area where land unit 1b occurs. Soils in this land unit are mainly Cununurra leached phase, with a little coarse sand throughout the profiles and a light-weight, brittle character when dry similar to that of the soils in land unit 10a. Some intergrades with soils of Weaber family also occur in areas close to occurrences of land units 2c and 2e. As for land unit 10a, it is likely that these land units are associated with old sandy levee and point bar deposits.

Soil physical attributes

A.J. Clarke and B.A. Wren

The sampling techniques used and the distances and methods of transport available meant that the samples obtained were not ideal. Some distortion of the samples inevitably occurred as the sampling tubes were hammered into the soil and most of the clods broke up in transport.

The results obtained must be considered to have low levels of precision and reliability and are of only limited value in predicting soil response to irrigation.

In this circumstance it is useful to consider the results obtained in other areas with similar soils. Hearn (1975) has discussed the similarity between the Sudan Gezira and the Ord Valley in respect of both soils and climate. Soils of both areas are very similar in physical properties. Farbrother (1972) reviewed the field behaviour of Gezira clay under irrigation. He showed that the behaviour of the highly cracking clay is so different from normal well-aggregated soils that soil water analyses do not provide an understanding of what happens after watering.

Farbrother suggested that only two mechanisms were involved in the movement of water into Gezira clay. These were, firstly, the free flow of water downwards to fill those cracks present and then secondly, the rapid redistribution of this water horizontally and vertically on the surfaces of the cracks from wet soil to dry soil. Farbrother suggested that gravity played no part in the distribution of water and that the quantity of water entering is dependent on the volume of the cracks.

Once the cracks had been filled by expansion of the clay, even though surface soil moisture was maintained by frequent flooding, the moisture content of lower layers remained fairly constant, showing how slow the rate of transfer was after the initial rapid phase had ended. Downward moisture movement from then on would continue, but at a very slow rate.

If the similarity between soils of the Sudan Gezira and the Ord Valley is accepted, the implication is that irrigations effectively only supply water to replenish the easily rechargeable zone. The capacity and depth of this zone would depend on the interval between irrigations and the effective depth of rooting of the crop being grown. Amounts of water in excess of this capacity would mostly pond, or drain off the surface.

Because of the very slow subsoil drainage it is unknown whether there is any salinity build-up in surface layers, or whether the limited through-drainage can maintain an equilibrium. On some soils in this survey, particularly the high clay-content Aquitaine series, hydraulic conductivities of the lower layers sampled were very low and may not afford sufficient through-drainage to avoid possible future salinity problems.

Further work would seem essential to assess the leaching requirement of these soils. More efficient methods of assessing hydraulic conductivities are available and should be employed in the future to provide a more comprehensive knowledge of the physical characteristics of these soils.

Soil chemical attributes

P.W. Moody

My aim is to indicate any likely limitations to crop production associated with soil chemical properties which may be inherent or which may be induced following a history of irrigation. Analytical data are given in Appendix 3.

Inherent limitations

For assessing inherent limitations, the chemical attributes of the A11 and A12 horizons will be discussed as I consider these horizons to represent the root zone. S.T. Smith (1964, unpublished) noted that observations of cotton roots in wet season plantings indicated little root proliferation below 60 cm, and Northern Territory experience with irrigated rice suggested a shallower root depth (S. Baseden, personal communication). The A11 and A12 horizons of the soils of the Ivanhoe Plain comprise a depth which varies from 25 cm - 45 cm depending on soil family.

Inherent chemical attributes of the root zone which could affect crop productivity are:-

1. excess salinity
2. excess sodicity
3. excess bicarbonate
4. deficiencies of macronutrients
5. deficiencies of micronutrients

Excess salinity

The conductivity of the saturation extract (EC_e) in the root zone of cotton, sorghum and rice which reduces yield by 10% is 1000, 600 and 500 mS/m respectively at 25°C (Richards, 1954). From the relationship of the EC_e to the conductivity of the 1:5 soil:water suspension ($EC_{1:5}$) derived from similar soils of the Keep River Plains ($EC_{1:5} = 0.1667\ EC_e$ - (Aldrick and Moody, 1977), and $EC_{1:5}$ causing 10% yield reduction of these crops corresponds to 180 mS/m for cotton, 100 mS/m for sorghum and 80 mS/m for rice.

Using these upper conductivity limits as criteria of excessive salinity in the A11 and A12 horizons, none of the type profiles is sufficiently saline to affect crop production.

Excess sodicity

An excessively sodium-dominated exchange complex can have effects on the nutrition of the plant and on the physical properties of the soil.

American workers (Richards, 1954) have shown that rice can tolerate an exchangeable sodium percentage (ESP) in the root zone of 20 and cotton an ESP of 40 without showing adverse effects on nutrition. However, growth may be stunted because of the physical effects of poor aeration, surface crusting and impermeability. While an ESP in excess of 15 is regarded as being associated with undesirable physical properties Richards, (1954), Loveday and Pyle (1973) showed that dispersion in some Australian soils occurred when the ESP exceeded 6. As none of the ESPs of the A11 horizons of the type profiles exceed 1.4, physical problems associated with sodicity, such as surface sealing, are improbable in this horizon.

The A12 horizons of type profiles belonging to the Walyara and Cununurra (alkaline phase) families have pH readings > 8.5 indicating possible unfavourable physical conditions.

Excess bicarbonate

Following submergence of calcareous soils for rice production, Lian and Tanaka (1972) found a large sustained increase in the bicarbonate ion concentration in the soil solution. Subsequent work showed that the levels of bicarbonate in the soil solution caused reduced dry matter yield and potassium uptake of rice grown in water culture. Potassium addition did not completely overcome the effects of the bicarbonate ion on dry matter yield.

Soils of the Cununurra (alkaline phase), Keep and Walyara families, when submerged, may develop bicarbonate concentrations in the soil solution which are deleterious to plant growth because of the free carbonate present in the A11 and A12 horizons.

Deficiency of macronutrients

Nitrogen: All soils have low organic matter contents and it can be expected that the C/N ratio would be high as for similar soils of the Keep River Plains (Aldrick and Moody, 1977). Under these conditions mineralization of organic nitrogen would be of a small magnitude and a widespread nitrogen deficiency is likely.

This deficiency has already been recognized, and 150 to 200 kg N/ha as urea is applied to cotton crops in the irrigation area (I.D. Gordon, personal communication).

Phosphorus: Bicarbonate extractable phosphorus levels (Colwell, 1963) of <30 ppm indicate a likely phosphorus response by grain crops (Esdaile, 1963). The A11 horizons of all type profiles have considerably less than this level of extractable phosphorus, suggesting superphosphate application will be required for crop production.

While no assessment of the phosphorus "fixing" ability of the soils was made, it is likely that the soil families which are calcareous in the A11 and A12 horizons (Cununurra - alkaline phase, Keep and Walyara) will require higher application rates of phosphorus than those which are not calcareous because of the precipitation of added phosphorus in the largely unavailable form of calcium phosphates. The extent of this precipitation will be governed by the solubility products of the various calcium phosphates and by the concentration of calcium ions in the soil solution from the dissolution of free calcium carbonate.

Potassium: About 0.42 m.e./100 g exchangeable potassium was required for 90% maximum lint yield of cotton growing on clay soils of Israel (Halevy, 1977). The exchangeable potassium levels of the type profiles are above this critical value and a response to potassium fertilizer is therefore unlikely.

Deficiencies of micronutrients

Zinc: The EDTA - ammonium carbonate extractable zinc levels (Trierweiler and Lindsay, 1969) of the A11 horizons of all profiles fall in the range of 0.1 ppm to 7.7 ppm with only five sites having extractable zinc > 1 ppm, the mode value being 0.3 ppm.

Trierweiler and Lindsay (1969) found a critical level of 1.4 ppm extractable zinc separated zinc deficient from non-deficient soils in a glass house survey of 42 soils using maize as the test plant, while extractable zinc levels of <1.5 ppm in high pH soils were associated with zinc deficiency in rice (Anon. International Rice Research Institute 1970). Further, soil and plant analyses from rice trials at Kimberley Research Station have implicated zinc deficiency as one of the factors associated with the "rice disorder" at the research station.

It can be expected that, in view of the very low extractable zinc levels of all soil types, continuous cropping in association with high phophorus fertilization will result in zinc deficiency in rice and other crops.

Iron: Continuous cropping coupled with high pH in the A11 and A12 horizons of the Walyara and Cununurra (alkaline phase) families could lead to iron deficiency - "lime induced chlorosis". The availability of iron to plants decreases as soil pH rises above 7.0 and becomes minimal at pH readings >8.0.

Induced limitations

Limitations to crop production may be induced by the effects of irrigation water on soil chemical attributes such as salt content and exchangeable sodium percentage (ESP).

Table 3 indicates the average composition of Ord Dam water. Most of the constituents vary only slightly with magnesium being more variable than the others.

Table 3. Average composition of Ord Dam water (T.C. Stoneman, personal communication).

	me/L
Chloride	2
Bicarbonate	3
Calcium	1.5
Magnesium	1-2
Sodium	2
Conductivity	50 mS/m at 20°C

Sodium Absorption Ratio 1.5
Residual Sodium Carbonate 0-0.5 me/L

The water is classified as having a medium salinity hazard, low sodium hazard and a "safe" level of residual sodium carbonate. Furthermore, sampling by the Commonwealth Scientific and Industrial Research Organization over a period of months from irrigation wheels, an irrigation channel and a rice bay on Kimberley Research Station indicated no significant change in any of the chemical attributes of the water as it was distributed from the dam to the field. The water should have little deleterious effects on

Table 4. Effect of cropping history on ESPs of Cununurra clay (Stoneman 1971)

Depth (cm)	Inundated crops			Furrow irrigated crops			
	Virgin crops ESP	2 rice crops ESP	4 rice ESP	Virgin ESP	2 crops ESP	crops ESP	7 crops ESP
0- 30	1	1	1	1	2	2	2
30- 60	3	4	4	2	6	5	4
60- 90	7	10	7	6	12	10	9
90-120	10	16	10	8	17	15	14
120-150	12	19	13	10	19	17	17
150-180	13	20	14	10	19	19	19

ESP = Exchangeable sodium percentage

soil properties provided sufficient is leached through the root zone to prevent significant salt build up.

S.T. Smith (1964, unpublished) studied the effect of different cropping and irrigation histories on the soil chemical properties of the Cununurra clay. There was a slight accumulation of salt from 120 to 180 cm under furrow irrigation with the salt level tending to increase with increasing number of crops. There was no evidence of upward salt movement. This salt accumulation did not occur after two or four rice crops, indicating that ponding of water produced sufficient leaching to move salt through the profile. If the accumulation of salts at depth is considered to be undesirable, then a period of rice growing may be necessary after prolonged furrow irrigation.

Calculation of the ESPs of the same profiles indicated that, after two rice crops, the ESPs were higher than in the virgin situation, exceeding 15% at depths >120 cm (Table 4). ESPs following four rice crops were identical to those under virgin conditions. Two, three and seven furrow irrigated crops caused increases in the ESPs over the virgin situation from the surface down.

Stoneman (1972, unpublished) hypothesized that the bicarbonate in the irrigation water combined with waterlogging (either temporarily as in furrow irrigation or for longer periods as in rice growing) of soil with calcium carbonate present throughout most of the profile could lead to changes in the cation composition of the percolating irrigation water. He suggested that bicarbonate would cause the precipitation of some calcium and magnesium from the water in the upper part of the profile thus producing a water of higher sodium absorption ratio (SAR) to leach through the subsoil.

The ESPs down the profile after three furrow irrigated crops were similar to those after seven crops suggesting the soil was at equilibrium with the percolating irrigation water. The increase in ESP caused by furrow irrigation could be expected to decrease the hydraulic conductivity of the soil, but whether there is also a deleterious effect on crop production through inadequate aeration in the root zone is unknown.

Summary

Widespread deficiencies of nitrogen, phosphorus and zinc are probable in all soils, with iron deficiency a possibility in Walyara and Cununurra (alkaline phase) soils.

Bicarbonate toxicity may affect rice production from Walyara, Keep and Cununurra (alkaline phase) soils.

Furrow irrigation leads to an increase in soluble salts below 120 cm, but there is no upward salt movement.

Both furrow and flood irrigation lead to an increase in exchangeable sodium percentages down the profile. Whether this increase affects crop production or soil physical properties needs to be determined.

Suitability of the soils and land units for irrigation

J.M. Aldrick

Cracking clays in world agriculture

Large areas of cracking clay soils are cultivated for agricultural purposes throughout the world. Their use is governed by a combination of physical, economic and social factors, but emphasis here is placed on the physical factors. They are the most commonly irrigated soils of the tropics and subtropics and in places such as the Sudan Gezira, Ghana and Hyderabad in India relatively large areas are irrigated. However, most cultivated areas are used for non-irrigated farming and these rely on rainfall, often supplemented by natural seasonal flooding or periods of fallow (Dudal 1965).

Cotton is the principal cash crop grown on cracking clay soils, but sugar cane, sorghum, rice and millet are also important. Other widely grown crops include maize, wheat, soybeans, tobacco, sunflower, safflower, mung-beans, peanuts, kenaf and forage crops (Dudal 1965).

Problems related to their use for cropping are common to nearly all cracking clay soils (Hubble, 1973). They have a very low permeability when wet, which causes water entry problems under irrigation and difficulty in providing sufficient through-flow for leaching. Poor drainage, internal waterlogging and sometimes inundation also occur. Dry consistence is extremely hard, leading to generally high costs of cultivation. When wet the soils become very sticky and adhere to machinery and implements and immobilize tractors and other vehicles.

Other problems on these soils include erosion on low slopes and a tendency to "droughtiness" because of their ability to crack deeply and allow evaporation to occur. Wilting points are reached at relatively high soil moisture levels and several centimetres of water may be required on an air dry soil to provide useful moisture for a crop. Rainfall is often erratic and unpredictable in areas where cracking clays occur. Chemical problems are also common and high pH, induced iron and zinc chlorosis and phosphorus fixation are typical.

In addition, the shrinking and swelling of the clay leads to engineering problems when structures, including earthworks, are built. Buildings, dams, channels, roads, airstrips, benchmarks, fences and power lines may fail because of movement of the foundations with changes in soil moisture content. Some cracking clays have a tendency to disperse and this can lead to "piping" failure of dams and channel banks. The rough gilgaied microrelief of the virgin soils is also a limitation.

A favourable feature of cracking clay soils is their high moisture-holding capacity, which allows accumulation and storage of water in fallows and reduced frequency of irrigation. When dry and cracked, infiltration rates are very high and water can penetrate rapidly. Surface structure is often strong and fine ('self-mulching') which allows good seedbed tilth and helps conserve moisture. Actual fertility levels are not usually high, but the soils turn over and replenish the upper layers because of the action of gilgai and a sustained productivity is obtainable (Dudal 1965).

The potential productivity of these soils is high and there is much scope for increasing their yield. To a large extent, higher yields are the result of improved management practices such as irrigation, drainage, application of fertilizers, use of selected seeds and pesticides, better tillage implements, erosion control and adequate crop rotations. The greatest benefit is obtainable from a combination of these practices.

Natural leaching regimes on the Ivanhoe Plain

Under natural conditions before the irrigation scheme was laid out, three different leaching regimes prevailed in the cracking clay soils of the Ivanhoe Plain. An understanding of these and the chemical conditions they have produced naturally is essential to assessing the probable performance of the superimposed irrigation regime. Intrinsic, pre-existing conditions that might prove hazardous under irrigation are associated with two of the leaching regimes.

The land units containing soils that have been subjected to each of these leaching regimes are listed in Table 5.

Table 5. National leaching regimes of the land units

Leaching regimes	Land units						
Normal rainfall leaching	1a	1b	2c	2e	5d	10a	10b
Minimal leaching	4c	9a	9b	9c			
Intense leaching	5a	5b	5c	8a	8b		

Normal rainfall leaching

Incident rainfall has infiltrated into the soils of land units 1a, 1b, and others (Table 5) since they were first formed. Actual rates of leaching have probably been similar and the extent to which leaching has proceeded has been controlled mainly by the length of time the soil has been exposed to rainfall.

Leaching has progressed further in land unit 1b than for land unit 1a, as the former occurs in the northern (older) province and the latter in the southern (younger) province. Details of the evidence for and results of these differences has already been given.

Most of the irrigable areas fall into this "leached by rainfall" category.

Minimal leaching situations

The soils that occur in land units 9a, 9b, 9c and 4c are only weakly leached. This is mainly a result of their elevated micro-topography. The soils concerned are members of the Walyara family, which occurs on low rises and the Keep family, which is best developed on gilgai mounds. Walyara/Cununurra intergrades are also included. The originally high levels of carbonates have been retained in these soils for two main reasons. Firstly, some incident rainfall runs off the raised sites and less is able to infiltrate and contribute to leaching effects. Secondly, there is some evidence that upwards capillary movement of water from adjacent temporarily ponded depressions occurs especially where gilgai with mukkara (Paton 1974) exist. Small amounts of dissolved carbonates could have been transferred to the elevated sites in this water and re-precipitated. This was suggested as a possible mechanism for secondary carbonate infusion into both Keep and Walyara soils on the Keep Plain by Aldrick and Moody (1977) and it is likely that it also applies at least in the northern (older) province of the Ivanhoe Plain.

Intense leaching situations

In the seasonally inundated swamps where land units 5a, 5b, 5c, 8a and 8b occur, increments of water in addition to normal rainfall are regularly received. The extra contributions arrive as run-off from other areas of the clay plains and from creeks in the nearby sandy land systems, mainly the latter. There are two aspects of relevance to leaching; firstly, the increased volume of water available and secondly, the load of solutes contained in the contributed portions that are not present in rainwater. A complication is the accompanying load of suspended clay.

The pre-development situation

In general, conditions that might be problems in terms of salinity, sodicity, or carbonate content have not developed naturally in the virgin soils subjected to normal rainfall leaching. This is largely because the leachant has been almost pure water. The small patches of Cununurra/Walyara intergrade soils that occur in land unit 1a are an exception and are included in the soils having minimal leaching.

Two potential problems are apparent in the soils subjected to either minimal or intense natural leaching effects. Firstly, levels of calcium carbonate are sufficiently high to be detrimental in the root zone of the soils that have had minimal leaching. Secondly, exchangeable sodium percentages are ~15% and therefore potentially hazardous in the lower part of the root zone of soils that have had either minimal or intense leaching.

Irrigation of the soils that have been subjected to only minimal leaching is likely to be hazardous and fraught with failure. Reclamation would be possible and Gunn (1969) has suggested techniques that might be used, if it was thought to be worthwhie. However, the areas concerned are small, and they may be best regarded as incapable of economic returns and set aside as farm storage and work areas. Some of the soils (Walyara) are not cracking clays and may be suitable for the erection of buildings.

Natural salinity levels are nowhere high enough to constitute a potential hazard, but it is useful to observe the trends in salinity that have developed naturally in the swamps.

Levels of total soluble salts and percentages of sodium chloride were found to be slightly higher in these intensely leached areas than for the areas subjected only to normal rainfall leaching. Salts have tended to accumulate slightly in the intensely leached soils because the leachant there was not pure rain water, but run-on water, presumably containing dissolved salts.

The essential problem in irrigating the intensely leached swamp areas is that the soils have a very low permeability partly because of the illuvial clay that has invaded the profiles and lodged in them as argillans. If irrigation water containing solutes is applied, the water will be extracted by crop plants, but the solutes will tend to accumulate as through-flow of water will be minimal. If interactions between chemicals in the irrigation water and the soil occur that lead to a further increase in the exchangeable sodium percentage, an even lower permeability could result and the salinity problem could be exacerbated.

The intensely leached areas may be best used if crops requiring inundation for prolonged periods such as rice were to be grown. The imposed leaching regime would then be more intense, and adequate through-flow may occur.

Soil changes recorded following irrigation

Changes in soil chemistry occur as a result of irrigation. However, few investigations of this nature have been undertaken and the information is incomplete.

Investigations by S.T. Smith (1964, unpublished) and T.C. Stoneman (personal communication) have shown that there has been a slight accumulation of salts in the lower parts of the soils after some years of furrow irrigation. There did not appear to be any upward movement of these salts into the root zone. Under flooded conditions in rice bays no salt accumulation seemed to occur.

It was also found that subsoil exchangeable sodium percentages increased markedly after irrigation and this effect seemed to worsen with increased applications of irrigation water. It may be due to a complex interaction between dissolved materials in the irrigation water and the exchange complex of the soils (T.C. Stoneman 1972, unpublished).

During this survey it became evident that topsoil pH had increased significantly in some of the irrigated areas. This may also be related to interactions between the irrigation water and the soil. Results obtained by Gunn (personal communication) on Kimberley Research Station in 1969 show a topsoil pH 1 to 1 1/2 units higher in irrigated Cununurra clays compared with similar virgin soils. Rises in topsoil pH could induce plant nutritional imbalances and may also lead to direct toxicity effects. Investigation of this phenomonon is needed.

Adverse responses in the soils following irrigation certainly seem to occur and if they continue serious economic effects may eventuate. This may well prove to be an aspect of critical importance for the future of the irrigation scheme.

Now that the problems have been identified more research needs to be done. Investigations need to be extended to include all of the important potentially irrigable soils and soil performance under different crop-production regimes needs to be evaluated. Little or nothing is known about the following:

- Rates of water entry into the soils. These need to be measured in relation to land grade, length of furrows, liability to erosion of the topsoils and quantities of water that need to be applied.
- Quantities of water percolating through the soil. This relates to leaching efficiency and contributions to groundwater tables. Soil permeability is known to be generally very low, but it is possible that excessive contributions to ground water tables could occur through the soils in land units 10a, 10b, and 2c and it is doubtful whether these should continue to be irrigated.
- Chemical interactions between the irrigation water and the soil. Some have already been recorded, but further investigations of salinity trends, exchangeable sodium percentage increases and topsoil pH rises are needed as well as studies of how these might be managed. The residual effects of applied fertilizers, herbicides and insecticides are largely unknown.
- The extent of possible compaction and loss of porosity and structure because of physical cultivation are unknown. Optimal moisture contents of the soils that will allow cultivation without physical damage need to be determined. The role of organic matter will be important here.
- Continued monitoring of irrigation water quality is desirable, especially for contents of dissolved chemicals and seasonal fluctuations in solute content.

The soil and the irrigation water are the two prime physical resources of the irrigation scheme. If there is doubt about their continued performance it may be prudent to instigate a programme of monitoring and research. It is important that the long-term response of the soils to irrigation is known, so that future extensions to the irrigated area can be safely selected and management practices adopted on the existing irrigation areas that will avoid the possibility of a reclamation undertaking being necessary in the future.

Some notes on Kimberley Research Station

Kimberley Research Station seems to be located directly astride the boundary between the northern (older) and southern (younger) province. The justification for placing this boundary through the middle of the research station is based on a number of factors which show that the northern portion of the research station is similar in many of its characteristics to the bulk of the northern (older) province, while the southern portion is similar to the southern (younger) province.

In general, soil pH in the virgin Cununurra clays on the research station north of the boundary is slightly lower in the upper 30 - 40 cm than for similar virgin soils to the south. However, the difference is not as marked as is usual between Cununurra clays of the alkaline and leached phases.

The two large levee remnants in the northern portion of the station have gradational-textured soils, but these have slightly lower topsoil pH and texture than do comparable soils to the south. About 80% of the levee remnant sites described by Gunn in 1969 (personal communication) had "non calcareous" (Northcote, 1971) Gn3 soils, compared with only about 20% of the sites to the south.

The vegetation on the levee remnants in the northern portion of the research station includes stands of *Eucalyptus clavigera*, but this species does not occur to the south. Vegetation on the Cununurra clays is noticeably less dense to the north than to the south of the boundary.

The orientation of the levee remnants in the northern portion of the station is 50 to 90 degrees at variance with the orientation of those in the southern areas. Further, the northern levee remnants seem to be related geomorphogenetically to a prior stream to the north-east of the research station, the relict bed of which can be observed faintly on aerial photographs, but no such relationship is evident for remnants to the south of the boundary.

An area just north of the boundary in the east of the research station has been mapped as land unit 4c because of its high pH soils and characteristic photopattern. Other soils of land unit 4c occur only in the northern (older) province, and this represents their southernmost observation in this area.

Different agronomic responses that might occur on soils of the southern (younger) province and corresponding soils in the northern (older) province would probably occur to some degree on soils of the southern and northern portions of Kimberley Research Station. However, the research station is very near the probable site of capture of the Ord and the soils immediately north of the boundary may not be as old and leached as those more distant from the site of capture. Experiments designed to be representative of soils in the northern (older) province may therefore be best located further to the north-east, away from the research station.

Individual soils of the southern portion of the research station seem to represent soils of the southern (younger) province well, but there is a much higher proportion of calcareous soils (Walyara and intergrades) on this part of the station than is usual for the southern (younger) province. It may be difficult to locate extensive areas of uniform Cununurra clay (alkaline phase) for research work on the southern part of the station.

A number of attributes of the land that could be considered to be limitations for irrigated agriculture are now considered. Natural, pre-existing limitations are shown in Table 6 and those that the available evidence indicates might develop after irrigation are shown in Table 7. Because of insufficient evidence, the latter group of potential limitations is considered somewhat speculative.

Some of the pre-existing limitations are capable of amelioration or complete removal, for example, inundation. However, most of them are intrinsic and not capable of economic removal by existing technology.

Irrigated cropping is the only form of land use considered. If information is required in relation to other forms of land use, details about the nature of the land in question is provided in the land unit descriptions given earlier. An appropriate significance could be attached to each factor for the land use proposed.

The land unit map is a multi-attribute map in that the land units can be used as base units to portray any of a number of specific attributes of the land. Thus, an inundation map or a high topsoil pH map could be constructed by simply identifying the land units having the relevant attribute.

The factors identified as limitations for irrigated cropping are defined as follows:

Natural, pre-existing limitations (Table 6)

Relief: Some areas are too steep to be considered irrigable. Rivers and their frontages are obvious examples.

Microrelief: Gilgai with amplitudes in excess of about 30 cm occur in some areas. In others broad shelves and depressions with relatively great microrelief occur and in others highly calcareous soils occur on low rises. Usually, all these areas have soil differences between the mounds and depressions such that land levelling exposes chemically undesirable subsoil zones in the mounds.

Erosion: Existing severe erosion is characteristic of the zone between the Ord River and the clay plain and along the major creeks. Some peripheral areas of the clay plains carry large volumes of run-off naturally and would be susceptible to erosion if disturbed.

Presence of stone or gravel: These are of minor importance, but are observable features of some areas. Larger stones could be a physical hazard and gravel contents detract from soil moisture holding capacity.

Inundation: This is a seasonal feature of some areas. Depth and duration of inundation vary up to maxima of about 50 cm and five months respectively, although some seasons are wetter than others. Where large microrelief differences exist, such as where areas of Keep flooded phase soils occur, only the depressions are inundated.

Poor internal drainage: This is generally associated with low soil permeability. It is a limiting factor as it reduces leaching efficiency and promotes salt accumulation and may also directly affect plants. Rates of water movement through these soils are probably considerably slower than for other clay soils.

Poor topsoil tilth: Following cultivation, this is likely to be a problem in some of the more poorly drained areas that have only shallow self-mulching layers and a coarse cloddy sturcture. It can be alleviated to some extent by an increased number of secondary cultivations. Poor tilth affects seedling emergence and rates of moisture loss from the topsoil.

The need for different irrigation frequency and amounts: This relates to soils having a greater permeability or lower moisture storage capacity than the normal clays. Such soils may occur on gilgai mound or shelf areas, or as more extensive "islands" in the clays. Management problems arise when these different soils are irrigated in the same run as ordinary cracking clays as they absorb water at a different rate, have a different leaching requirement and usually dry to wilting point more rapidly.

High topsoil pH: High pH values in the topsoils were recorded for some families. These soils have mostly been mapped within specific land units, but small isolated patches occur throughout land unit 1a. High topsoil pH is associated with high calcium carbonate contents. Plant nutrition deficiencies and imbalances and nutrient fixation in the soil are likely to occur in these areas.

High subsoil exchangeable sodium percentages (ESP): High ESP values were recorded for some soil families. There are no records of topsoils being affected. This can mean that the clays are prone to disperse when wet and the resultant colloidal clay can block soil pores and further reduce permeability.

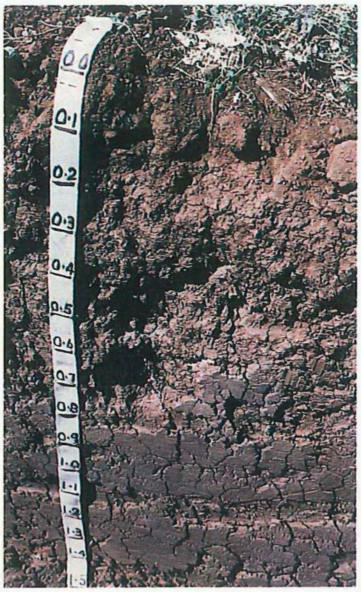
Limitations that irrigation may induce (Table 7)

Increased exchangeable sodium percentages (ESP): Information indicates that ESP may increase with the amount of irrigation water applied. Most soils are probably susceptible, particularly those with naturally high ESP, as increases there could affect the root zone.

Increased salinity: Most soils would be mildly susceptible, but probably not the more permeable ones where leaching would be more rapid. The worst areas would probably be those with soils having an initially low permeability.

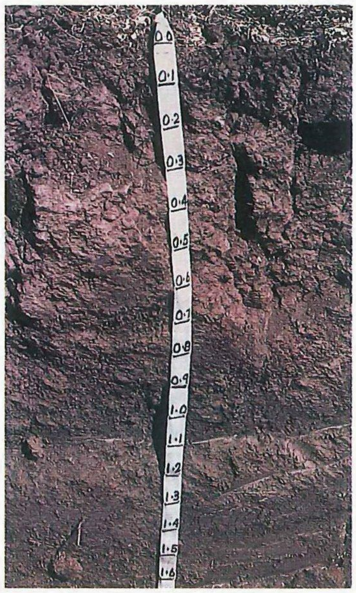
Raised topsoil pH: This is probably caused by bicarbonates in the irrigation water and all areas would be susceptible. Raised pH values could cause nutrient deficiency and imbalance problems in crops.

Nutrient imbalance and unavailability: This could occur where topsoil pH values are high. The worst areas would be where pH values and levels of carbonates were initially high.



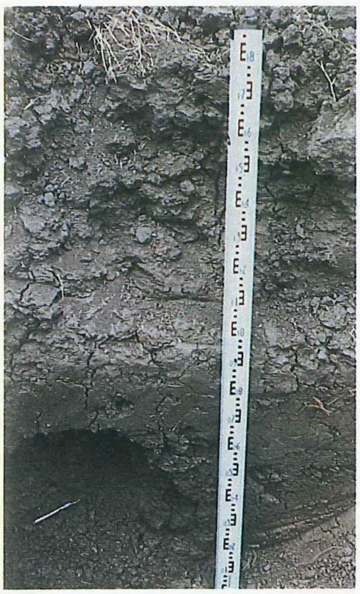
1
Finely structured Cununurra clay alkaline phase, Land unit 1a, southern province.

2
Wooded landscape of Land unit 1a with *Lysiphyllum cunninghamii* and *Carissa lanceolata*.

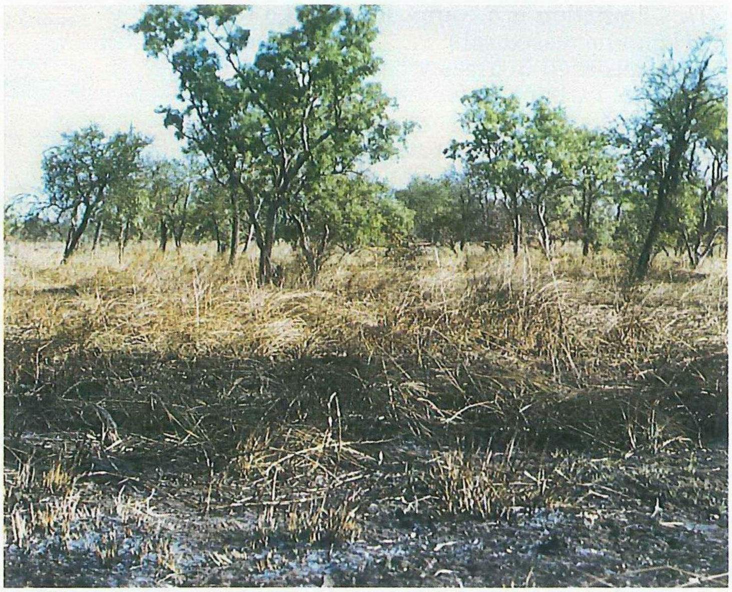


3
Coarsely structured Cununurra clay leached phase, Land unit 1b, northern province.

4
Treeless surface of Land unit 1b.

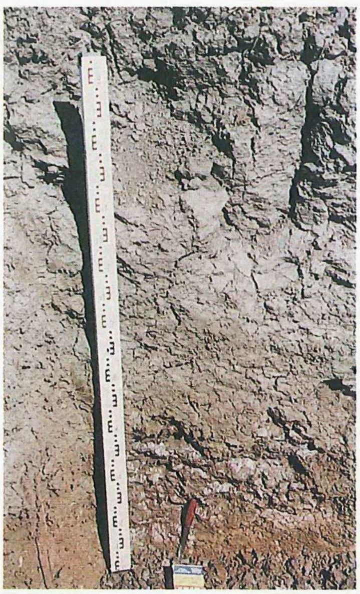


5
Coarse block structure of Aquitaine bluish phase, Land unit 5a, northern province.



6
Dense woodland of Land unit 5a with *Eucalyptus microtheca* and *Excoecaria parvifolia*.

8
Open woodland of Land unit 5b with *Eucalyptus microtheca* and *Excoecaria parvifolia*.



7
Coarse block structure of Aquitaine greyish phase, Land unit 5b, northern province.

Note: Photographs 4 to 8 taken from identical map units on the Weaber Plain.

This limitation is a composite of high topsoil pH and increased salinity. Zinc deficiency has been recorded in areas where topsoil pH and levels of carbonates were high.
Land units 5a and 5b are exceptions as they occupy considerable areas and special management practices may be worth considering for them. A possible approach is discussed elsewhere in this Bulletin.

Table 6. Pre-existing limitations on land use for irrigation

Factors considered to be limitations.	Land units																		
	1a	1b	2c	2e	4c	4f	5a	5b	5c	5d	7a	7b	8a	8b	9a	9b	9c	10a	10b
1. Relief									x		x x	x x x	x						
2. Microrelief					x	x					-	-	x x		x	x	x		
3. Erosion									x	x	x	x	x	x		x			
4. Presence of stone and gravel									x		-	-	x	x				x	
5. Inundation							x x	x	x x x		-	-	x x						
6. Poor internal drainage		x					x x x	x x	x x x	x x	-	-	x x x						
7. Poor tilth after cultivation		x					x x x	x x	x x x	x x	-	-	x x x						
8. The need for different irrigation timing and amounts			x x	x		x					-	-	x x	x x x				x x x	x
9. High topsoil pH	x				x x						-	-			x x x	x x x	x x		
10. High subsoil ESP				x	x	x	x	x	x x	x	-	-	x x	x	x	x x x	x x x		

x = minor limitation, x
x = moderate limitation, x
x
x = severe limitation,

- = not applicable

Table 7. Limitations that irrigation may induce

Factors considered to be limitations.	Land units																		
	1a	1b	2c	2e	4c	4f	5a	5b	5c	5d	7a	7b	8a	8b	9a	9b	9c	10a	10b
1. Increased ESP	x x	x	x	x	x x	x	x x	x x x	x x	x x x	-	-	x x	x x	x x	x x x	x x x	x	x
2. Increased salinity	x	x x		x	x	x	x x x	x x	x x x	x x	-	-	x x x	x	x x	x x	x		x
3. Raised topsoil pH	x	x	x	x	x	x	x	x	x	x	-	-	x	x	x	x	x	x	x
4. Nutrient imbalance and unavailability	x x	x	x	x	x x	x	x	x	x	x	-	-	x	x	x x x	x x x	x x	x	x

x = minor limitation, x
x = moderate limitation, x
x
x = severe limitation,

- = not applicable

Summary of land unit suitability for irrigated agriculture

Land unit 1a

The generally high topsoil pH, especially in the calcareous patches, and low zinc contents in the soils indicate possible chemical limitations producing zinc and other deficiencies in crops, especially if phosphatic fertilizers are applied. If small areas of Walyara soils occur in experiment plots anomalous results are likely to ensue. Other hazards associated with the more calcareous soils are outlined in the notes on land unit 9a. The strong fine topsoil structure leads to a fine seedbed even after initial cultivations. The native timber density may constitute a minor limitation in uncleared areas.

Land unit 1b

Relatively poor internal drainage and low subsoil permeability are mild limitations on the use of these areas for irrigation. The degree of the limitation is not pronounced and would be most evident in years of higher than usual rainfall. Topsoil pH is about neutral in the virgin soils and induced zinc deficiency and other chemical problems would not be expected to be severe. However, after a period of use for irrigated cropping these soils have been observed to show a major pH rise in the cultivated topsoil and subsequently chemical limitations similar to those occurring in land unit 1a may become apparent. Following initial cultivation, topsoils often tend to be coarse and cloddy and more numerous secondary workings may be necessary to achieve an acceptably fine seedbed tilth.

Land unit 2c

Land unit 2c is not extensive on the Ivanhoe Plain. However, occurrences of it form a significant proportion of individual farms. The soils are permeable and well drained and dry out more rapidly than adjoining cracking clays after irrigation. This poses significant management problems in timing and amounts of water applied. Soil fertility would also need different management because of the different physical and chemical nature of the soils. Rates of wear on agricultural machinery parts, such as tractor tyres, cultivator points and plough discs would be high because of the more abrasive nature of the soil. The sandy texture of the topsoils in these land units may render them suitable for peanut growing, except where topsoil consistence is high.

Land unit 2e

As for land unit 2c, areas of this land unit are not extensive, but occurrences of it form a significant proportion of individual farms. Soil management requirements such as irrigation timing and the amounts of water and fertilizer that need to be applied do not seem to vary significantly from those of the adjoining cracking clays, probably because of the heavier texture of these reddish soils. However, some differences may later be discovered.

Land Unit 4c

Keep family soils have a high topsoil pH and are sometimes calcareous at shallow depths. Land levelling would expose the more alkaline lower layers of the soil. The chemical nature of Keep soils identifies them as a distinct hazard for irrigated use. Nutritional problems in crops such as phosphorus and micronutrient availability and uptake are likely to occur and, after a period of irrigation, a decrease in subsoil drainage capacity may occur. It is expected that the agronomic capabilities of this land unit would be similar to those for land unit 9c.

Land unit 4f

The proportion of the Ivanhoe Plain occupied by this land unit is small. The variety of soils with differing permeabilities and moisture-holding capacities would introduce problems of timing and quantities of irrigation water. If microrelief before clearing was of significantly great amplitude subsoil materials would be exposed where mounds occurred previously i.e. in the areas of Weaber soil and its intergrades with Cununurra soils. These materials are likely to be less fertile than the original topsoils.

Land unit 5a

Before these areas could be irrigated, drainage works would be necessary to prevent seasonal inundation. Because of the occasional large contributions of uncontrolled run-on water from the adjacent sandy land systems, soil erosion would be a significant hazard in the drains. The soils in this land unit are very poorly drained internally and, if irrigated, waterlogging, slow salt accumulation and poor topsoil tilth could be limitations. In addition, after a period of irrigation, the internal drainage capacity of the soils could be reduced as the exchangeable sodium percentage and pH of the subsoils are high.

Accumulation of salts in these soils may be less of a problem if crops requiring periods of inundation (such as rice) are grown. The imposed leaching regime would then be closer to the normal one for these soils. The dense timber cover may be a limitation if these land units are to be cleared.

Land unit 5b

As for land unit 5a, surface drainage would be necessary before irrigation could proceed. The soils are very poorly drained internally and if they were irrigated, waterlogging, slow salt accumulation and poor topsoil tilth could be limitations. The exchangeable sodium percentage which is >15% in the subsoils may lead to further reduced internal drainage capacity after a period of irrigation. As for land unit 5a, the accumulation of salts under irrigation may be less of a problem if crops requiring periods of inundation (such as rice) are grown. The native woodland may represent a minor limitation if clearing were to be undertaken.

Land unit 5c

These areas are of little agricultural significance. They often occur as a component of land unit 8 in the 'junction complex'. Seasonal inundation, stony, waterlogged soils, poor topsoil tilth and a tendency to suffer salt accumulation and increasing drainage impedance if irrigated are typical limitations. The low relief and peripheral location of these land units would render them ideally suitable for drain construction. However, because of the large uncontrolled run-on and seepage from the adjoining sandy land systems, soil erosion following drain construction would be a significant hazard.

Land unit 5d

Poor internal drainage of the soil because of low subsoil permeability, would be a limitation on the use of these land units for irrigation. The degree of limitation is greater than for the surrounding 1b land units, but would not be excessive. Poor drainage would be more evident in years of higher than usual rainfall. Topsoil pH is about neutral in the virgin soils, but like land unit 1b, these areas tend to show an increased pH after a period of irrigation and this may lead to induced deficiencies of elements such a zinc in crops. Following initial cultivation a coarse cloddy tilth would be produced on these soils.

Land unit 7a

The Ord River is scenically and aesthetically attractive to local residents and an increasing number of tourists, and deserves to be preserved. In spite of the annual flood (now under some control by the main dam), pollution and despoilation of the environment are significant hazards and deposits of domestic and industrial wastes have already occurred. If drainage water carrying salts or pesticide and fertilizer residues from the irrigation scheme is allowed to flow into the Ord River, significant pollution of the river could result.

Land unit 7b

These are frontage areas and have no agricultural value, except for the levees. The levees are suitable for irrigated agriculture. If planted with suitable trees and shrubs the levees would also form ideal recreational reserves or parkland. Irrigation may be needed to establish and maintain this vegetation. Apart from the levees, land unit 7b is intrinsically erodible and clearing of native timber, or earthworks, would allow the erosion to accelerate. Uncontrolled discharges of irrigation drainage water into this land unit would also accelerate the erosion. Control of introduced noxious weeds, fire and feral animals in unused areas may need to be exercised.

Land unit 8a

These are very varied areas, but they have a uniformly low capability for irrigated agriculture. Poor drainage, waterlogging and inundation are obvious limitations. The variety of soils and the relatively great microrelief would produce a patterned effect of physical and chemical factors after levelling and this pattern would be reproduced in crops. The low relief and peripheral location of land unit 8a render it ideally suitable for drain construction. Run-on from the sandy land systems adjoining this land unit is not as great as that for the sandy areas adjoining land unit 5c and erosion would be less of a hazard.

Land unit 8b

These areas have considerable variation which makes them a difficult proposition for irrigated agriculture. The variety of soils with differing permeabilities and water holding properties and their irregular patterned distribution would cause great difficulty in planning an irrigation schedule and considerable variation in crop performance. Run-off from the adjoining sandy land systems could cause erosion problems on the soils of this unit.

Land unit 9a

The matrix of Cununurra alkaline phase soils is similar in potential to land unit 1a and similar comments apply. The inclusions of Walyara soils and the intergrades are a significant hazard in crop production. Their calcareous high pH nature is likely to cause nutritional problems such as poor phosphorus and micronutrient availability and uptake in crops. The high exchangeable sodium percentage in the subsoils is likely to lead to decreasing subsoil drainage capacity following a period of irrigation. Levelling of these slightly elevated soils will expose lower layers of the soil profiles, in which the chemical hazards are greater. The presence of these soils in areas of Cununurra clay is a hazard in agronomic experiments.

Land unit 9b

Factors affecting land use are similar to those for land unit 9a. However, because the proportion of Walyara and related soils in land unit 9b is about half that for land unit 9a, a lesser degree of chemical limitations is involved. Otherwise details given in the notes on land unit 9a apply here.

Land unit 9c

The calcareous, high pH nature of the soils found in land unit 9c is a distinct chemical limitation on the use of the land for irrigated agriculture. As for land units 9a and 9b, nutritional problems such as phosphorus and micronutrient availability and uptake are likely to occur in crops and after a period of irrigation there may be a decrease in subsoil drainage capacity. These limitations apply to a lesser degree than they do for land units 9a and 9b, but to a greater degree than for land unit 1a.

Land unit 10a

This area was regarded as a problem area by landholders, as it imbibed more water when irrigated than the surrounding soils, yet dried out more rapidly and allowed the crop to wilt. Weed invasion was also a problem. It seems likely that applied irrigation water is able to permeate more easily through this soil than through normal Cununurra clays and that it reaches the underlying deposit of coarse sand, which conducts it into deeper aquifers.

Land unit 10b

The more porous, brittle nature of the Cununurra soils in land unit 10b would probably allow them to absorb applied irrigation water more rapidly than usual. The soils would also retain less moisture and would dry out more rapidly and would thus constitute a minor management problem.

Total areas of land units

The total area of each of the land units and hence their relative importance are given in Table 8. Combined data from Tables 6, 7, and 8 indicate that the land units having the greatest severity of limitations for irrigated use are land units 4c, 5a, 5b, 5c, 5d, 7a, 7b, 8a, 8b, 9a, 9b and 9c. Most of these are peripheral units or are of relatively small total area.

Table 8. Extent of each map unit

1a	3,063 ha
1b	5,738 ha
2c	5 ha
2e	45 ha
4c	85 ha
4f	59 ha
5a	2,841 ha
5b	1,795 ha
5c	183 ha
5d	237 ha
7b	3,000 ha
8a	322 ha
9a	43 ha
9b	120 ha
9c	245 ha
10a	2 ha
10b	68 ha

Development of the scheme beyond Stage I

J.M. Aldrick

The pilot area (Stage I)

Before 1969, although a number of soils investigations had been carried out, it had been generally reported that the Cununurra clay soils on the Ivanhoe Plain were essentially uniform in their main characteristics. However, as the development of Stage I progressed, some of the farmers and others began to question the validity of this view, in particular the assumption that the soils of the Kimberley Research Station were representative of all other areas of the plain.

During 1969, a soil survey of the Kimberley Research Station was carried out by the CSIRO (Gunn, 1969) and the soils there were described in more detail. For the first time it became apparent that the soils of the plains were not as uniform as had been thought and that some of them had undesirable chemical characteristics.

Subsequent surveys by Stoneman (1972) on the Packsaddle Plain and Aldrick and Moody (1977) on the Keep and lower Weaber Plains revealed considerable variation in the soils of those areas and indicated that agronomic responses under irrigation could be expected to vary significantly.

During this survey of the Ivanhoe Plain, 18 different land units containing 16 different soils were described and mapped. The plain was divided into two geomorphic provinces and the presence of ancient river channels, levees, point-bar systems and swamps was recorded. Clearly, a significant degree of variation occurs in the soils and this report predicts that variations in their performance when irrigated are to be expected.

When the farms in Stage I were allocated, the existing soil survey map (G.H.Burvill 1945, unpublished), showed only the major variations and nearly all of the Ivanhoe Plain was mapped as Cununurra clay, either normal or flooded phase. Consequently, it was not then possible to assess the performance of different crop species in relation to differences in the soil. However, using the soils map that accompanies this report, it should now be possible to correlate the performance of crops with the various soils and so obtain an index of the way in which the soils of the Pilot area have performed. This possibility is discussed further below.

An approach to the evaluation of new areas

If further expansion of the irrigated area is contemplated, it seems logical to consider the likely performance of the proposed new area in the light of what has actually happened in the Pilot area. Intrinsic aspects of past agronomic performance and other factors recorded there could be extrapolated to comparable areas in the proposed extension, thus enabling information from the performance history of the Pilot area to be applied in a predictive way.

However, if comparable areas are to be identified in the proposed extensions a uniform approach in soil mapping is essential. Comparison of soils maps produced by different surveyors defining different mapping units and having differently classified soils is often almost impossible and, at best, a major correlative effort is involved. It is proposed here that a common map key should be adopted and that all soils maps for the clay plains of the Ord Scheme should conform to it. A copy of the common map key is given in Appendix 2.

So far the soils maps for the Keep River, lower Weaber, and Ivanhoe Plains have been produced or modified to accord with the common key and it is intended that the map of the remainder of the Weaber plain will also conform (J.C. Dixon, personal communication). However, soil surveys of the irrigable areas of the Ord Scheme have so far proceeded in piecemeal fashion, partly because the Western Australian - Northern Territory border has been regarded as of greater significance then the geographic boundaries of the scheme as a whole, and partly because of the political uncertainties that have prevailed.

As a result, none of the surveyors involved has been able to gain a co-ordinated overview of the geomorphic relationships between the plains, or a balanced view of soil genesis and distribution. The units of the proposed common key can not now be logically arranged, as one of the survey reports is

already published. Consequently, a logical hierarchical grouping of the units cannot be attempted and the common key is structured as a simple list of units, to which further additions will no doubt be made in the future.

Minor discrepancies in the land unit descriptions given in the common key and those appearing on individual maps will occur. These are partly modifications to accommodate local variations, and partly because of the need for keys printed on maps to be brief.

I hope that users of any of the maps will use the map keys purely for brief reference and will refer to the detailed descriptions of the land units and other details given in the respective reports for more comprehensive information.

Descriptions of the units currently included in the common map key are included at Appendix 5.

Performance predictions for scheme extensions

Declining yields and quality, the buildup of resistance by cotton pests to commercial insecticides, and rising freight and other input costs led to the cessation of commercial cotton growing on the Ivanhoe Plain in 1974. This was a serious setback to development plans. The absence of an alternative commercially viable crop has brought the Ord project into a 'transitional phase', without any clear indication of its future direction (Department of Natural Resources, 1976). At present, (1977) both the Western Australian and the Australian governments are assisting in the maintenance of the project by financing short-term trials and longer-term research work, pending the next phase of development.

This is an appropriate time to examine the agronomic results that have been obtained and soil chemical changes that have occurred during irrigation to evaluate the performance history of the various soils now identified.

So far, many experiment results have been reported in relation to 'Cununurra clay' as defined by G.H. Burvill (1945, unpublished), but it should be possible now to correlate these results with the location of the various land units described in this report.

Gunn (1969) has already correlated the poor recorded performance of rice and other crops with the presence of a particularly calcareous soil (Walyara family), which occurs in land units 9a, 9b and 9c. Similar correlations should be obtainable for other land units. Research and trial findings from CSIRO and the Western Australian Department of Agriculture experiment sites concerning both crop responses and chemical changes that have occurred in the soils are readily available and, in addition, it may be possible to assemble crop performance parameters from the results obtained by selected farmers.

In keeping with the well recognized precept that research and trial work should be undertaken on sites that are representative of the area the results are to be applied to, logical extrapolation of the findings could be undertaken on the basis of the common map key. For example, if it were to be proposed that areas of land unit 5a (such as those in Green and Martin's Swamps or on the Weaber Plain) should be irrigated, the past performance of the area of land unit 5a that occurs on the Pilot area could be taken into account in decision-making.

Success or failure of particular agricultural industries will remain difficult to predict, but if all of the clay plains are mapped on a similar basis and if the results obtained in the Pilot area can be systematically extrapolated, such predictions will have a more secure foundation.

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Appendix 1

Survey methods

J.M. Aldrick, A.J. Clarke and M.H.R. van Cuylenberg

Preparatory photo-interpretation and the field work were carried out in 1974. The black and white photography used at a scale of 1:15,840 was Kimberley Research Station runs flown in 1960 and 1961. Colour photography, at a scale of 1:25,000, flown in 1972 was also available, but because almost all of the irrigation area had been cleared was not useful for photo-interpretation. The earlier black and white photography was of moderately good quality and readily discernible photo-patterns enabled useful initial photo-interpretation which was clarified by field investigation.

Field work involved three two-man teams equipped with 4-wheel drive vehicles. Soil sampling was by 50 mm steel coring tubes driven into the ground by power hammers. Surface samples were collected at every site and samples of full profiles at selected sites. The cores were described on site cards with descriptions of native vegetation, if present, and any comments concerning features such as relief or periodic flooding. Site inspections were made of each distinct photo pattern with more than one site in some patterns and sampling of mound and depression in certain gilgai formations.

The soils are described from nearly 300 profiles, most of which were inspected to a depth of 2 m. Nearly all of the profiles were exposed as relatively undisturbed cores about 5 cm in diameter using thin walled sampling tubes driven by power hammers, but some were augered by hand. Others were inspected in gullies and cuttings around the edges of the plain. Occasionally cores were taken from both mound and depression of gilgai, especially in areas where microrelief was pronounced.

The profile descriptions given here are based on field assessments of colour, texture, consistence, structure, fabric, reaction, mottling, concretions and other accumulated materials, microrelief, cracking pattern and additional factors.

Samples of surface soil (0 to 10 cm) were taken at every inspection site for analysis of pH (reaction), salinity and zinc content and typical profiles of each major soil group were taken for full analysis (Appendix 3).

Because land levelling, cultivation and irrigation had been carried out at most of the inspection sites the upper 20 to 30 cm of soil was often grossly disturbed and both morphological and chemical attributes of that zone were different from those of virgin profiles. The higher topsoil pH of many irrigated soils at first confused the distribution patterns of the leached phase of Cununurra clay.

Soil classification

The soils were classified according to the system described by Stace *et al.* (1968) into Great Soil Groups (Table A-1-1). Further classification into soil families was based on variation in parent materials and in pedogenetic factors such as degree of leaching and waterlogging. At this level of classification the families had characteristic principal profile forms as defined by Northcote (1971). Subdivision into phases (i.e. series) was based on further minor variations in colour, pH profile, degree of leaching, degree of waterlogging, degree of erosion and topsoil texture.

Horizon designation

In describing the cracking clay soils the A1 -AC - C horizon notations as defined by Dudal (1965) were used. In this sequence, the A1 horizon is recognized as the dark-coloured clay material constituting the bulk of the soil profile to depths of 120 cm or more. This horizon is relatively uniform in its main characteristics, but three distinct sub-horizons have been recognized - the A11, the A12 and the A13.

The A11 is a thin, finely structured loose "self-mulching" layer, and the A12 is a more coarsely structured cloddy layer with accommodated peds that lies directly beneath it. Seasonal cracks that form in these soils penetrate most commonly to the bottom of the A12 horizon. The A13 is the remaining and major part of the A1 and it is here that the main features of the soil at the soil family level of classification are found. The soil material of

Table A-1-1. Outline of soils classification

Great Soil Group (Stace *et al.* 1968)	Soil family	Phase (series)	Principal profile form (Northcote 1971)
Grey, brown and red clays	Cununurra	Normal phase	Ug 5.15
	Cununurra	Alkaline phase	Ug 5.34 (.25)
	Cununurra	Leached phase	Ug 5.25
	Cununurra	Wetter phase	Ug 5.25
	Aquitaine	"Bluish" phase	Ug 5.29 (.25)
	Aquitaine	"Greyish" phase	Ug 5.25 (.29)
	Aquitaine	"Olive-yellow" phase	Ug 5.15
	Keep	Normal phase	Ug 5.34
	Keep	Flooded phase	Ug 5.25 (.34)
Red earths	Weaber	Normal phase	Gn 2.12
	Weaber	Heavier phase	Uf 6.31 (.53)
Desert loams (?)	Walyara	Normal phase	Gc 2.12 (1.22)
Other soils	Cununurra	Darker phase	Ug 5.15
	Cununurra	Eroded phase	Ug 5.34
	Milligan	Normal phase	Uf 6.31
	Mottled clay	Normal phase	Ug 5.15

the A13 horizon is usually dense and moist throughout the year, with prominent slickensides.

The AC horizon is a thin zone regarded as being transitional to the underlying parent material of the soils. Down this transitional zone almost all features of the soil are progressively modified and accumulations of carbonates occur. This is regarded as the depth to which most incident rain water normally percolates. The unmodified parent material below this is termed a C horizon, but in most profiles it was not unequivocally identifiable within the chosen sampling depth. Usually the AC horizon was subdivided into an AC1 and AC2 to accommodate the range of characteristics encountered.

Soil colour

As for the Keep River plain, soil colour was often difficult to assess, but because of the clear relationship between colour and soil attributes of agronomic importance it was important to devise a means of assessing it. The problems were greater in this survey because three soil surveyors were involved. Attempts at standardization were made on several occasions and 'standard clods' of specific soil colours were often carried. Moist Munsell colours were used as a basis.

Normal Cununurra clay soils had hues of 10YR or 2.5Y, with value/chroma readings of 3/2. The alkaline phase was distinctly browner, with value/chroma readings of 3/3, 4/3 and 4/2. The latter reading was common and as it indicates a value/chroma rating of 2 according to Northcote's (1971) notation, these soils should be classified as Ug 5.25.

However, even these were distinctly brownish rather than greyish and had other features conforming with the alkaline phase.

The leached phase soils appeared greyer and with value/chroma readings of 4/2 had a principal profile form (Northcote 1971) of Ug 5.25. However, some leached soils that appeared similarly greyish had a moist Munsell value/chroma reading of 3/2, and these were included in the leached phase because they conformed in other characteristics.

Acquitaine family soils were either 'bluish', 'greyish' or 'olive-yellow' in appearance, especially along earth roads or tracks. The 'bluish' phase had a hue as yellow or yellower than 2.5Y and value/chroma readings of 5/2 or 5/1.

The 'greyish' phase had hues of 10YR or 2.5 Y, and value/chroma readings of 4/2 or 4/1. In addition to their distinctly greyer appearance these soils showed evidence of inundation and other hydromorphic attributes similar to those of other Aquitaine soils and thus differed from members of the leached phase of Cununurra clay. The 'olive-yellow' phase soils had hues of 2.5Y and value/chroma readings of 3.5/2 and, according to the Munsell charts, their moist colour is dark greyish-brown. However, they appear distinctly yellowish or olive and showed evidence of inundation and other hydromorphic attributes.

Some members of the Keep family (flooded phase) appeared to have a definite brownish or reddish tinge when dry, but their moist Munsell colours indicated a value/chroma rating of 2 instead of the more usual 5. However, they had all the other attributes of members of the flooded phase and were accordingly classified with them.

Additional notes on soil colour and the local conventions adopted appear in the report on the lower Weaber and Keep Plains by Aldrick and Moody (1977).

Appendix 2

Detailed description of the soils

J.M. Aldrick, A.J. Clarke and M.H.R. van Cuylenberg

Great Soil Group:	Grey, brown and red clays
Soil family:	Cununurra (normal phase)
Principal profile form:	Ug 5.15
Drainage:	Poor
Parent material:	River alluvia
A11 (0 - 5 cm)	Very dark greyish-brown (2.5 Y 3/2) light to medium clay; dry and loose ("self-mulching"); granular structure and smooth-ped to rough-ped fabric, pH 7.5.
A12 (5 - 25 cm)	Very dark greyish-brown (2.5 Y 3/2) medium to heavy clay; dry extremely firm with medium blocky structure and smooth-ped fabric; pH 8.0, traces of carbonate nodules and some manganiferous concretions; some indistinct slickensides. Shrinkage cracks very evident. Peds about 4 cm x 8 cm.
A13 (25 - 125 cm)	Very dark greyish-brown (2.5 Y 3/2) heavy clay; dry extremely firm; coarse blocky structure evident in the drier parts with peds 15 cm x 30 cm; smooth-ped fabric; pH 8.5, traces of carbonate nodules and some manganiferous concretions; some lenses of fine sand. Shrinkage cracks sometimes penetrate into the top of this horizon.
AC1 (125 - 140 cm)	Dark brown (10 YR 3/3, 7.5 YR 3/2) medium to heavy clay; slightly moist extremely firm; smooth-ped fabric; pH 8.6, 2 to 5% carbonate nodules and traces of manganiferous concretions. Some weakly bound concretions of soil material, and inclusions of AC2 horizon material.
AC2 (140 - 160 cm+)	Dark reddish-brown (5 YR 3/4) medium clay; slightly moist very firm; pH 8.5, up to 5% large carbonate nodules; smooth ped faces evident, but fabric may be earthy. Increasing micaceous material.

Great Soil Group:	Grey, brown and red clays
Soil family:	Cununurra (alkaline phase)
Principal profile form:	Ug 5.34 (.25)
Drainage:	Imperfect to poor
Parent material:	River alluvia, relatively recent
A11 (0 - 10 cm)	Dark brown (10 YR 4/3) medium clay; dry and loose ("self-mulching"); granular structure, rough-ped to smooth-ped fabric; pH 7.8 to 8.0 (higher in transitions to Walyara). Up to 2% small carbonate nodules.

A12 (10 - 35 cm)	Dark brown (120 YR 3.5/3) medium to heavy clay; dry very hard or moist very firm; medium blocky structure and smooth-ped fabric; pH 8.3 to 8.5, 2 to 3% small carbonate nodules and some manganiferous concretions. (Amorphous carbonates also present in transitions to Walyara).
A13 (35 - 135 cm)	Dark brown (10 YR 3.5/3) medium to heavy clay; moist very firm; structure probably coarse blocky, with smooth-ped fabric and slickensides; pH 8.5 to 8.8, 2 to 3% carbonate nodules and some manganiferous concretions. Some sand lenses. (Amorphous carbonates also present in transitions to Walyara).
AC1 (135 - 145 cm)	Brown (7.5 YR 4/4) medium clay; moist extremely firm; smooth-ped fabric; pH 8.5 to 8.8, 5% large carbonate nodules and some manganiferous concretions. Some weak concretions of soil material.
AC2 (145 - 160 cm+)	Reddish-brown (5 YR 4/4) or yellowish-red (5 YR 4/6) light to medium clay; slightly moist very firm; smooth ped faces evident, but fabric predominantly earthy; pH 8.5, 5 to 10% large carbonate nodules. Increasing micaceous material.

Great Soil Group:	Grey, brown and red clays
Soil family:	Cununnura (leached phase)
Principal profile form:	Ug 5.25
Drainage:	Poor to very poor
Parent material:	River alluvia, relatively old
A11 (0 - 5 cm)	Dark greyish-brown (10 YR 3.5/2) medium to heavy clay; dry and loose ("self-mulching"); granular structure with rough-ped to smooth-ped fabric; pH 6.8 to 7.5.
A12 (5 - 25 cm)	Dark greyish-brown (10 YR 4/2) heavy clay; dry extremely hard or moist very firm; strong medium blocky structure and smooth-ped fabric; pH 7.5 to 7.8, rare small carbonate nodules and occasional traces of manganese.
A13 (25 - 130 cm)	Dark greyish-brown (10 YR 4/2) heavy clay; moist very firm; structure probably coarse blocky with smooth-ped fabric and very evident slickensides; pH 8.5, traces of carbonate and manganese and some sand lenses. The less well drained members tend to have slightly heavier textures, softer consistence, no visible carbonates, less distinct structure and some evidence of clay argillans.
AC1 (130 - 145 cm)	Dark brown (7.5 YR 3/4) heavy clay; slightly moist extremely firm; smooth-ped fabric; pH 8.8, traces of carbonate nodules and manganiferous concretions.
AC2 (145 - 160 cm)	Dark brown (5 YR 3/4) medium to heavy clay; slightly moist extremely firm; fabric mainly smooth-ped; pH 8.9, 1 to 2% carbonate nodules.

Great Soil Group:	Grey, brown and red clays
Soil family:	Aquitaine ("bluish" phase)
Principal profile form:	Ug 5.29 (.25)
Drainage:	Very poor
Parent material:	River alluvia
A11 (0 - 8 cm)	Grey (5 Y 5/1, 2.5 Y 5/1, 10 YR 5/1) or greyish-brown (2.5 Y 5/2, 10 YR 5/2) medium clay; weakly "self-mulching", fine blocky to platy structure with rough-ped to smooth-ped fabric; pH 6.0 to 7.0. Distinctly "bluish" when dry and disturbed.

A12 (8 - 30 cm)	Grey (5 Y 5/1, 2.5 Y 5/1) or greyish-brown (2.5 Y 5/2) medium to heavy clay; dry extremely hard; smooth-ped fabric, coarse blocky structure; pH 6.5 to 7.5, traces of carbonates and manganese. Few fine faint greyish mottles.
A13 (30 - 135 cm)	Grey (5 Y 5/1, 2.5 Y 5/1) or greyish-brown (2.5 Y 5/2), but sometimes olive-grey (5 Y 5/2, 4/2) or dark greyish-brown (2.5 Y 4/2) medium to heavy clay; moist very firm; smooth-ped fabric with slickensides, but indistinct pedality, some grey clay argillans; pH 7.5 to 8.0, some carbonate nodules and manganiferous concretions, occasional sand lenses. Common fine to medium yellowish-brown mottles.
AC (135 - 150 cm+)	Dark brown (7.5 YR 4/4), rarely yellowish-red (5 YR 4/6) medium clay; smooth-ped fabric and weak pedality, some clay argillans in upper parts; pH 8.5 to 9.0, up to 5% carbonate nodules. Some mottling.

Great Soil Group:	Grey, brown and red clays
Soil family:	Aquitaine ("greyish" phase)
Principal profile form:	Ug 5.25 (.29)
Drainage:	Very poor
Parent material:	River alluvia
A11 (0 - 8 cm)	Dark grey (10 YR 4/1) medium clay; weakly "self-mulching", fine blocky to platy structure with rough-ped to smooth-ped fabric; pH 6.5 to 7.5.
A12 (8 - 30 cm)	Dark grey (10 YR 4/1) or dark greyish-brown (2.5 Y 4/2, 10 YR 4/2) medium to heavy clay; dry extremely hard; smooth-ped fabric and coarse blocky structure; pH 7.5 to 7.8; traces of carbonate nodules and manganiferous concretions.
A13 (30 - 130 cm)	Dark grey (10 YR 4/1) or dark greyish-brown (2.5 Y 4/2, 10 YR 4/2) heavy clay; moist very firm; smooth-ped fabric with slickensides, but indistinct pedality, some grey clay argillans; pH 8.0 to 8.5, some carbonate nodules and manganiferous concretions, occasional sand lenses. Few to common greyish or yellowish-brown mottles.
AC (130 - 150 cm+)	Dark brown (10 YR 3/3, 7.5 YR 3/2), rarely reddish-brown (5 YR 4/4) medium to heavy clay; smooth-ped fabric and weak pedality; pH 8.5 to 9.0, to up 5% carbonate nodules. Some mottling.

Great Soil Group:	Grey, brown and red clays
Soil family:	Keep (normal phase)
Principal profile form:	Ug 5.34
Drainage:	Imperfect to poor
Parent material:	River alluvia
A11 (0 - 5 cm)	Dark brown (10 YR 3/3) light to medium clay, dry and loose ("self-mulching"); rough-ped fabric, pH 8.0; some carbonates, with a surface strew of carbonate nodules.
A12 (5 - 35 cm)	Dark greyish-brown (2.5 Y 3.5/2) to dark brown (10 YR 4/3) medium to heavy clay; dry extremely hard, smooth-ped fabric and blocky structure; pH 8.0 to 8.5. About 5% carbonate nodules and some manganiferous concretions.

A13 (35 - 110 cm)	Dark greyish-brown (2.5 Y 3.5/2) to dark brown (10 YR 4/3) heavy clay; moist very firm; smooth-ped fabric and blocky structure; pH 8.5 to 8.8. About 5 to 10% carbonate nodules and some manganiferous concretions; calcareous. Occasional sand lenses and weak slickensides.
AC (110 - 160 cm+)	Dark yellowish-brown (10 YR 3/4) medium to heavy clay; slightly moist extremely firm, earthy to smooth-ped fabric, weakly pedal; pH 8.8. About 10% carbonate nodules, calcareous.

Great Soil Group:	Grey, brown and red clays
Soil family:	Keep (flooded phase)
Principal profile form:	Ug 5.25, (.34)
Drainage:	Very poor
Parent material:	River alluvia
A11 (0 - 8 cm)	Brown (10 YR 4/3) or greyish-brown (10 YR 5/2) medium clay; dry and loose, granular, "self-mulching", with a surface strew of carbonate nodules; pH 8.0, some carbonate nodules and manganiferous concretions.
A12 (8 - 25 cm)	Brown (10 YR 5/3) or dark yellowish-brown (10 YR 4/4) medium clay; dry extremely hard; smooth-ped fabric and blocky structure; pH 8.0, some carbonate nodules and manganiferous concretions. Occasionally calcareous.
A13 (25 - 120 cm)	Brown (10 YR 5/3) or dark yellowish-brown (10 YR 4/4) medium to heavy clay; moist and very firm; smooth-ped fabric and blocky structure, evidence of slickensides; pH 8.5, moderate amounts of carbonate nodules and sufficient amorphous carbonates to make the soil material calcareous. Some manganiferous concretions. Few fine faint yellowish-brown mottles.
AC (120 - 150 cm)	Dark brown (10 YR 3/3) medium to heavy clay; slightly moist extremely firm; fabric mainly smooth-ped, but structure indistinct; pH 9.0, 5 to 10% carbonate nodules and some weakly cemented concretions of soil material. Calcareous. Some mottling.

Great Soil Group:	Red earths
Soil family:	Weaber (normal phase)
Principal profile form:	Gn 2.12
Drainage:	Moderately to well drained
Parent material:	River alluvia, coarser than usual
A1 (0 - 15 cm)	Dark reddish-brown (5 YR 3/4) fine sandy clay loam or sandy clay; dry and hard; massive and earthy; pH 6.5.
A3/B1 (15 - 45 cm)	Dark reddish-brown (2.5 YR 3/4) light clay with fine sand; dry very hard; massive and earthy; pH 6.5. Textures may be subplastic.
B2 (45 - 150 cm+)	Dark reddish-brown (2.5 YR 3/4) light or medium clay with sand; subplastic; dry very hard to moist very firm; massive and earthy; pH 6.5 to 7.0.

Great Soil Group:	Red earths
Soil family:	Weaber (heavier phase)
Principal profile form:	Uf 6.31 (.53)
Drainage:	Moderately to well drained
Parent material:	River alluvia, coarser than usual
A1 (0 - 20 cm)	Dark reddish-brown (5 YR 3/4, 2.5 YR 3/4) light to medium clay; very hard, massive, porous and earthy; pH 6.5.
B1 (20 - 70 cm)	Dark red (2.5 YR 3/6) or yellowish-red (5 YR 4/6) medium clay; massive and earthy, or weakly structured with some smooth-ped fabric; dry extremely hard; pH 7.0. Textures mildly subplastic; some grit or fine sand common.
B2 (70 - 150 cm)	Dark red (2.5 YR 3/6) or yellowish-red (5 YR 4/6) medium clay; massive and earthy, or structured with smooth-ped fabric; moist very firm; pH 7.5. Textures sometimes subplastic; grit or fine sand common components of the silica skeleton. Occasional mottling.

Great Soil Group:	Not known; similar to desert loams
Soil family:	Walyara (normal phase)
Principal profile form:	Gc 2.12, 1.22
Drainage:	Imperfect to poor
Parent material:	River alluvia, probably levee remnants
A1 (0 - 10 cm)	Dark brown (10 YR 3/3) clay loam; dry and hard, massive and earthy; pH 8.0, calcareous. A thin dark curled crust occurs on the surface with a few siliceous gravels.
A3 (10 - 20 cm)	Dark brown (10 YR 3/3) light clay; dry very hard, massive and earthy; pH 8.5, some finely divided carbonates; calcareous.
B1 (20 - 100 cm)	Dark brown (10 YR 4/3) medium clay; dry extremely hard; earthy to smooth-ped fabric and weak blocky structure; pH 8.8, up to 20% finely divided carbonates; calcareous.
B2 (100 - 160 cm)	Dark yellowish-brown (10 YR 3/3 3/4). Medium to heavy clay; slightly moist extremely firm; smooth-ped fabric and weak blocky structure; pH 8.8, some finely divided carbonates and a few pale mottles. Calcareous.

Appendix 3

Analytical methods and results

Physical analyses

The physical characteristics of the soils sampled in this survey were analysed mainly according to the methods described by Loveday (1974). Sampling was generally by 5 cm diameter tubes driven into the soil by a mechanical hammer. Clods were also collected in the field. Table A-3-1.

Aggregate stability

Aggregate stability was assessed by determining the dispersion index. Air-dry aggregates were dropped into distilled water and the dispersion index assessed. If the aggregates did not disperse initially, they were assessed at 2 and 20 h after remoulding, wetted to 100 cm suction water content. Table A-3-2.

Hydraulic conductivity

Air-dry material passing a 2 mm sieve was packed in cylinders using a packing machine (packed for 2 minutes at 180 times per minute), and hydraulic conductivities measured. Table A-3-2.

Bulk density (packed core)

This was measured after the mechanical packing of cylinders used in the hydraulic conductivity measurements. Table A-3-2.

Moisture characteristics

The sample passing a 2 mm sieve was saturated for about 24 h before pressurization at 1/3 atmosphere and 15 atmospheres to give figures for assessment of available water capacity. Table A-3-2.

Table A-3-1. Mechanical analyses

Soil family	Site	Horizons	Clay %	Silt %	Fine sand %	Coarse sand %
Cununurra Walyara intergrade	AG	A11	31	9	35.4	24.6
		A12	39	7	28.75	24.25
		A13	37	7	27.25	28.75
Cununurra (leached)	AT	A11	58.5	13.5	27	1.0
		A12	59.5	12.5	27	1.0
		A13	61.5	12.5	25	1.0
Cununurra (leached)	DT	A11	47.5	10.5	38.25	3.75
		A12	51.5	8.5	36.25	3.75
		A13	53	8.0	34.5	4.5
Cununurra (leached)	CP	A11	53.5	15.5	30.0	1.0
		A12	54.5	16.5	28.5	0.5
		A13	58.0	17.0	24.25	0.75
Weaber (heavy)	GI	A1	32.5	11.5	60.0	6.00
		B1	44.0	9.0	43.5	5.5
		B2	41.5	12.5	41.5	4.5
Cununurra (alkaline)	GJ	A11	37.0	16.0	42.0	5.0
		A12	47.0	14.0	32.25	3.75
		A13	51.5	9.5	36.5	2.5
Keep (normal) (puff)	RG	A11	50.0	13.0	31.0	6.0
		A12	57	14	23	6.0
		A13	60	14	21.5	4.5
Keep (normal) (Dep.)	RG	A11	46	17	31.25	5.75
		A12	56	18	23.0	3.0
		A13*	54.5	122.5	27.0	6.0

* Dep. = depression

Table A-3-2. Soil physical analyses

Soil family	Sample site and horizon	Dispersion Index	H.C. cm/h	1/3 atm.	15 atm.	Avail. H_2O %	B.D. packed core	Agg. B.D.
Walyara	AA A11	6	3.6	23.6	11.4	12.2	1.29	1.72
	A12	0	2.0	25.8	14.6	11.2	1.34	1.87
	A13		0.07	35.5	17.4	18.1	1.37	1.95
	Trans.*		0.02	37.0	17.0	20.0	1.34	1.93
Cununurra Walyara intergrade	AG A11	6	2.5	21.9	10.3	11.6	1.36	1.75
	A12	0	2.8	21.6	12.2	9.4	1.38	1.89
	A13		2.4	22.8	12.1	10.7	1.42	1.98
	Trans.*		0.03	29.2	13.4	15.8	1.43	2.00
Cununurra (alkaline) Walyara intergrade	AH A11	1	3.6	27.8	14.0	13.8	1.26	1.73
	A12	0	1.9	26.2	14.0	12.2	1.30	1.87
	A13		0.01	35.2	16.4	18.8	1.36	1.95
	Trans.*		0.01	39.4	18.5	20.9	1.40	1.96
Cununurra (leached)	AT A11	0	0.4	39.9	22.5	17.4	1.22	1.71
	A12	8	0.2	43.0	21.8	21.2	1.32	1.85
	A13		0.01	47.0	22.5	24.5	1.32	1.92
	Trans.*		0.01	46.6	23.6	23.0	1.31	1.90
Cununurra (leached)	BT A11	0	0.8	24.4	19.6	14.8	1.23	1.77
	A12	0	0.3	36.2	17.7	18.5	1.27	1.84
	A13		0.1	40.8	20.4	20.4	1.33	1.89
	Trans.*		0.01	40.2	19.9	20.3	1.28	1.93
Cununurra Weaber intergrade	CH A11	9	1.3	27.8	14.5	13.3	1.31	1.68
	A12	2	1.3	26.2	15.0	11.2	1.36	1.82
	A13		0.2	29.2	16.6	12.6	1.43	1.90
	Trans.*							
Weaber (normal)	CI A11	9	2.7	16.1	8.2	7.9	1.40	1.63
	A12	2	3.0	23.2	13.4	9.8	1.30	1.71
	A13		2.0	24.0	14.4	9.6	1.40	1.85
Cununurra (leached)	CP A11	0	0.3	37.8	20.3	17.5	1.29	1.77
	A12	2	0.3	38.2	19.8	18.4	1.30	1.80
	A13		0.05	42.0	21.0	21.0	1.33	1.91
	Trans.*		0.01	42.6	21.2	21.4	1.34	1.92
Keep?	DB A11	0	1.1	28.8	14.6	14.2	1.34	1.87
	A12	0	0.6	28.4	15.2	13.2	1.41	1.95
	A13		0.2	32.8	17.5	15.3	1.38	1.99
	D			18.0	8.7	9.3		1.95
Cununurra (normal)	DT A11	0	0.8	32.8	17.6	15.2	1.26	1.74
	A12	0	0.5	32.0	18.0	14.0	1.29	1.82
	A13		0.02	39.2	19.0	20.2	1.33	1.89
	Trans.*		0.01	43.8	20.4	22.4	1.36	1.95
Weaber (heavy)	GI A11	8	1.6	22.6	10.2	12.4	1.39	1.70
	A12	1	2.3	23.6	13.1	10.5	1.33	1.75
	A13		0.5	25.2	13.9	11.3	1.46	1.91

Table A-3-2. continued

Soil family	Sample site and horizon	Dispersion Index	H.C. cm/h	1/3 atm.	15 atm.	Avail. H_2O %	B.D. packed core	Agg. B.D.
Cununurra (alkaline)	GJ A11	3	0.5	27.4	14.2	13.2	1.34	1.69
	A12	0	1.5	27.1	15.6	11.55	1.32	1.81
	A13		0.1	33.2	16.8	16.4	1.33	1.97
	Trans.*		0.04	34.1	17.1	17.0	1.39	1.93
	C		0.2	27.4	12.4	13.0	1.41	1.87
Weaber (normal)	HJ A11	10	1.0	18.8	8.2	10.6	1.46	1.88
	A12	10	1.6	17.4	8.3	9.1	1.46	1.80
	A13		0.3	19.2	9.8	9.4	1.48	1.89
	C			23.6	12.2	11.4		
Cununurra (alkaline)	IC A11	0	0.8	30.9	18.0	12.9	1.26	1.76
	A12	0	1.0	31.0	16.9	14.1	1.30	1.83
	A13		0.5	35.6	18.6	17.0	1.38	1.92
	Trans.*		0.04	34.0	16.6	17.4	1.42	1.87
Aquitaine ?	IE A11	0	0.3	49.4	27.6	21.8	1.22	1.69
	A12	3	0.3	48.9	27.6	21.3	1.19	1.70
	A13		0.01	54.5	29.0	25.5	1.28	1.80
	Trans.*		0.03	56.2	30.8	25.4	1.29	1.80
Cununurra (alkaline) Walyara intergrade	JR A11	0	3.3	25.3	14.3	11.0	1.29	1.68
	A12	0	0.9	29.5	17.4	12.1	1.30	1.84
	A13		0.01	37.6	18.2	19.4	1.27	1.94
	Trans.*		0.01	38.3	18.8	19.5	1.38	1.96
Cununurra (Puff)	RG A11	6	1.4	33.5	19.6	13.9	1.17	1.55
	A12	0	1.6	34.2	20.2	14.2	1.24	1.69
	A13		0.5	37.8	21.5	16.3	1.26	1.75
	Trans.*		0.1	40.8	22.4	18.4	1.29	1.82
Cununurra ? (Dep.)	RG A11	8	1.1	44.4	25.2	19.2	0.96	1.44
	A12	6	0.9	35.1	20.6	14.5	1.22	1.62
	A13		0.9	34.6	19.6	15.0	1.26	1.71
			0.1	38.7	21.4	17.3	1.38	1.84
Keep (flooded)	RM A11	0	0.3	46.0	27.2	18.8	1.15	1.62
	A12	2	0.3	47.1	27.8	19.3	1.25	1.72
	A13		0.2	54.4	27.8	26.6	1.30	1.86
	Trans.*		0.01	57.4	28.6	28.8	1.34	1.86
Aquintaine	RP A11	0	0.4	45.7	26.3	19.4	1.18	1.64
	A12	0	0.3	47.6	29.2	18.4	1.24	1.67
	A13		0.1	57.8	28.2	29.6	1.32	1.87
	Trans.*		0.01	58.6	30.9	27.7	1.34	1.85

H.C. = hydraulic conductivity
B.D. = bulk density
Trans. = transitional
Agg. = aggregate

Chemical analyses

1. Sample preparation: All samples were air dried and ground to pass through a 2 mm sieve. No gravel was present in any sample.

   Determinations were carried out on the < 2 mm soil fraction and results reported on an air-dry basis.

2. Soluble salts: 1:5 soil:water suspension, 1 hour shaking.

   EC determined at 25°C.
   EC_{25} (mmhos/cm) x 0.32% total soluble salts.

3. $pH_{1:5}$: Determined on the stirred 1:5 soil:water suspension following EC measurement.

4. Chloride: Determined on an aliquot of the 1:5 soil:water suspension by electrometric titration using a silver electrode and a Backman fibre junction calomel electrode.

5. Exchangeable cations and CEC: Non-calcareous samples - 60% ethanol wash and leaching with 1.0N NH_4Cl pH 7.0 for exchangeable cations, followed by 0.05N NH_4Cl wash and leaching with 1.0N Na_2SO_4 for CEC determination.

6. Sodium and potassium were determined by flame photometry: Calcium and magnesium by titration with 0.05N EDTA.

7. Calcareous samples: Glycol-ethanol wash and leaching with alcoholic 1.0N NH_4Cl pH 8.5 for exchangeable cations, followed by 0.05 N NH_4Cl wash and leaching with 1.0N Na_2SO_4 for CEC determination (Tucker, 1971).

8. Organic carbon: The wet-combustion method of A. Walkley and I.A. Black, (1934). Results reported as uncorrected Walkley and Black values.

9. Per cent organic matter per cent organic carbon x 1.72.

10. Total nitrogen: Dumas method using a Coleman N Analyzer.

11. "Available" P: 0.5M $NaHCO_3$, pH 8.5 after J.E. Colwell (1963).

12. Mechanical analysis: Plummet balance method after Hutton, (1955).

13. Extractable zinc: EDTA/ammonium carbonate extractable Zn after the method of J.F. Trierweiler and W.L. Lindsay (1969).

Table A-3-3. pH, per cent total soluble sales, per cent NaCl of type profiles

Soil family	Site no.	Horizon	pH 1:5	T.S.S. %	NaCl %
Cununurra (normal)	DT	A11	7.7	0.01	negl.
		A12	8.1	0.01	negl.
		A13	9.1	0.04	negl.
Cununurra (leached)	AT	A11	8.1	0.02	0.005
		A12	8.6	0.02	negl.
	A13	9.3	0.04	0.007	
		Trans.	9.2	0.22	0.106
	BT	A11	7.8	0.01	negl.
		A12	8.1	0.01	negl.
		A13	9.0	0.04	0.005
		Trans.	8.7	0.17	0.071
	CP	A11	7.5	0.01	negl.
		A12	7.1	0.03	negl.
		A13	7.2	0.02	negl.
Cununurra (alkaline)	GJ	A11	7.2	0.02	negl.
		A12	8.6	0.02	negl.
		A13	9.0	0.03	negl.
		Trans.	9.1	0.06	negl.
		C	9.2	0.06	0.007
	IC	A11	8.7	0.02	negl.
		A12	8.7	0.02	negl.
		A13	8.7	0.03	negl.
		Trans.	8.9	0.10	0.013
		C	9.1	0.10	0.014
Cununurra (alkaline)/ Walyara intergrade	IC	A12	7.9	0.01	negl.
		A13	9.1	0.06	negl.
		Trans.	9.5	0.19	0.071
	AH	A11	8.1	0.01	negl.
		A12	8.5	0.03	negl.
		A13	9.4	0.14	0.029
		Trans.	9.2	0.32	0.175

Table A-3-3. continued

Soil family	Site no.	Horizon	pH 1:5	T.S.S. %	NaCl %
	JR	A11	8.3	0.02	negl.
		A12	8.9	0.07	negl.
		A13	9.0	0.11	0.02
		Trans.	9.0	0.35	0.21
	JS	A11	8.5	0.10	0.017
		A12	8.5	0.04	negl.
		A13	8.7	0.05	0.011
Walyara	AA	A11	7.8	0102	negl.
		A12	8.9	0.05	negl.
		A13	9.4	0.12	0.011
		Trans.	9.3	0.18	0.060
		C	9.4	0.16	0.058
Weaber (normal)	CI	A1p	7.5	0.01	negl.
		A3/B1	7.1	0.03	negl.
		B2	7.2	0.02	negl.
	HJ	A11	6.7	0.01	negl.
		A12	6.0	0.02	negl.
		B	6.2	negl.	negl.
		C	7.1	0.01	negl.
Weaber (heavier)	GI	A1	7.2	0.01	negl.
		B1	7.2	0.01	negl.
		B2	7.5	0.01	negl.
Cununurra/ Weaber Intergrade	CH	A12	7.8	0.01	negl.
		A13	8.6	0.03	0.014
Aquitaine	IE	A11	8.4	0.03	0.005
		A12	8.5	0.03	0.01
		A13	8.8	0.06	negl.
		Trans.	8.7	0.14	0.04
	RP	A11	8.0	0.03	0.005
		A12	8.3	0.02	negl.
		A13	9.2	0.11	0.008
		Trans.	8.9	0.42	0.199
Keep (normal) (Puff)	RG	A11	8.5	0.04	0.007
		A12	8.6	0.04	negl.
		A13	8.8	0.07	0.008
		Trans.	8.9	0.09	0.010
Keep (Dep.)	RG	A11	7.4	0.04	0.007
		A12	7.6	0.02	negl.
		A13	8.5	0.04	negl.
		Trans.	8.7	0.05	negl.
Keep (flooded)	RM	A11	7.8	0.03	0.005
		A12	8.2	0.03	0.007
		A13	9.0	0.10	0.017
		Trans.	8.9	0.22	0.079

Table A-3-4. Exchangeable cations, extractable P and organic matter content of type profiles

Soil family	Site no.	Horizon	Exchangeable cations Ca++ me%	Mg++ me%	Na+ me%	K+ me%	C.E.C. me%	Extr. P ppm	Organic matter %
Cununurra (normal)	DT	A11	17.3	12.8	0.34	0.58	31.0	3.6	0.98
Cununurra (leached)	AT	A11	20.9	15.9	0.46	1.00	38.4	5.6	0.68
	BT	A11	18.1	15.5	0.32	0.62	34.6	10.0	0.91
	CP	A11	21.5	19.7	0.24	0.42	41.3	2.4	0.75
Cununurra (alkaline)	GJ	A11	11.0	13.8	0.22	0.76	25.0	4.2	2.10
	IC	A11	21.3	14.5	0.30	0.72	37.5	16.8	1.90
Cununurra (alkaline)/ Walyara intergrade	AH	A11	15.3	11.5	0.48	0.42	27.2	3.6	0.88
	JR	A11	24.1	7.6	0.26	0.38	32.9	3.6	0.98
	JS	A11	17.1	5.0	0.26	0.66	22.5	9.6	0.75
Walyara	AA	A11	17.1	5.1	0.24	0.46	22.4	3.2	1.30
Weaber (normal)	CI	A11	8.9	1.1	0.16	0.64	11.3	10.0	0.56
	HJ	A11	5.4	2.4	0.08	0.42	10.4	3.2	0.88
Weaber (heavier)	GI	A1	6.7	4.8	0.10	0.52	12.4	4.6	1.17
Aquitaine	IE	A11	33.1	15.2	0.46	2.16	50.3	20.0	1.30
	RP	A11	23.1	18.6	0.48	1.10	43.4	3.2	0.46
Keep (normal) (Puff)	RG	A11	21.3	5.8	0.26	1.48	29.3	5.6	1.30
Keep (normal) (Dep.)	RG	A11	18.2	9.3	0.26	1.54	29.9	0.6	6.10
Keep (flooded)	RM	A11	25.3	18.0	0.40	1.26	44.8	3.6	2.50

Table A-3-5. Extractable zinc of A11 horizons

Site no.	Extr. zn	Site no.	Extr. zn	Site no.	Extr. zn	Site no.	Extr. zn	Site no.	Extr. zn	Site no.	Extr. zn
	ppm		ppm		ppm		ppm		ppm		
AA	0.4	BH	0.8	CS	0.2	GO	0.7	HT	0.3	JA	0.3
AB	2.4	BI	0.4	CU	0.3	GP	0.6	HU	0.2	JB	0.2
AC	0.4	BK	0.4	CW	0.8	GQ	0.4	HV	0.3	JC	0.2
AD	0.4	BL	0.3	CX	0.2	GR	0.4	HW	0.2	JD	0.4
AF	0.3	BM	0.6	CZ	0.2	GS	0.4	HX	0.2	JE	0.2
AG	1.6	BN	0.3	DD	0.3	GT	0.3	HY	0.3	JF	0.2
AH	1.3	BO	0.2	DE	0.3	GU	0.3	HZ	0.3	JG	0.2
AI	0.8	BP	0.3	DF	0.2	GV	0.6	IC	0.3	JI	0.6
AJ	1.0	BQ	0.3	DG	0.2	GW	0.4	ID	0.3	JJ	0.2
AK	0.9	BR	0.2	DH	0.4	GX	0.4	IE	0.4	JK	0.9
AL	1.1	BS	0.2	DI	0.4	GY	0.4	IF	0.4	JL	0.4
AM	7.7	BT	0.2	DJ	0.3	GZ	0.5	IG	0.3	JM	0.4
AN	0.7	BU	0.4	DK	0.5	HA	0.4	IH	0.3	JR	0.1
AO	0.5	BV	0.3	DL	0.2	HB	0.4	II	0.3	JT	0.1
AP	0.9	BQ	0.4	DM	0.3	HC	0.3	IJ	0.2	JU	0.1
AQ	0.5	BX	0.3	DN	0.4	HD	0.2	IK	0.3	JV	0.1
AR	0.3	BY	0.4	DO	0.3	HE	0.3	IL	0.3	PA	0.2
AS	0.3	BZ	0.4	DQ	0.3	HF	0.3	IM	0.3	PB	0.2
AT	0.6	CA	0.3	DR	0.2	HG	0.3	IN	0.2	PC	0.1
AU	0.4	CB	0.7	GA	0.5	HH	0.3	IO	0.3	PD	0.2
AV	0.7	CC	0.5	GC	0.4	HI	0.3	IP	0.4	PE	0.1
AW	0.8	CD	0.2	GD	0.4	HJ	0.4	IQ	0.4	PF	0.2
AX	0.8	CF	0.2	GE	0.6	HK	0.3	IR	0.3	PG	0.2
AY	0.6	CG	0.3	GF	0.4	HL	0.3	IS	0.7	PH	0.2
AZ	0.5	CH	0.4	GG	0.4	HM	0.3	IT	0.2	PI	0.1
BA	0.9	CI	0.5	GH	0.4	HN	0.3	IU	0.2	PJ	0.2
BC	0.7	CK	0.2	GI	0.8	HO	0.4	IV	0.3	PK	0.3
BD	0.8	CL	0.3	GJ	0.6	HP	0.5	IW	0.2	PL	0.3
BE	0.4	CM	0.4	GL	0.4	HQ	0.4	IX	0.2	PM	0.2
BF	0.7	CP	0.2	GM	0.5	HR	0.3	IY	0.3	PN	0.2
BG	0.8	CQ	0.2	GN	0.3	HS	0.2	IZ	0.3	PO	0.2
PP	0.2	QI	0.5	RF	0.4	PQ	0.2	QJ	0.6	RH	0.4
PR	0.4	QK	0.6	RI	0.2	PT	0.2	QL	0.5	RJ	0.3
PU	0.2	QM	0.6	RL	0.3	PV	0.3	QN	0.5	RM	0.3
PW	0.1	QO	0.5	RQ	0.2	PX	0.2	QP	0.5	RU	0.3
PY	0.2	QR	0.5	RZ	0.3	PZ	0.2	QS	0.5	SH	0.2
QA	0.1	QV	0.7	SI	0.1	QB	0.2	QW	0.6	SK	0.5
QC	0.3	QX	0.5	SM	0.2	QD	0.2	QY	0.7	SN	0.3
QE	0.3	RA	0.6	SO	0.5	QF	0.3	RB	0.5	SP	0.5
QG	0.5	RC	0.8	SQ	0.3	QH	0.6	RD	0.4		

Appendix 4

Map key for the Ivanhoe Plain

J.M. Aldrich and A.J. Clarke

1a. Brownish cracking clays with finely structured high pH topsoils (Cununurra alkaline phase); confined to southern (younger) province.

1b. Greyish cracking clays with relatively coarsely structured almost neutral pH topsoils (Cununurra leached phase); confined to northern (older) province.

2c. Sandy-surfaced red earths (Weaber normal phase) occurring as 'islands' in the clay plain.

2e. Heavy-textured red earths (Weaber heavier phase) occurring as 'islands' in the clay plain.

4c. Brownish cracking clays with carbonate nodules and high pH topsoils (Keep normal phase), minor Cununurra clays; confined to northern (older) province.

4f. Complex areas surrounding land units 2c and 2e, a mixture of cracking clays (Cununurra) and red earths (Weaber); confined to southern (younger) province.

5a. Cracking clays (Aquitaine 'bluish' phase, Keep flooded phase) with thick *Eucalyptus microtheca / Excoecaria parvifolia* woodland; seasonally inundated to moderate depths for long periods.

5b. Cracking clays (Aquitaine 'greyish' phase) with open *Eucalyptus microtheca / Excoecaria parvifolia* woodland; seasonally inundated to shallow depths for short periods.

5c. Cracking clays (Aquitaine 'bluish' phase) with 'debil-debil' microrelief and inclusions of stone and rock; seasonally inundated to significant depths for long periods; treeless.

5d. Cracking clays with reduced internal drainage capacity (Cununurra wetter phase); seasonally waterlogged; confined to northern (older) province.

7a. Rivers and major creeks with associated steep banks; frontage vegetation.

7b. Severely eroded cracking clays (Cununurra eroded phase) and other soils bordering rivers and major creeks; predominantly *Lysiphyllum cunninghamii* woodland.

8. Complex depressed peripheral zones adjoining sandy land systems; soils very variable, but mainly heavy clays; seasonally inundated; *Eucalyptus microtheca / Excoecaria parvifolia* woodland.

9a. About 40% gradational calcareous clays (Walyara) in a matrix of brownish cracking clays with finely structured high pH topsoils (Cununurra alkaline phase); confined to southern (younger) province.

9b. About 20% gradational calcareous clays (Walyara) in a matrix of brownish cracking clays with finely structured high pH topsoils (Cununurra alkaline phase); confined to southern (younger) province.

9c. Brownish cracking clays with finely structured high pH topsoils (Cununurra alkaline phase) and intergrades with Walyara soils; about 2% gradational calcareous clays (Walyara); confined to southern (younger) province.

10a. Cracking clays (Cununurra leached phase) with considerable coarse sand throughout; reduced moisture-holding capacity.

10b. Cracking clays (Cununurra leached phase) with some coarse sand and slightly reduced moisture-holding capacity; some intergrades with Weaber soils.

R. Isolated small rock outcrops or areas of land unit 6.

Appendix 5

The common map key

J.M. Aldrich

1. Cracking clays (Cununurra normal phase); relatively uniform over large areas of broad plains, minor inclusions of Cununurra wetter, darker and browner phases and some variation in topsoil pH. Vegetation variable, but mostly treeless.

1a. Brownish cracking clays with finely structured high pH topsoils (Cununurra alkaline phase); relatively uniform over large areas of broad plains; minor inclusions of calcareous soils with finely divided carbonates. *Lysiphyllum cunninghamii* woodland.

1b. Greyish cracking clays with relatively coarsely structured almost neutral pH topsoils (Cununurra leached phase); relatively uniform over large areas of broad plains; minor inclusions of Cununurra wetter phase. Mostly treeless.

2a. Red-brown earths* (Bonaparte normal phase); occurs as 'islands' in broad cracking clay plains; low eucalypt woodland.

2b. Red-brown earths* with sandy topsoils (Bonaparte sandy-surfaced phase); occurs in association with land unit 2a as 'islands' in broad cracking clay plains; variable tall woodland or open forest.

2c. Red earths with sandy topsoils (Weaber normal phase); occurs as 'islands' in broad cracking clay plains; eucalypt woodland.

2d. Red earths with abundant gravel throughout (Weaber gravelly phase); occurs on raised, linear, old stream-bed areas; non arable; sources of gravel. Eucalypt woodland.

2e. Red earths with heavy-textured topsoils (Weaber heavier phase); occurs as 'islands' in broad cracking clay plains; eucalypt woodland.

3a. Red-brown earth*/solodic soil intergrades (Benton); occurs in association with other '2', '3' and '4' land units within broad clay plains; contains seasonally inundated depressions; thick *Melaleuca minutifolia* woodland.

3a1. Red-brown earth*/solodic soil intergrades (Benton); occurs in association with other '2', '3' and '4' land units within broad clay plains; contains seasonally inundated depressions, treeless.

3b. Red-brown earth*/solodic soil intergrades (Benton); occurs in association with other '2', '3' and '4' land units within broad clay plains; contains seasonally inundated depressions; *Grevillea striata* open woodland.

3c. Red-brown earth*/solodic soil intergrades (Benton) on narrow areas and cracking clay intergrades (Milligan) on broad areas; occurs in association with other '2', '3' and '4' land units within broad clay plains; contains seasonally inundated depressions; *Eucalyptus microtheca* open woodland.

3d. Cracking clay intergrades (Milligan) and minor red-brown earth solodic soil intergrades (Benton); occurs in association with other '2', '3' and '4' land units within broad clay plains; contains seasonally inundated depressions; *Eucalyptus papuana* open woodland.

4a. Cracking clays (Cununurra) in large depressions, various non-cracking soils (Bonaparte, Benton, Walyara) on large intervening shelves; occurs in association with other '2', '3' and '4' land units within broad clay plains or adjoining stream frontage areas; depressions inundated seasonally, variable vegetation.

4b. Cracking clays (Cununurra) in medium-sized depressions, various other soils (Keep, Benton) on medium-sized intervening shelves and mounds; occurs in assocation with other '2', '3' and '4' land units within broad clay plains or adjoining stream frontage areas; depressions inundated seasonally; variable vegetation.

4c. Brownish cracking clays with carbonate nodules and high pH topsoils (Keep normal phase, minor Cununurra) mainly on gilgai mounds, other cracking clays (Cununurra) in some depressions; occurs within broad clay plains, sometimes in association with other '2', '3' and '4' land units or adjoining stream frontage areas; gilgai depressions inundated seasonally; usually treeless.

4d. Cracking clays with hydromorphic attributes (Cununurra wetter phase, Mottled clays) in depressions, cracking clay intergrades (Milligan) on broad shelves; occurs in seasonally swampy areas at the junction between broad clay plains and sandy or lateritic land systems, but only depressions are inundated; *Eucalyptus papuana* open woodland.

4e. Cracking clays with hydromorphic attributes and high topsoil pH (Keep flooded phase) strongly gilgaied; occurs in seasonally swampy areas, but only gilgai depressions are inundated; dense woodland.

4f. Cracking clays (Cununurra; usually alkaline phase) and red earths (Weaber) with some intergrades; occurs around areas of land units 2c and 2e, but sometimes separately; not yet observed in undeveloped condition.

5a. Cracking clays with hydromorphic attributes (Aquitaine 'bluish' phase, minor Keep flooded phase); occurs in broad low-lying areas, usually where the clay plains adjoin sandy or lateritic land systems; seasonally inundated to moderate depths for long periods; thick *Eucalyptus microtheca / Excoecaria parvifolia* woodland.

5b. Cracking clays with hydromorphic attributes (Aquitaine 'greyish' phase); occurs in broad low-lying areas of the clay plains, often near land unit 5a; seasonally inundated to shallow depths for short periods; open *Eucalyptus microtheca / Excoecaria parvifolia* woodland.

5c. Cracking clays with very hydromorphic attributes (Aquitaine 'bluish' phase) with 'debil-debil' microrelief and inclusions of stone and rock; occurs in depressed linear zones marginal to land unit 5a and immediately adjacent to sandy or lateritic land systems; seasonally inundated to significant depths for long periods; treeless.

5d. Cracking clays with reduced internal drainage capacity (Cununurra wetter phase); occurs within broad cracking clay plains; seasonally waterlogged; usually treeless.

6. Small steep hills and outcrops of sandstone and other rock types in a matrix of stony cracking clay; random occurrence, vegetation varied.

7a. Rivers and major creeks with associated steep banks; frontage vegetation.

7b. Cracking clays in a severely eroded and truncated conditions (Cununurra eroded phase) and other soils bordering and rivers and major creeks; minor levees, point bars and swamps; predominantly *Lysiphyllum cunninghamii* woodland.

8a. Complex, depressed peripheral zones adjoining land unit 8b at sandy or lateritic land systems; soils very variable, but mainly heavy clays with sand inclusions; depressions are seasonally inundated; *Eucalyptus microtheca* dominated woodland, some *Excoecaria parvifolia*.

8b. Complex zone between unit 8a and sandy land systems; soils very variable, mostly duplex soils : variable woodland with *Eucalyptus polycarpa* and *E. microtheca*.

9a. About 40% gradational calcareous clays (Walyara) in a matrix of land unit 1a (brownish cracking clays) with finely structured high pH topsoils - Cununurra alkaline phase); vegetation relatively thick and includes *Lysiphyllum cunninghamii, Carissa lanceolata* and occasional eucalypts.

9b. About 20% gradational calcareous clays (Walyara) in a matrix of land unit 1a (brownish cracking clays with finely structured high pH topsoils - Cununurra alkaline phase); vegetation includes *Lysiphyllum cunninghamii* and *Carissa lanceolata*.

9c. Brownish cracking clays with finely structured high pH topsoils (Cununurra alkaline phase) and intergrades with Walyara soils; about 2% gradational calcareous clays (Walyara); vegetation includes *Lysiphyllum cunninghamii* and *Carissa lanceolata.*

10a. Cracking clays (Cununurra leached phase) with considerable coarse sand throughout and reduced moisture-holding capacity; possibly old stream bed areas; often underlain by sand.

10b. Cracking clays (Cununurra leached phase) with a little coarse sand and slightly reduced moisture-holding capacity; some intergrades with Weaber soils.

* Now recognized as non-calcic brown soils.

Appendix 7

Co-ordinates of observation points

Site	Easting	Northing
AA	467971	8270157
AB	467986	8270036
AC	468566	8269794
AG	467136	8269570
AH	467342	8268991
AI	467239	8268662
AJ	467040	8270455
AK	466357	8270524
AL	464916	8269553
AM	465759	8269759
AN	468610	8268565
AO	465074	8270200
AP	466629	8270956
AQ	466736	8270892
AR	471101	8270636
AS	470942	8270507
AT	471076	8269311
AU	466754	8272044
AV	467508	8272821
AX	469542	8271558
AY	469790	8271322
BA	469718	8272628
BB	470414	8272580
BC	470845	8272588
BD	470775	8272208
BE	470756	8271976
BF	470763	8271734
BG	471146	8271597
BH	471051	8271050
BI	469823	8273914
BJ	470170	8273845
BK	469988	8274596
BL	470111	8275299
BM	470133	8275850
BN	470623	8275992
BO	468973	8275784
BP	467845	8275374
BQ	467890	8275257
BR	468655	8275686
BS	466686	8275680
BT	466772	8275882
BU	466738	8275365
BV	468080	8277544

Site	Easting	Northing
BW	468402	8277521
BY	465618	8276837
BZ	464284	8274562
CA	464552	8274218
CB	471879	8271885
CC	472040	8271898
CD	472592	8273540
CE	472592	8271973
CF	471997	8271528
CG	472863	8271997
CH	473633	8271592
CI	473810	8271517
CJ	473549	8271223
CK	473702	9274158
CL	475342	8273196
CM	473554	8273752
CN	473047	8273917
CO	473664	8272701
CP	473365	8272687
CQ	472973	8272694
CR	473656	8272536
CS	474528	8272815
CT	474471	8272559
CV	474367	8272408
CW	476481	8271741
CX	476540	8271739
CY	476205	8271279
CZ	476114	8271431
DA	475843	8271799
DB	472477	8271184
DC	471810	8269861
DD	471986	8269735
DE	473541	8270269
DF	473906	8269977
DG	474063	8269548
DH	473692	8269302
DI	473538	8269235
DJ	469138	8266448
DK	469550	8266417
DL	469822	8266782
DM	469559	8267860
DN	471340	8267876
DO	471464	8268003
DP	471365	8268177
DQ	470890	8267673
DR	470796	8267997
DT	468025	8268095
GA	468454	8255144
GB	468485	8255530
GC	468123	8255194
GD	466694	8255986
GE	465468	8255833
GF	464992	8255992
GG	467263	8256742
GH	466921	8256827
GI	465839	8255758
GJ	466056	8255584
GK	466380	8255472

Site	Easting	Northing
GL	464738	8257078
GM	467868	8257034
GN	467595	7257102
GO	468019	8256165
GP	467707	8256192
GQ	467504	8255107
GR	465771	8256323
GS	465604	8256437
GT	466377	8256862
GU	466952	8257464
GV	466873	8258299
GW	466972	8257141
GX	468218	8256874
GY	468413	8257381
GZ	468413	8257381
HA	467884	8257781
HB	467716	8258703
HC	467836	8258854
HD	467567	8259036
HE	467434	8257341
HF	467723	8259669
HG	467464	8259812
HH	467191	8259720
HI	467738	8260118
HJ	467731	8260450
HK	466643	8259906
HL	466479	8260204
HM	466640	8260096
HN	467010	8260069
HO	467148	8260238
HP	467340	8260528
HQ	466699	8260629
HR	467012	8260760
HS	466791	8260999
HT	466605	8260769
HU	465604	8260762
HV	466125	8260263
HW	466155	8261348
IA	467350	8261201
IB	467474	8261237
IC	466095	8261867
ID	466341	8261873
IE	466729	8261803
IF	465289	8261190
IG	464582	8261149
IH	462791	8262550
II	466335	8262998
IJ	4666909	8262923
IK	467722	8263381
IL	468101	8263296
IM	468563	8263241
IN	467506	8263399
IO	467293	8263624
IP	467903	8263852
IQ	467549	8264195
IR	467137	8264658
IS	467899	8264266
IT	466052	8264517
IU	466170	8264909
IV	466287	8265188
IW	466617	8265750
IX	466191	8264117
IY	464777	8264117
IZ	468739	9266104
JA	468735	8265916
JB	469089	8266052
JC	469080	8265713
JD	4699277	8265582
JE	469677	8265602
JF	462695	8263318
JG	462421	8262805
JH	465783	8266390
JI	467635	8265943
JK	469165	8264415
JL	469144	8264729
JM	469107	8264993
JN	463505	8262655
JO	466589	8262889
JP	467444	8263010
JQ	466995	8264063
JS	467524	8264278
JT	466446	8266143
JU	467137	8265202
JV	467257	8262216
PA	472122	8277908
PB	472350	8279230
PC	473278	8277941
PD	473316	8277386
PE	474300	8276783
PF	473164	8276985
PG	473525	8276962
PH	474307	8277624
PI	474487	8278105
PJ	473606	8274532
PK	473941	8275686
PL	475106	8277241
PM	474939	8277373
PN	474552	8277542
PO	474890	8277689
PP	477022	8279381
PQ	477343	8279448
PR	477509	8278470
PS	478567	8280780
PT	478288	8280934
PU	478628	8281568
PV	479317	8282085
PW	479437	8282058
PX	478912	8280737
PY	479096	8280636
PZ	479320	8280614
QA	488058	8281289
QI	479198	8281569
QJ	479026	8281806
QK	479115	8281528
QM	480120	8281146

Site	Easting	Northing
QQ	473054	8274520
QR	472510	8275033
QS	477314	8275120
QT	472105	8275327
QU	471821	8275559
QV	471636	8275800
QW	472634	8279315
QX	472876	8279789
QY	472569	8279873
QZ	472196	8280245
RA	471202	8280096
RB	470924	8280385
RC	470032	8281074
RD	469178	8281000
RE	469288	8280121
RF	468969	8280290
RG	468525	8280360
RH	468134	8280364
RI	470085	8279635
RJ	469756	8279298
RK	468486	8281177
RL	470348	8281739
RM	470716	8281139
RN	471634	8280961
RO	472135	8280870
RP	472434	8280828
RQ	472816	8280747
RR	468561	8278852
RS	468111	8279191
RT	467378	8280871
RU	467734	8280561
RV	467366	8280496
RW	470722	8277964
RX	471571	8279296
RY	470931	8278479
RZ	470411	8279348
SA	475192	8277170
SB	474149	8275636
SC	470247	8276850
SD	469181	8277568
SE	469054	8277732
SF	469099	8277955
SG	468956	8278129
SH	477274	8273744
SI	477990	8273937
SJ	477267	8274130
SK	477288	8274130
SL	477881	8272684
SM	477802	8272879
SN	478149	8274338
SO	478805	8274357
SP	479087	8274265
SQ	478320	8275024

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