Appendix 1: Additional Information

Determining spatially variable achievable yield through remote sensing

For variable rate fertiliser application, it is assumed that the paddock average achievable yield is equal to that calculated with the French and Schultz equation. This average yield is then distributed spatially within the paddock according to spatial patterns of historical yield. Satellite imagery measured as Normalised Difference Vegetation Index (NDVI) can be used as a surrogate in the absence of yield maps because nutrient demand is driven by plant growth and biomass production. In our field experiments, NDVI measured by satellite imagery in late August was linearly related to fresh wheat biomass (t/ha) (equation 1).

$$\text{Biomass}_{\text{wheat}} = 39.9\ \text{NDVI} - 6.8,\ r^2 = 0.87 \qquad (1)$$

In the absence of adverse conditions between late August and harvest, wheat yield should be related to the biomass through its harvest index. Saturation of the NDVI values occured at about 20 t/ha fresh wheat biomass due to canopy closure. The relationship for lupin was noisier and the logarithm of the fresh biomass was therefore used (equation 2). This linear relationship breaks down at about 12 t/ha fresh lupin biomass due again to NDVI saturation at high yielding zones.

$$\text{Log Biomass}_{\text{lupin}} = 0.97\ \text{NDVI} + 0.51,\ r^2 = 0.72 \qquad (2)$$

In addition to distributing paddock average yield, these relationships between biomass and NDVI are also an important step in using satellite imagery for predicting yield and for minimising the risk of input investment by directing mid season agronomic interventions according to the development of the crop.

Checking patterns of achievable yield with inherent landscape properties

Historical spatially variable paddock performance expressed as scaled yield (between 0 and 1) for 1999-01 at Rex Heal's property was linearly related to the PAW of the soil profile down to 1 m depth (equation 3). Simulated actual annual yield using APSIM for the past 100-year climatic data and different nitrogen fertiliser scenarios confirmed the importance of PAW for determining achievable yield. Soils with the lowest PAW yielded consistently poorly throughout the simulation runs and yield performance increased with increasing PAW.

$$\text{Scaled yield} = 0.015\ \text{PAW} - 0.52,\ r^2 = 0.92 \qquad (3)$$

PAW is expensive to measure and can be estimated more cheaply for non-rocky and non-gravelly areas by gamma ray spectrometry (Fig. 1).

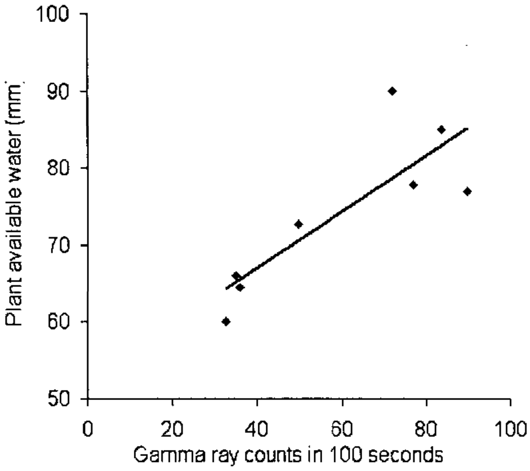


Fig 1. Estimate of plant available water from gamma ray emission from ^{40}K for non-gravelly and non-rocky areas.

The regression equation for plant available water is

$$PAW = 0.36 \text{ Gamma counts} + 52.5, r^2 = 0.69 \quad (4)$$

The expression for PAW using gamma counts (equation 4) can be substituted in equation 3 to give the relationship between PAW and gamma-ray emission from ^{40}K. This gives us a cheap surrogate method to estimate (1) spatially variable PAW and (2) spatially variable yield performances driven by an enduring soil property. When used with yield maps, gamma ray emission provides a means of checking the reliability of distributing achievable yield according to past paddock performance.

Determining soil available K

On-ground measurement of gamma-ray emission on several paddocks on Rex Heal's property showed good ability to predict Colwell K in most areas of the paddock. In some areas, there was a mismatch due to occurrence of superficial rocks and lateritic gravels that emit gamma ray strongly and out of proportion to the Colwell K content. These superficial rocks and lateritic gravels occurred mostly on the higher parts of the landscape and a Land Monitor digital elevation model (DEM) and ground truth was used to locate the elevation for such occurrence. This elevation based method is not perfect as some gravelly outcrops occurred as rises in lower parts of the paddock. These gravelly areas could be indentified visually by consulting the grower with digital aerial photos. More recent work showed that measurements of gamma emission from thorium contained in lateritic rocks and gravel provided a reliable means of locating these outcrops. Outside those areas, Colwell K was linearly related to the gamma counts (expressed as counts per 100 seconds) from ^{40}K (equation 5).

$$\text{Colwell K} = 0.74 \text{ counts}_{100} - 29.7, r^2 = 0.75. \quad (5)$$

Estimating potassium fertiliser requirement

The grower is ready to estimate K fertiliser requirement with values of achievable yield and soil Colwell K. The K recommendation can be read from a simple graphical form of the DSS (Fig. 2) for wheat for uniform paddock and zone applications. Although little wheat yield response is expected for soil Colwell K > 60 mg K / kg and achievable yield < 2.5 t / ha, we recommend that for marginal soil test values of around 60 mg K / kg, the grower applies a maintainance application of K equal to the amount removed by grain in order to safeguard against K depletion and the onset of deficiency. Wheat harvest removes about 4 kg K / t grain and lupins removes about 8 kg K / t grain. This maintainance rate should also be applied in the years following the corrective applications recommended in Fig. 2 to guard against reversal to deficient conditions.

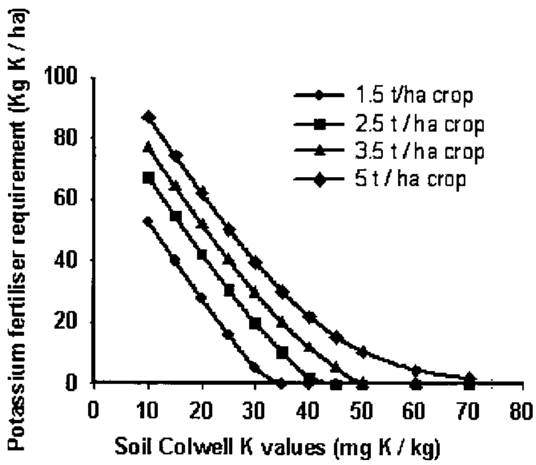


Fig. 2. Fertiliser recommendation for combinations of soil Colwell K and achievable yield values

Economic benefits of potassium fertiliser use

The anticipated wheat yield response (B) due to K application is needed in order to determine the economic benefits of K use. The maximum response measured in the Western Australian wheat experiments in a previous project could be expressed as equation 5, where A is the the achievable yield with optimum K fertiliser and K_o is the soil test value for Colwell K (Wong et al., 2001).

$$B = A[1-(0.95 - 2.60 \exp(-0.095 K_o))],\ r^2 = 0.77 \qquad (5)$$

A graphical form of equation 5 allows growers to estimate likely maximum yield benefits of K fertiliser (Fig. 3a). The economic benefit was calculated in figure 3b for combinations of fertiliser requirement (Fig. 2) and yield response scenarios (Fig 3a) by assuming a price of wheat of \$ 200 / t and a cost of K fertiliser of \$ 800 / t K. The grower can substitute the wheat and fertiliser costs with his own values and calculate his own farm benefits. The analysis shown in figure 3b predicts high benefits from applying K in high achievable yield areas (>2.5 t/ha) with low soil available K. Those situations are relatively uncommon since the high yielding areas are typically found on less sandy soils which inspite of long term K depletion since cropping still typically contain more than 25 mg Colwell K / kg soil.

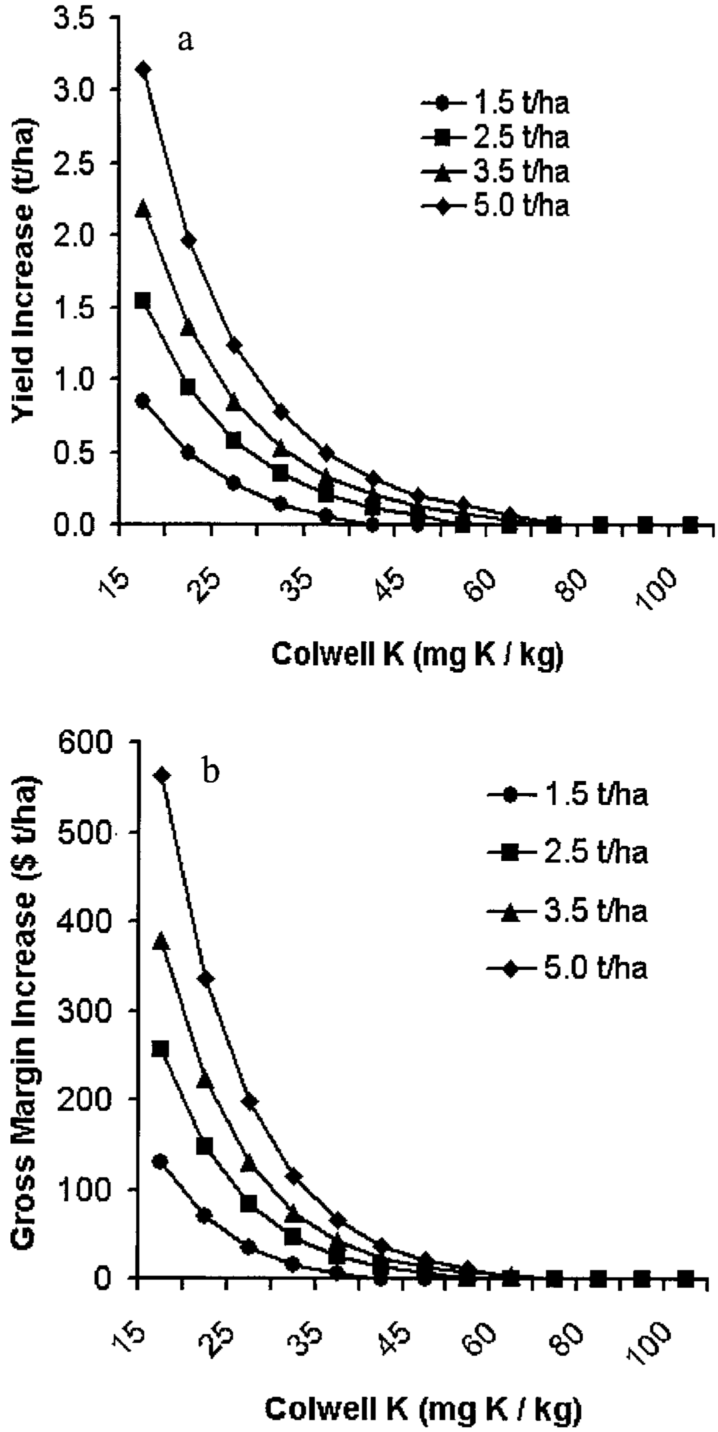


Fig. 3. Benefits of potassium fertiliser on wheat yield (a) and gross Margins increase (b) for combinations of soil test values and yield targets

The cost of determining the size of the crop to be fertilised (achievable yield) and of the soil test values should be substracted from the benefits shown in Fig 3a. The first entry point to site specific management is zone management. The economic analysis of zone management is problematic because the cost and benefits of each data layer cannot be ascertained accurately. The cost of yield maps can be estimated by assuming that the yield monitor depreciates completely within 5 years. Five years of historical yield maps will cost about $30,000 per farm or about $15/ha. The equivalent satellite imagery provided by commercial contractors in WA currently costs about \$800 per paddock or about \$8/ha. The corrobarating gamma ray emission data costs \$ 10,000 per farm or about \$5/ha. For a grower using yield and gamma maps for zoning, the zoning cost is about \$20/ha. This is a one off cost as the zones are driven by relatively permanent soil and landscape properties. This cost can also be offset if the yield and gamma data are also used for other purposes. Local calibration of the gamma data for soil available K with about 10 soil samples would add little (\$ 0.15/ha) to the cost of K recommendation.

Identifying zones with the Dempster Shafer weight of evidence model

The Dempster Shafer weight of evidence model allows the yield maps (or its surrogate NDVI) plus additional independent layers of evidence for the causes of yield variation to be processed to identify management zones. The independent layers of evidence may include gamma ray, soil conductivity maps (EM38) and digital terrain model of the farm (Fig. 4). The number of yield and NDVI maps increases yearly whereas the number of other layers of evidence remain conatant. The risk of increasing number of yield and NDVI maps diluting the other layers of evidence was removed by combining these maps by weighted linear combination (WLC) before use in the weight of evidence model. The user must then decide the probability of support (basic probability assignment) of each available layer of evidence for the zoning category. This is based on the user's judgement or known relationships between the layer of evidence and cropping suitability.

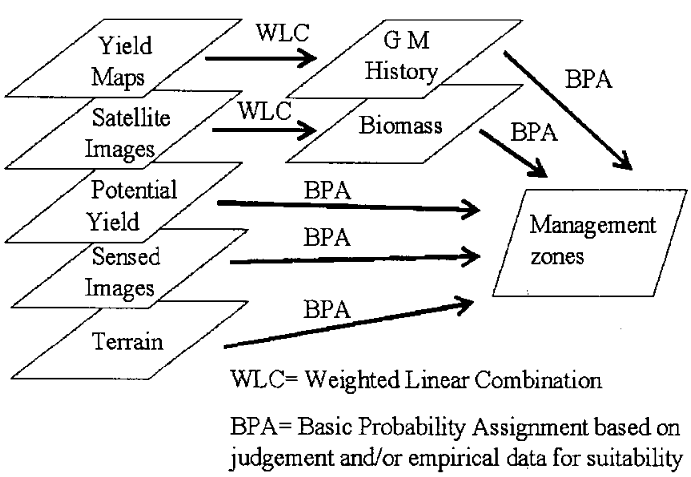
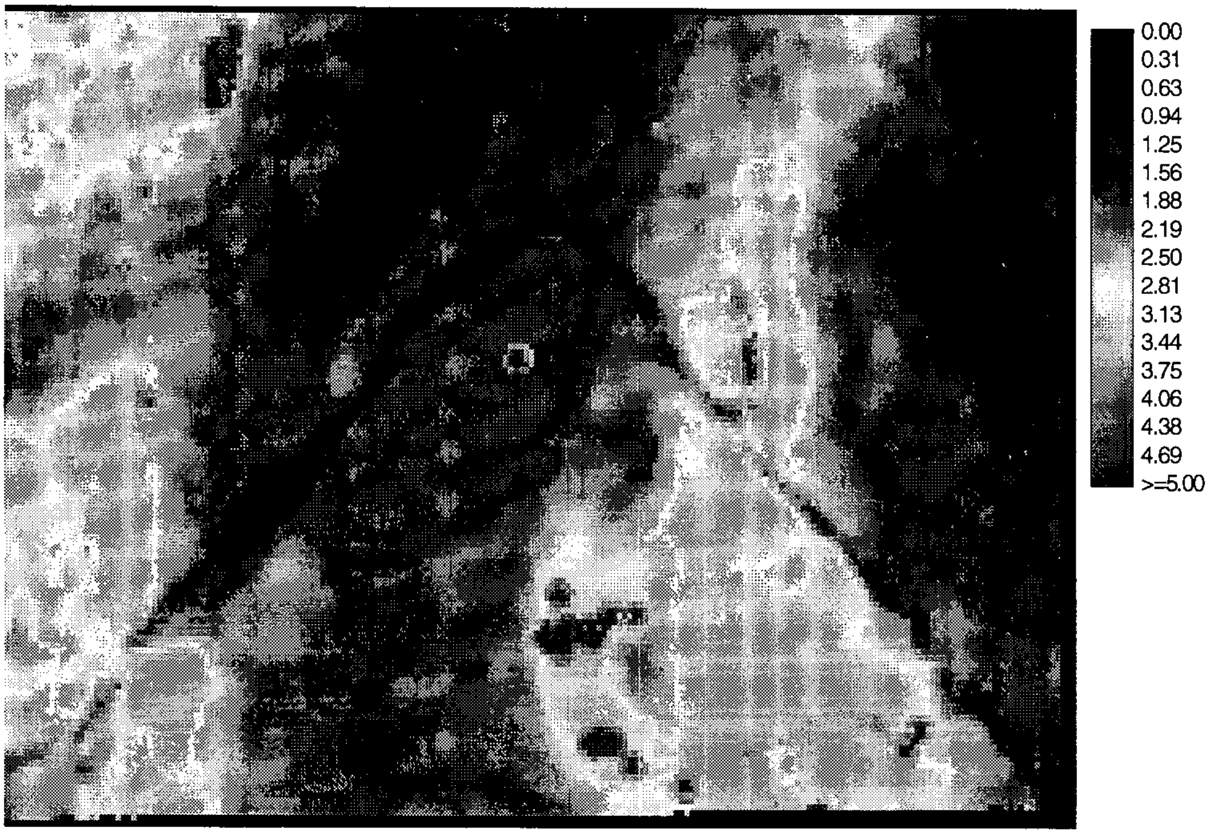


Fig. 4. Conceptual weight of evidence model

These zones simplified fertiliser recommendation by assuming relative spatial uniformity within the zones. The weight of evidence model can also help growers assess land use options based on past yield performances and inherent landscape properties.

ISSN 1448-0352
Bulletin 4584

Zone Management in Precision Agriculture by Matching Fertiliser Input to Crop Demand



Yield map of a paddock

JUNE 2003

Government of Western Australia
Department of Agriculture

GRDC
Grains Research & Development Corporation

CSIRO
AUSTRALIA

ZONE MANAGEMENT IN PRECISION AGRICULTURE BY MATCHING FERTILISER INPUT TO CROP DEMAND

Daya Patabendige (Department of Agriculture), Mike Wong (CSIRO)
and Bill Bowden (Department of Agriculture)

Introduction

Growers in Western Australia who have been yield mapping since the mid 1990s have come to realise that grain yield varies across different zones of their paddocks in any given year, as well as between years depending on the seasonal conditions and crop type. This within paddock variation can be as much as tenfold. Higher yielding areas can be due to better growing conditions (which increases the demand for nutrients) and/or better nutrient supply (which reduces the need for some fertiliser inputs). Hence, it is essential to determine the cause of the variation before optimum fertilising strategies can be developed.

When there is substantial yield variation between different zones within a paddock, farmers may be wasting their fertiliser dollars by applying uniform rates of fertiliser to the whole paddock. If farmers can divide their paddocks into different management zones based on the production potential and nutrient supply of the soil, they can increase their profits by tailoring fertiliser inputs to match the requirements of each management zone. Some farmers have variable rate application controllers (VRC) in their seeders, fertiliser spreaders and spray rigs which makes it easy to change fertiliser rates and types on the go according to an application map.

The aims of this brochure are:

- to provide guidelines to farmers on how to delineate management zones within a paddock,
- how to match fertiliser inputs according to crop demand and supply from the soil,
- how to carry out simple on-farm experimentation to fine tune fertiliser application rates and
- to provide an overview of the process of diagnosing the causes of yield variation.

The generic concepts used here have been developed during the GRDC project "Maximising the efficiency of potassium and nitrogen use and profits by matching supply to crop demand" (CSO205).

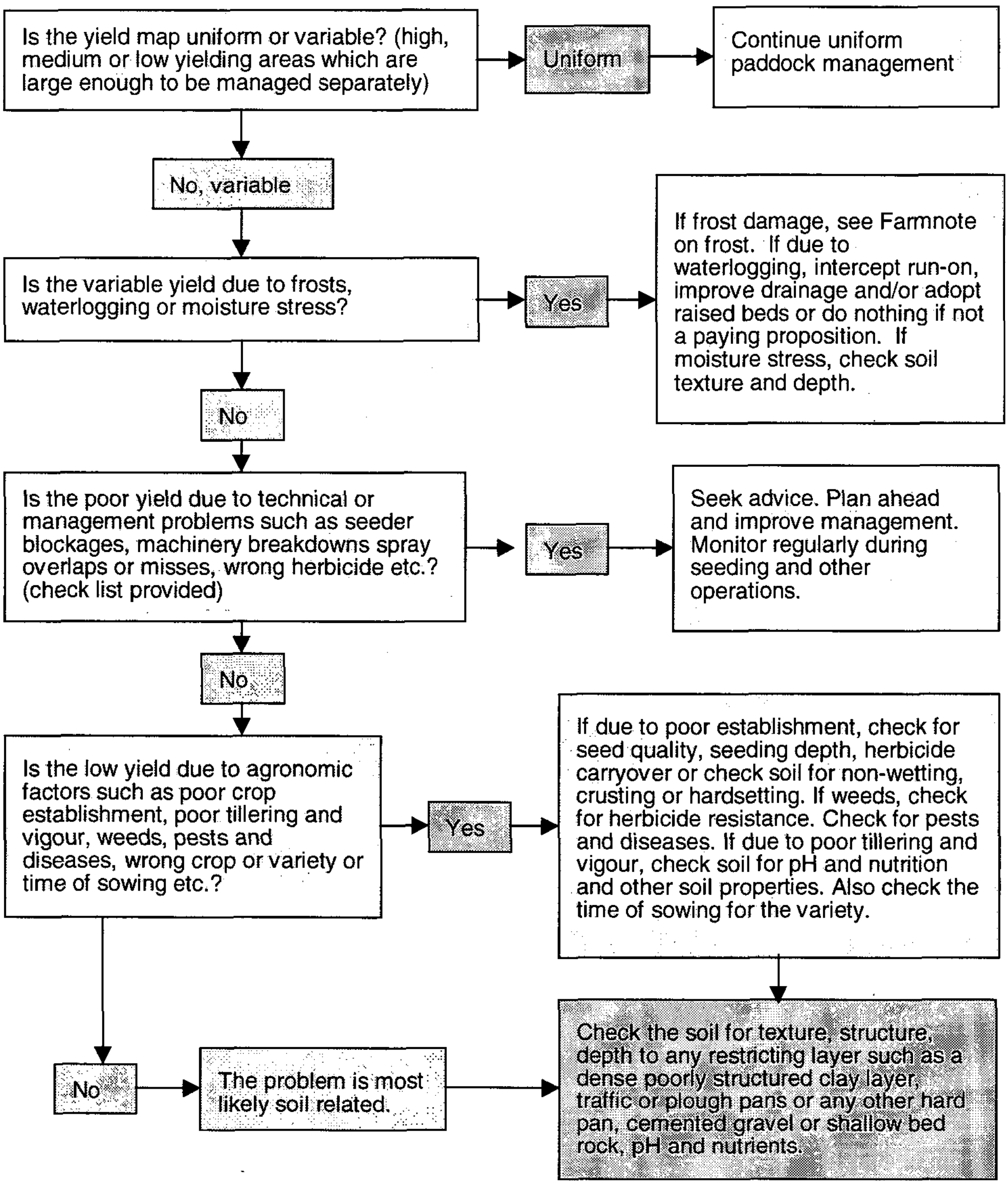
Diagnosing the causes of yield variation

There are numerous causes why certain parts of a paddock do not achieve the potential yield attainable from the seasonal rainfall. The causes of yield variation include: inherently variable water holding capacity of the soil, soil resistance to root growth, acidity, nutrient deficiency, pests and diseases interacting with management and agronomic factors. In addition, seasonal climatic conditions interact with soil and landscape features, which can result in variable frost damage or waterlogging or moisture stress. If management, agronomy and seasonal conditions are all good, then variable yields are usually due to variable soil properties.

A diagnostic key to identify the most likely causes for poor yields in one part of a paddock compared with another is being developed by the Western Australian Department of Agriculture, which will be available in the near future. An overview or a summary of the diagnostic process is given below.

It is important that growers monitor their crops and keep records throughout the growing season so that they can then identify the likely causes of poor yields. Satellite images are helpful in selecting monitoring sites.

An Overview of the Steps in Interpreting Yield Maps



Note: For soil problems, refer to 'Diagnosing and Ameliorating Problem Soils' by Daya Patabendige. Miscellaneous Publication 20/2003, Department of Agriculture, WA.

Figure 1. Overview of the diagnostic process.

Once the main causes of yield variation are identified, it is important to assess the need to rectify them, whether they are management problems, agronomic problems or soil problems. In most cases the soil problems are confined to parts of paddocks. Many soil problems can be corrected if they are within ripping depth. The cost of amelioration treatments can be kept to a reasonable level, as they will be applied only to problem areas and not the whole paddock.

Delineating paddock zones

In Western Australia there is usually more than one soil type in a paddock. Even within a soil type there can be variations in soil chemical and physical properties, which can affect the yield potential of the soil. Landforms, which affect the hydrology and consequently, the soil water status also have an effect on yield potential. All these factors have to be considered along with past yield maps when delineating management zones within a paddock.

Researchers (Mike Wong and others) at CSIRO Land & Water in Perth are developing a tool based on a 'weight of evidence' model to help growers demarcate management zones within a paddock. This process takes into account past yield maps, remotely sensed biomass maps, soil property maps measured by remotely sensed EM38 (soil conductivity) and gamma radiometry (soil texture) and soil chemical analysis. The yield data are weighted according to seasonal rainfall, with data from average rainfall years receiving more weight than below or above average rainfall years. Yields from different crops are converted to a common base by calculating gross margins. These independent spatial sources of information are used to delineate management zones.

Once management zones are identified, decisions can be made on land use and input management for each of the zones.

Soil limitations in poor yielding zones should be corrected if technically and economically feasible. Where the soil limitations cannot be corrected and the grower is consistently losing money by cropping that zone, then, he/she should consider culling that area from cropping and find an alternative land use for that zone. If it is not practicable to cull that area, inputs should be reduced to a bare minimum.

In zone management, inputs such as fertiliser and seed rate should match the yield potential of each zone. It may even be possible to vary the herbicide type and rates, where different weed species tend to be associated with different soil types.

Nutrient management within zones

The crop demand for nutrients depends on the crop, its variety, yield potential and grain quality. In rain-fed crops, the yield depends on the amount and the distribution of rainfall and the yield potential of the soil. The main soil properties which determine the yield potential are those which help the soil to retain plant available water and nutrients. These properties include texture (proportion of sand, silt and clay), structure (how the sand silt and clay particles are aggregated together to form structural units which relates to porosity) and structural stability. The crop rooting depth and the depth to any barrier to root growth or water movement are also critical factors.

Farmers can use their estimate of anticipated seasonal rainfall to determine the paddock average yield potential. Using their knowledge of the paddock and/or previous yield maps or satellite imagery for crop biomass, they can scale the yield potential up or down to set yield targets for each zone. Based on yield targets for each zone they can estimate the corresponding demand for each major nutrient (Figure 2).

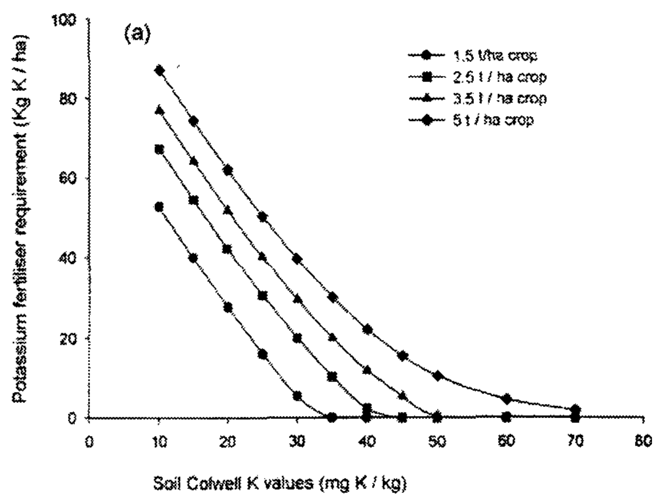


Figure 2. The effect of soil available potassium on K fertiliser requirement for different achievable wheat yields – an example only.

Soil sampling for nutrient analysis

The next step is to determine the amount of each nutrient that can be supplied by the soil. For this purpose it is important to take a sufficient number of soil samples to adequately represent the spatial distribution of the level of each nutrient in the paddock. The best option is to sample the management zones described previously. The number of samples from a zone depends on the size of the area and the amount of variability. When taking samples, log the GPS readings so that the same area can be sampled in subsequent years to monitor the trend in nutrient levels. Take about 10 or more cores to the depth specified by the analytical laboratory (usually 0-10 cm) around the GPS antenna within a radius of 5 m and bulk them. When sampling, take the usual precautions and take cores within and between previous plant rows.

The analytical results need to be interpreted and for some nutrients converted to plant available amounts during the growing season using local calibrations. For this purpose tools such as SYN, NPDECIDE (Diggle, Bowden and Burgess) and ABC of K. (Wong) are available.

On-farm experimentation

Farmers can carry out their own trials using precision agriculture equipment to fine tune their fertiliser rates or seed rates or a combination of both across their management zones. They could also experiment with different fertiliser types, ameliorants, deep ripping treatments, different varieties or any other treatment.

These on farm trials can be categorised into single factor experiments where only one factor such as different varieties or different rates of the same fertiliser is studied or two factor experiments where 2 factors are studied at the same time such as different seed rates and fertiliser rates. Experimenting with 3 or more factors is not recommended, as they are complicated and difficult to analyse.

Single factor experiments

Single factor experiments are the easiest to do and can be layed out in long strips for up and back seeding or as a doughnut for round and round seeding. The following are examples of the type of factors that can be studied in single factor experiments.

- Fertiliser rates – (e.g. 3 N rates or 3 K rates or 3 rates of a compound fertiliser)
- Varieties – different crop varieties
- Seed rates
- Ameliorants – (e.g. lime rates, dolomite, lime sand and burnt lime, gypsum rates)
- Deep ripping treatments

In all these trials it is important to keep all the other treatments and paddock operations the same except for the factor that is being tested. For example, if you are applying a herbicide to a variety trial, apply the same herbicide at the same rate on the same day throughout the trial area.

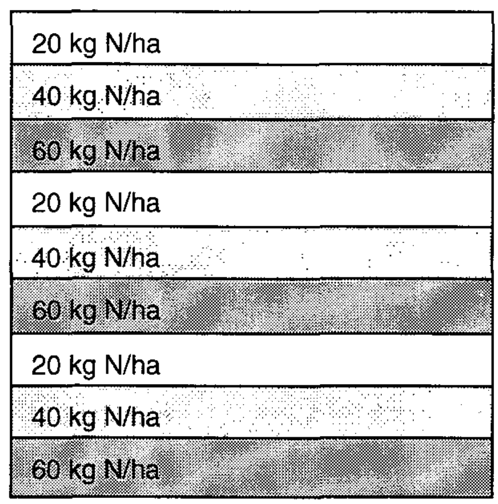


Figure 3a. An example of a Nitrogen rate trial in strips (may be randomised but not necessary if there are many replicates).

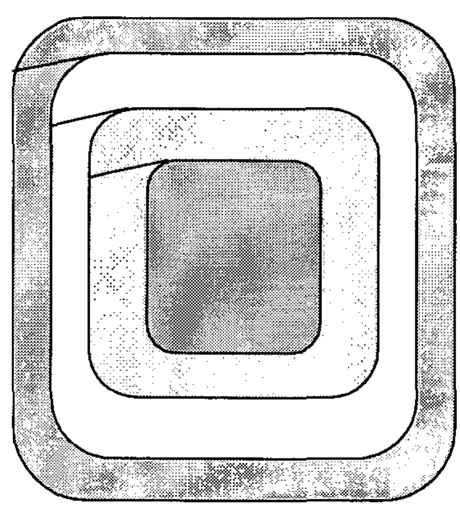


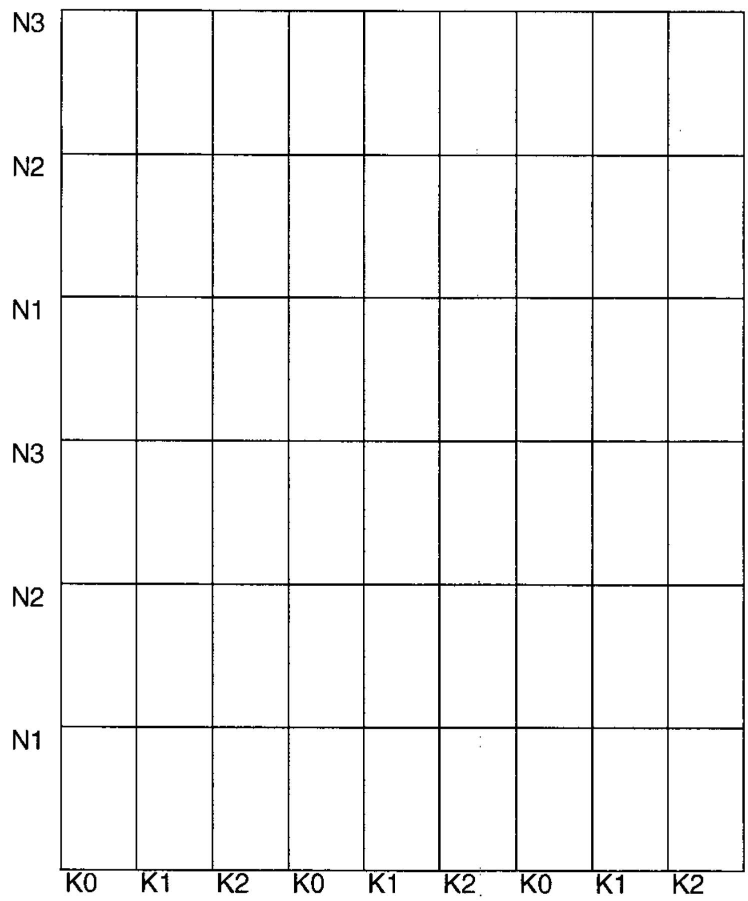
Figure 3b. Doughnut design with 3 treatments.

Two factor experiments

Two factor experiments are suitable for testing 2 variables and their interactions and can be layed out easily by growers. Some of the common treatments that can be tested are:

- Two fertilisers (e.g. 3 rates of K and 3 rates of N)
- Seed rates and fertiliser rates (e.g. 3 seed rates and 3 rates of N fertiliser)
- Varieties and fertiliser rates

The treatments can be layed out cross wise at right angles to each other across the whole paddock or part of the paddock.



Seeding, K application and harvesting to be done up and back the paddock. N application to be done across the K strips at right angles to the direction of seeding. The plots should be at least 50 m long in the direction of seeding and harvesting. The width of plots could be 2-4 seeder widths. It is good if multiple widths of the header match multiple widths of the seeder.

Figure 4. Example of a 2 factor experiment with 3 N rates and 3 K rates (replicated 6 times).

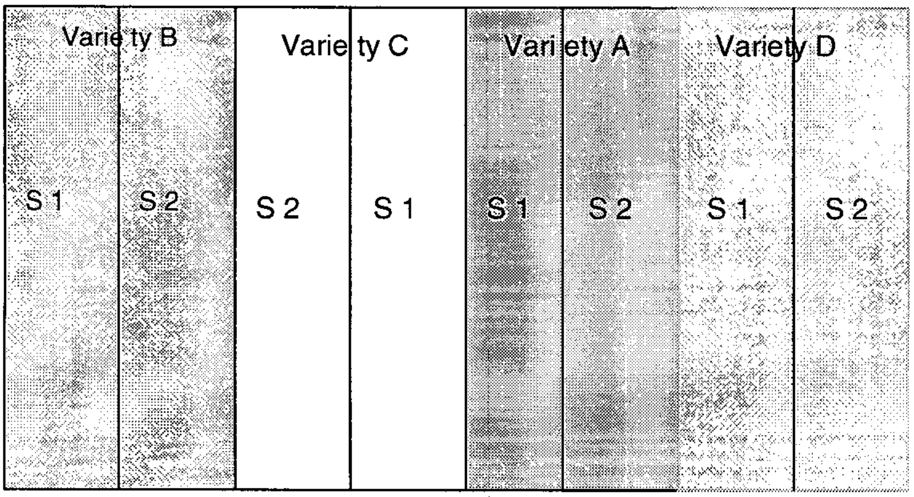


Figure 5. Example of a 2 factor experiment on a split plot design with 4 varieties as main treatments and 2 seed rates S1 and S2 as sub- treatments (need to be replicated).

It is important to repeat the trials to account for different seasonal conditions before conclusions are drawn.

Acknowledgments

We thank the GRDC for supporting this work as part of CSO 205, Dr Wal Anderson and Chris Gazey (DAWA) for their useful suggestions, Malcolm Howes (DAWA) for editing, and Judi Fisher (DAWA) for type setting this bulletin.

Further information

Growers may contact the following people for further information.

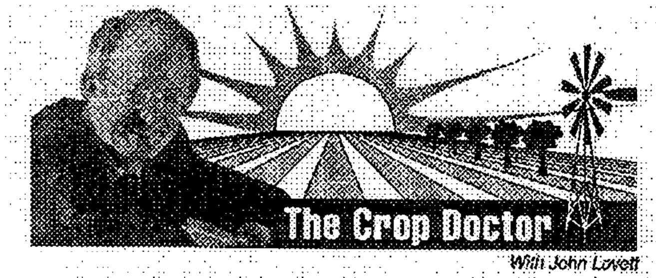
Precision Agriculture experimentation or matching fertiliser inputs to crop demand:
Mike Wong
CSIRO
PERTH
Telephone: (08) 9333 6000.

Diagnosing the causes for yield variation or Precision Agriculture experimentation:
Daya Patabendige
Department of Agriculture
Lot 12 York Road
NORTHAM
Telephone: (08) 9690 2000.

Fertiliser application decisions (SYN, NPDECIDE):
Bill Bowden
Department of Agriculture
Lot 12 York Road
NORTHAM
Telephone: (08) 9690 2000 and

Art Diggle
Department of Agriculture
SOUTH PERTH
Telephone: (08) 9368 3333

On-farm experimentation (Test as You Grow Kit):
Jeff Russell
Department of Agriculture
Lot 12 York Road
NORTHAM
Telephone: (08) 9690 2000.



ROBBING THE RICH TO FEED THE POOR 9.4.03

WA graingrowers spend approximately 13 per cent of farm income on fertilisers, but tend to apply them equally across individual paddocks despite substantial yield fluctuations between fence lines.

Yield and soil test values can vary by factors of 10 within paddocks, meaning the uniform application of fertilisers might not meet crop needs in some areas and could be wasted in others.

The Grains Research and Development Corporation (GRDC) recently supported CSIRO researcher, Mike Wong to investigate variable crop/soil interactions and how fertiliser needs waiver within paddocks.

His findings could help growers rationalise applications to improve business profitability by 'stealing fertiliser from rich soils to give to the poor'. Matching inputs with needs would also prevent nutrients from leaching into water courses where they could fuel algal blooms.

To understand the plant/soil interaction, research generated a map of soil characteristics across paddocks and compared these with actual and potential yields. Potential was determined by applying the 'French and Schultz' equation to the seasonal rainfall and then distributing the resultant average yield spatially across paddocks.

The yield for specific areas was manipulated around the paddock average in accordance with historical yield variations or, where such records were unavailable, by linking them to trends emerging from midseason satellite biomass imagery.

Soil characteristics were gathered by observing relationships between soil total carbon and soil total nitrogen identified in past GRDC supported research to determine plant available nitrogen (nitrate).

Potassium content was gauged by measuring gamma rays emitted from its radioactive isotope, K-40.

With support from growers and the Federal Government, through the GRDC, Dr Wong and his team developed software to identify discrepancies between potential and actual yields, which, when compared against soil potassium and available nitrogen content, generated fertiliser recommendation maps.

These maps can integrate with variable rate technologies (VRT) to apply fertilisers where they are most needed and moderate them where they are not. Crop responses under fertiliser regimes designed using this technique suggest the system is reliable.

Although expensive now, VRTs are developing rapidly and costs should ease as the technology is more commonly adopted.

The researchers found that zones with similar soil properties, yield potential and fertiliser requirements can be identified within the paddock. Growers without access to VRT can identify these zones with the help of yield maps, satellite imagery and other spatial data to apply fertiliser more accurately.

The Crop Doctor is GRDC Managing Director, Professor John Lovett, Tel 02 6272 5525
www.grdc.com.au
Further Information: Dr Mike Wong, Tel 08 9333 6299
GRDC REF: CSO 205/cdapr031

New farm mapping tool lifts crop profitability

CSIRO Land and Water scientist Mike Wong explains how detailed yield mapping and landscape information can help farmers increase cropping profitability and reduce the risk of environmental problems such as salinity.

New precision farming technology is being developed which will enable grain growers to make sound management decisions about the suitability of land for cropping.

CSIRO Land and Water scientists are using a method known as 'weight of evidence modelling' to determine if it is economical to improve poor-performing areas of land or reassign the land to an alternative use such as perennial vegetation.

The model uses all available evidence to determine cropping suitability including historical yield maps, crop response to nutrient treatments and information gathered from a range of sources such as the individual farmer, entomologists and weed experts.

Paddock productivity in Western Australia's wheatbelt is highly variable and grain yields within any paddock can vary by more than two tonnes per hectare from the lowest to the highest yield.

Preliminary economic analysis suggests parts of a paddock could be consistently operating at a loss, lowering the paddock's overall financial performance.

This variability exists in farming systems characterised by inadequate water use responsible for rising saline ground water.

To increase water use, more than 30 per cent of WA's wheatbelt may need to be reassigned to an alternative land use to reduce the risk of salinity.

The scale of this land use change is significant and must be based on sound decision-making. It also needs to be economically viable for farmers.

CSIRO work aims to develop technology which can allow the identification of areas for land use change, based on land suitability evidence combined with the most advanced tools available in precision farming.

Beth Field

CSIRO researchers are developing new precision farming technology which will enable farmers to make accurate decisions on the most suitable land for cropping.

Yield mapping

Yield mapping provides an information rich environment where the performance of every 25 metre square pixel of the paddock can be assessed.

But it is impossible to explain all the details of yield maps and make management decisions based on this information as within paddock yield variation is dependent on up to 250,000 variables.

Land use decisions must be more soundly based so areas of truly poor potential can be separated from areas which can be economically improved.

Paddock trial

To test the accuracy of the weight of evidence model, CSIRO Land and Water carried out a paddock trial near Three Springs, WA.

The 70-hectare paddock was sown with wheat during 1998, lupins in 1999 and wheat during 2000. The year 2000 was the driest year and 1998 received almost the long-term seasonal average rainfall. The paddock was also treated to test crop responses to urea and potash.

The yield was measured each year using an AgLeader yield monitor. The data was then processed and yield maps made. Soil samples were also carried out.

The evidence used to assess cropping suitability included gross margin maps from 1998–2000, maps of crop response to fertiliser treatment (potassium and urea), soil properties such as soil organic matter content, potassium content, soil type and crop biomass.

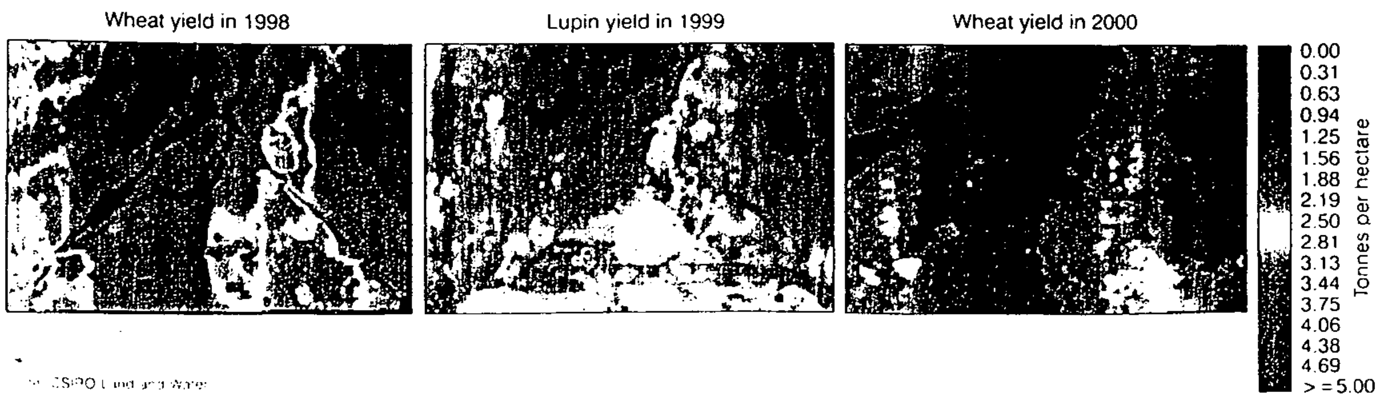
Previous research showed high potassium levels and soil organic matter increased cropping suitability while some soil types, for example deep grey sands, were inherently unproductive.

Mapping results

The results showed the yields varied across the paddock and from year to year according to seasonal conditions, type of crop grown and the match between land capability and use. But despite these changes, the results highlighted areas where consistently better grain yield performance was evident every year (see Figure 1).

The gross margin maps indicated the poor performing parts of the paddocks were consistently operating at a loss of $10 per hectare up to $100/ha each year irrespective of the crop grown. Poor performing areas varied from year to year according to

FIGURE 1 The grain yield (tonnes per hectare) at Three Springs, Western Australia, 1998–2000



CSIRO Land and Water

the season. During the dry year of 2000 a large area of the paddock was operating at a loss. Although soil types and topographic locations are fixed on the maps, the in-paddock pattern of yield variability changes every year. This makes it difficult to establish a clear boundary between high and low performing areas. But this problem can be overcome by converting yield maps into maps known as fuzzy sets where boundaries for poor and better performing areas gradually merge into one another.

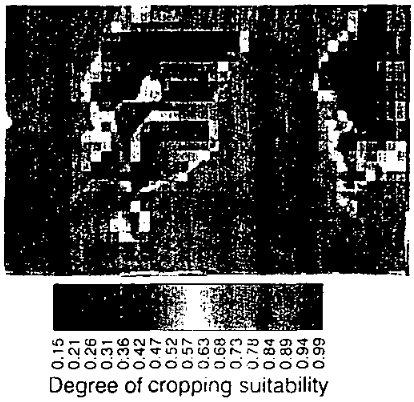
From this the evidence-based land use model is then able to determine the degree to which the area is suitable for cropping. The model calculates the degree of suitability from a scale of zero for not suitable to 1.0 for highly suitable.

Cropping suitability

By combining historical yield, gross margin maps, potassium availability, soil carbon, crop biomass and soil type, researchers are able to model where the best and most profitable cropping responses will be.

The weight of evidence model then overlays each factor to produce a map showing cropping suitability (see Figure 2). In this example the map shows a central area and an area to the north-east which have low cropping suitability. This is due to a combination of factors including poor soil type (pale deep sand), poor soil moisture retention and poor response to fertiliser inputs. These areas are suitable for reassigned land use (such as planting trees) unless alternative treatments which are economically viable (apart from the use of urea and potassium) can be identified. These results and recommendations are specific for the trial paddock. But the model can be applied to any farm in any location.

FIGURE 2 Cropping suitability



Source: CSIRO Land and Water

Ongoing research

Weight of evidence models are a powerful tool for determining whether to take areas out of production which are unprofitable (even during good years). They help minimise the decision risk.

The trial work is being extended to other paddocks where the evidence is more difficult as the lowest yielding areas were recorded where above average yields were expected. Work is also under way to include leakiness (water run-off) as another variable.

The technology will be available to farmers during the next 2–3 years

Acknowledgements: The work was funded by the Grains Research and Development Corporation.

For more information contact Mike Wong, CSIRO Land and Water, by email on mike.wong@csiro.au, phone (08) 9333 6299 or fax (08) 9387 8211.

Yield mapping enhances paddock management

Farm information

Farmers
Rex, Sue and Jim Heal

Location
Three Springs, WA

Property size
4000ha

Enterprise
Merino sheep, wheat, barley, lupins

Annual rainfall
494mm

Precision farming technology has provided Western Australian grain growers Rex, Sue and Jim Heal with detailed information to help them better understand in-paddock yield variations.

The Heal family operates a 4000-hectare property at Three Springs, cropping 2000ha of wheat, barley and lupins with 7000 Merino sheep.

They have been yield mapping since 1997, when they installed a Case AFS yield monitor on their new harvester.

According to Jim, on-farm application of the technology has given them an improved understanding of the land's capability and identified poor performing soil types enabling better management of these areas.

By using this information to provide an insight into what is happening in each paddock, they hope to increase crop yields and reduce inputs.

Yield variation

Initially Jim was surprised at the extent of yield variation within paddocks. On average, the better performing soils yielded much more than the poor performing soils. Within paddocks, yields have varied from 0.5 tonnes per hectare to more than 4t/ha.

Based on these results the Heal family has planted about 30,000 oil Mallee trees in areas with a history of poor crop yields, for example, white sandy soils which comprise about 10 per cent of the paddock. They plan to plant up to 20,000 more oil Mallee trees during 2002.

Jim said it was not economically viable to improve the soil and the trees will provide shade and shelter for livestock and a possible source of income in the future.

They are also mapping the problem weeds on their farm, including couch grass, annual ryegrass, wild radish and doublegee.

Jim believes this will aid in their herbicide management and increase their knowledge of weed population dynamics.

On-farm trials

Since 2000, the Heal family has been involved in research with CSIRO Land and Water looking at the effect on crop yield of variable potassium rates and residual soil levels.

The results showed there was a direct relationship between areas where potassium levels were low and poor crop yields. This has encouraged the Heal family to increase its annual potassium applications from 30 kilograms per hectare up to 60kg/ha.

The family is also considering applying a high rate of 100kg/ha to obtain any residual fertiliser benefits.

In the future, Jim hopes to apply variable fertiliser rates within a paddock but will wait until they have 10 years of yield mapping data available.

Evidence-based paddock maps

More recently the family has trialled the 'weight of evidence' model being developed by CSIRO.

Jim said the preliminary results demonstrated the accuracy of the model and confirmed previous yield mapping results. He said the map generated by the model showed the poor performing areas had low suitability for cropping and an alternative management option such as planting trees, was the correct decision.

Jim is confident the new technology, when combined with yield maps, has significant potential as it provides a more detailed and accurate paddock picture.

Model for land use decisions based on analysis of yield and soil property maps and remote sensing

M.T.F. Wong, G. Lyle
CSIRO Land and Water, Floreat, Western Australia, WA 6014, Australia
Email: ***mike.wong@csiro.au***

Abstract

About 50% of the Western Australia wheatbelt must be reassigned to perennial land use in order to increase water use and arrest salinity. We used the Weight-of-Evidence model to identify areas for perennial vegetation. The independent layers of evidence included gross margins, drainage values, soil properties, remotely sensed biomass and proximally sensed gamma-ray emission and soil electrical conductivity. Our case study at Three Springs showed that significant areas consistently operate at a loss due to zones of infertile, sandy leaky soils. These areas show up clearly in gamma ray and electrical conductivity maps. They are the most readily acceptable by growers for reassigning land use.

Keywords: Dempster-Shafer, fuzzy sets, Weight-of-Evidence model, land-suitability, maps

Introduction

The recent history of yield mapping in Western Australia since 1996 reveals that wheat yield typically varies spatially between 0.4 to 4.0 t/ha within fields of about 100 ha. Some areas within the fields were consistently operating at a loss over the period of study. This variability occurs in a farming system characterised by the replacement of perennial native vegetation with annual winter crops. Inadequate water use by annual crops compared with the native vegetation is responsible for rising saline ground water table. Water balance modelling suggests that about 50% of the wheatbelt must be reassigned to an alternative perennial land use in order to have a useful impact on water use and salinity (Pracillo et al., 2003). The scale of this land use change is massive and is faced with apprehension from farmers fearful of possible loss of income and with uncertainty about where to start. Our aim is to work with farmers, state agencies and other stakeholders to access vast amounts of spatial information and to develop a sound and transparent decision-making process for land use change that is economically and environmentally beneficial and socially acceptable. It is anticipated that the decision support system will allow farmers to determine land suitability for cropping and for alternative perennial vegetation and to determine where to start the land use change to maximise these triple bottom lines.

Materials and Methods

The case study was carried out with farmer Rex Heal on his 2000 ha property at Three Springs, Western Australia. The long-term seasonal (April to November) rain on his farm is 400mm. The field (H10) chosen for this work is about 70 ha and had a wheat-lupin-wheat rotation since 1998 when yield monitoring commenced. The year 2000 was the driest year (162 mm) and 1998 received near to the long-term seasonal average rainfall for the region. Spatially variable yield was measured on each occasion with a calibrated AgLeader yield monitor and was pre-processed to remove spikes and converted to yield maps. Soil was sampled in the field, analysed and maps of potassium, organic carbon content and nitrate release were made using ArcView. A remotely sensed Normalized Difference Vegetation

Index (NDVI) image for mid-August 2000 and a soil-type classification map were also available for the paddock. Proximal sensing was used to map soil electrical conductivity and gamma-emission from ^{40}K. The soil type map was used to estimate deep drainage based on a pedotransfer function developed using the DSSAT model (Zhang and Wong, 2003).

We used the Dempster-Shafer Weight-of-Evidence model to determine land suitability for cropping and perennial vegetation based on independent lines of spatial evidence (Caselton and Luo, 1992). The Weight-of-Evidence model is a further development of the Bayesian probability theory. It allows the use of all the evidence that we have to test the hypothesis of land suitability for cropping or perennial vegetation. It allows for ignorance in the decision making process and enables the use of expert knowledge where formal quantitative relationships between cause and effect are not fully understood. Sound decision can be made based on best available knowledge when we cannot afford to wait until we have a complete understanding of causal factors inducing within paddock variability. The spatial layers of evidence used to assess suitability for cropping included:

1. Financial performance measured by gross margin analysis for 1998 to 2000.
2. Environmental performance based on estimates of deep drainage and salinity risk.
3. Crop biomass measured by NDVI.
4. Soil exchangeable potassium as a measure of clay content and hence better water holding properties, crop growth and inherent fertility in WA.
5. Gamma ray emission from potassium: a cheaper remote or proximal sensing technique for measuring soil potassium.
6. Soil organic matter content: Another indicator of soil fertility.
7. Soil type maps: Some soil types for example, deep grey sands are inherently unproductive.
8. Soil electrical conductivity maps measured remotely by EM 38. This is correlated with crop performance.

As the spatial pattern of yield variability varies from year to year and as there is no sharp distinction between suitable and unsuitable cropping areas based on soil property maps and other spatial data, the evidence layers were transformed to fuzzy sets. These fuzzy sets include expert knowledge and hard data evidence to define the degree to which areas are suitable for cropping or perennial vegetation. Although the concept of fuzzy sets is somewhat new in GIS, it is increasingly clear that such sets are prevalent in land allocation decisions. Working with the farmer and with inputs from colleagues, we decided for each line of evidence where our understanding lies about the relationship between each of the lines of evidence and the hypothesis for cropping or perennial vegetation. The Dempster-Shafer model overlays each of the basic probability assignments to produce the map of degree of suitability for cropping

Results and Discussion

Yield varied spatially and from year to year according to seasonal conditions, crop grown and the match between the land capability and its use. In spite of these changes, consistently low and high yielding areas occurred in the field (Figure 1). Gross margin maps derived from yield data showed that the poor performing parts of the field were consistently operating at a loss each year irrespective of the crop grown. This suggests that the farmer would benefit financially if these poor performing areas were not cropped.

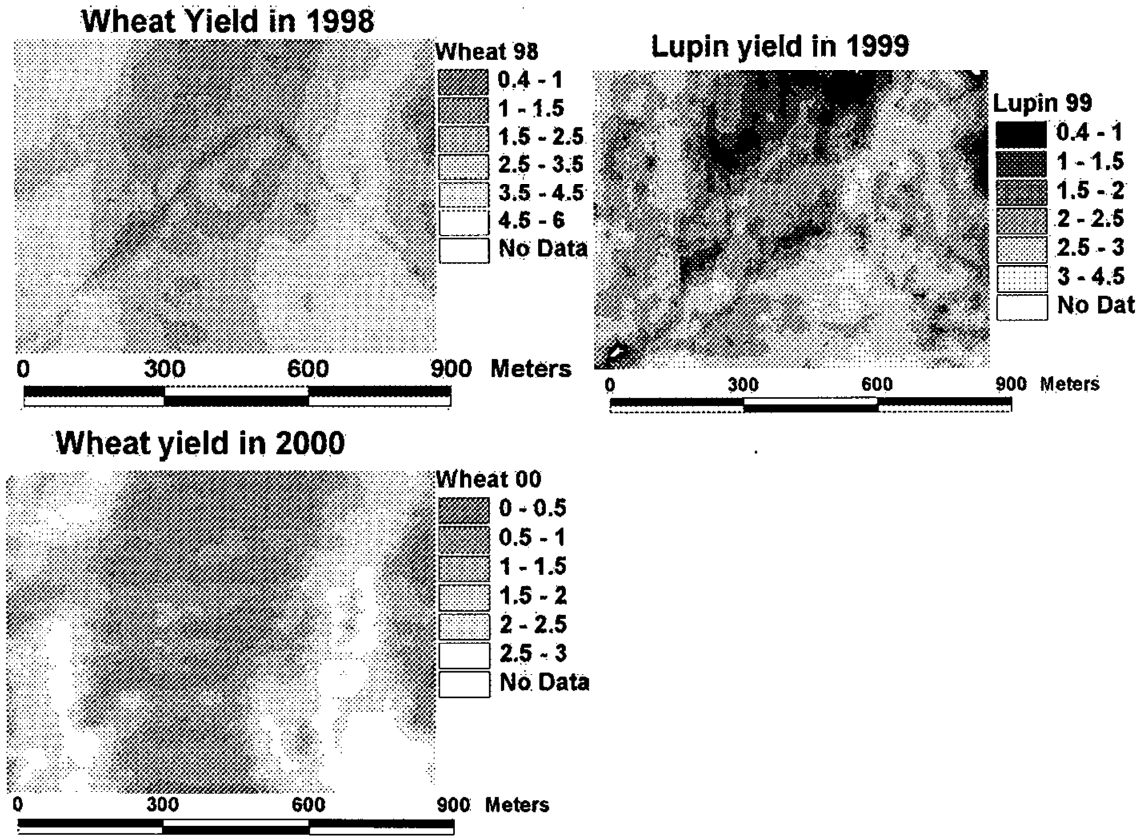


Figure 1. Grain yield (t/ha) at Rex Heal's field H10 to show consistency and temporal variability in yield in 1998-2000. Dark areas were the poorest performing.

Management zone suitable for cropping based on yield and gross margins alone is shown in Figure 2 by targeting a third of the land for perennial vegetation. This figure was trimmed to remove areas less than 2 ha, which are impractical to manage individually.

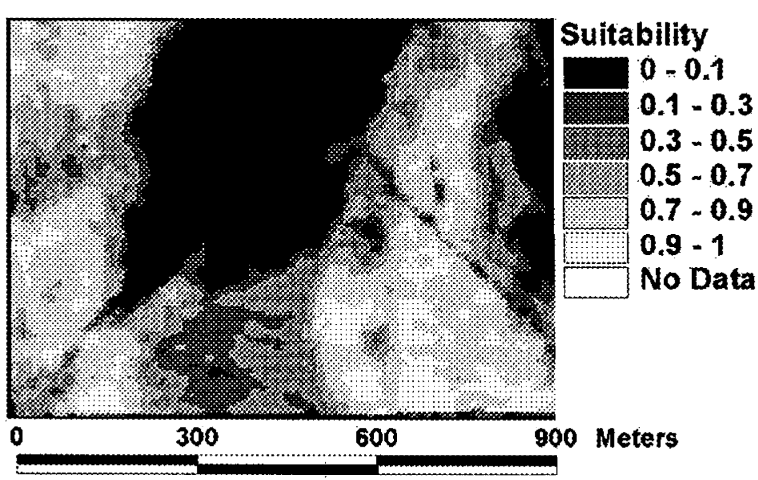


Figure 2: Management zones derived from gross margins for 1998-2000. Dark areas have a greater degree of unsuitability for cropping ranked between 0 (unsuitable) and 1 (suitable for cropping).

The question often asked is "can the poor areas be improved cost-effectively for cropping?" By considering additional independent lines of evidence derived from different sources, we can decrease the risk faced by the decision maker. Some of the poor performing areas may simply be suffering from a simple chemical limitation such as local soil acidification or nutrient deficiency that can easily be ameliorated by cost effective treatments. Other zones such as areas of infertile deep grey sands would be uneconomic to improve. Such areas would be best reassigned to alternative use in perennial vegetation. Figure 3 shows the map of suitability for cropping based on the layers of evidence already listed above.

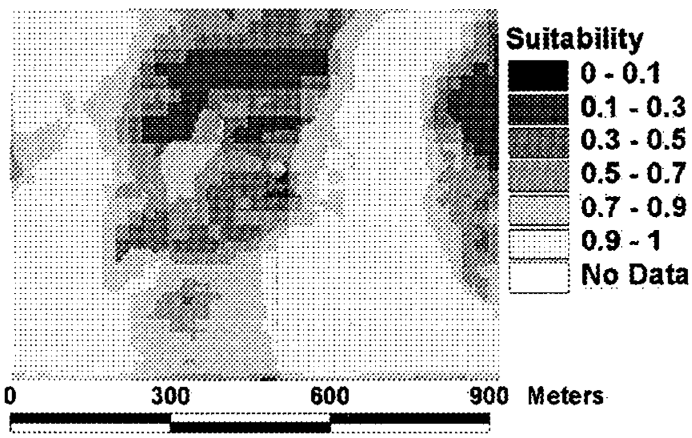


Figure 3. Land use zones based on weight of evidence for suitability for cropping. Areas more suitable for cropping have ranks closer to 1.

The map of land suitability for cropping based on these lines of evidence is similar to that derived from yield maps alone (Figure 2). This suggests that the low yielding areas were fundamentally infertile and that it would not be practical to ameliorate these areas in a cost effective manner. The areas identified as being of low suitability for cropping also had the highest drainage values and therefore posed the greatest salinity threat to the environment. The spatial patterns of the land suitability map were similar to maps of proximally sensed gamma radiometry from ^{40}K and soil electrical conductivity, which offer an inexpensive way of mapping the poor performing areas (Figure 4).

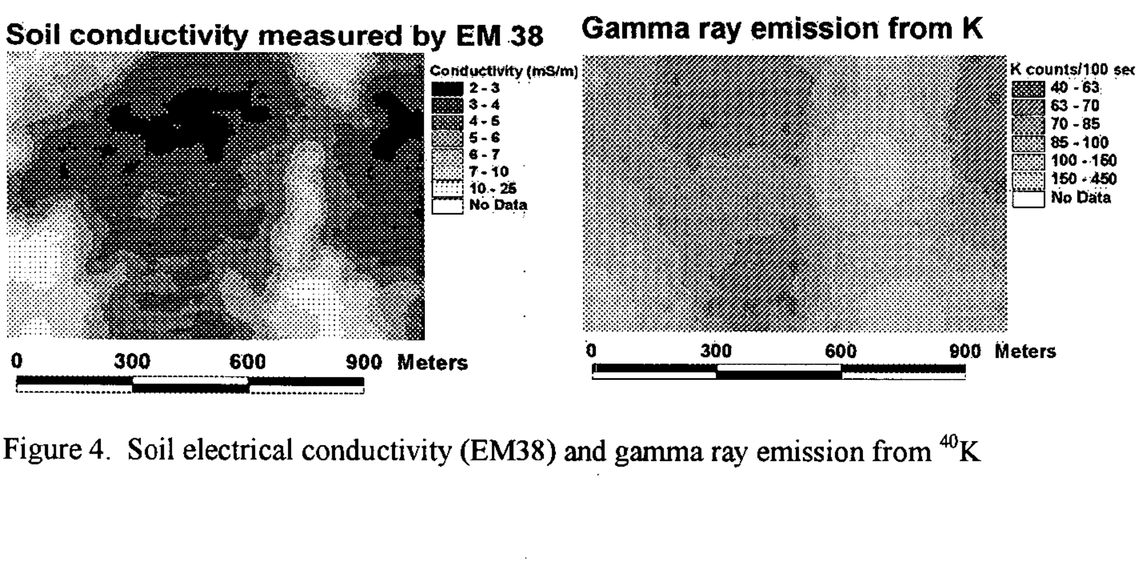


Figure 4. Soil electrical conductivity (EM38) and gamma ray emission from ^{40}K

Conclusion

The weight of evidence suggests that land use change could be achieved with beneficial effect on both profits and the environment because the low yielding areas were also the most leaky due to occurrences of low fertility coarse sandy soils that drained water readily. Those findings should lessen the apprehension of farmers to adopt land use change more readily. The poor areas can be identified by gamma-radiometry due to lack of emission of ^{40}K from clay minerals and by mapping soil electrical conductivity using EM_{38}. Further work is required in this case study to implement the suggested land use change and to measure impact on profits, deep drainage and the environment.

In this case study, the different lines of evidence for good and poor performing areas were coherent and the potential cropping zones are identified with little ambiguity. A companion paper, reports work on another farm where the balance of evidence is more complex since some of the lowest yield were recorded where good to high yields were expected based on independent evidence.

References

Caselton, W. F and Luo, W. 1992. Decision making with imprecise probabilities: Dempster-Shafer theory and application. Water Resources Research, **28** 3071-3083

Pracilio G., Asseng S., Cook S.E., Hodgson G., Wong M.T.F., Adams M.L. and Hatton T.J. 2003. Estimating spatially variable deep drainage across a central eastern wheatbelt catchment, Western Australia. Australian Journal of Agricultural Research, In press.

Zhang, H. and Wong M. T. F. 2003. Farm-scale nutrient balance for typical wheatbelt farms in Western Australia. Agriculture Ecosystems and Environment, In press.

Acknowledgement

We are grateful to the GRDC for co-funding this work as part of project CSO 205 and Mike Wong's participation at the 4th ECPA. We thank Rex Heal for his assistance on on-farm experiments and for discussing this work.

Precision agriculture solutions to underpin profitable land use change for a better environment: A case study in Western Australia

Mike T F Wong, Greg Lyle and Kathy Wittwer

CSIRO Land and Water, Private Bag 5, Wembley, WA 6913

Abstract

Within Western Australia, yield mapping reveals that wheat yield varies spatially between 0.4 to 4.0 t/ha within the paddock and by applying economic analysis we have shown that some parts of the paddock are consistently operating at a loss. This variability occurs in a farming system characterised by inadequate water use that is responsible for rising saline ground water table. Water balance modelling suggests that about 50% of the wheatbelt must be reassigned to an alternative perennial land use in order to have a useful impact on salinity. The scale of this land use change is massive and needs to be based on a sound decision-making process. The Dempster-Shafer Weight-of-Evidence model offers a rigorous methodology for assigning land use based on independent lines of evidence. We used this model in a case study at Three Springs to identify areas suitable for cropping and those that should be reassigned to perennial vegetation. The model used maps of historical gross margins, soil property, drainage values, soil type, remotely sensed biomass and proximally sensed gamma-ray emission as evidence. These maps were then converted to fuzzy sets to include varying degrees of expert judgement and hard data evidence to define which areas are suitable for cropping. Although the concept of fuzzy sets and Dempster Schafer modelling is somewhat new in agriculture, it is increasingly clear that building more intelligent modelling systems is a prerequisite for land allocation decisions. The expert in conjunction with the farmer and/or agronomist decides for each line of evidence where our understanding lies about the relationship between the evidence and the hypothesis. Additional lines of evidence can be added to include other discipline leaders such as entomologists, pathologists, weed scientists etc. By focusing on profits and environmental outcomes, the model has the potential to facilitate the adoption of land use change based on the combined contributions of the grower and discipline leaders.

Key words
Yield variability, Dempster-Shafer, weight of evidence model, fuzzy sets, land use, precision agriculture

Introduction

The productivity of grains / sheep farming in the Mediterranean region of Southern Australia is limited by insufficient rainfall. Paradoxically, the sustainability of this farming system is undermined by insufficient water use leading to raising saline ground water table and the onset of secondary salinity. The reason for this paradox is that the land is occupied for cropping for only half of the year. It remains bare for the rest of the year when water use falls short of that used by native vegetation. A third of the agricultural landscape of Western Australia is at risk and options to solve this problem include engineering and plant-based solutions. Model estimates suggest that up to half of the landscape need to be revegetated to perennial plants in order to decrease deep drainage to values comparable with those of native vegetation (Pracillo et al., 2002). This scale of land use change is massive and is unlikely to be adopted unless it is profitable to the farmer. The first question asked is where do we start revegetating the landscape. The answer to this question must include the farmer and be based on a transparent decision process that uses the best lines of evidence on productivity and environmental performance. Both these factors are highly variable spatially. Grain yield ranging from 0.4 to 4.0 t/ha is commonly measured at paddock scale resulting in some areas of the paddock operating at a loss. At the same scale, deep drainage ranges from 12 to 25 mm due to spatial variability in soil type, water holding capacities and depth of root penetration (Pracillo et al., 2002). This spatial variability offers the opportunity to identify the worst performing areas for re-assignment of land use that is economically and environmentally beneficial. Our aim is to develop a decision process for land use change based on our intimate understanding on the financial performance of the paddock derived from several years of yield mapping and analysis of land suitability for cropping based on different layers of evidence.

The experimental site

The experiment was performed on paddock H10 on Rex Heal's property in Three Springs, WA. The paddock is about 70 ha and had a wheat-lupin-wheat rotation since 1998. The year 2000 was the driest year and 1998 received near to the long-term seasonal average rainfall for the region. Paddock yield was measured on each occasion with an AgLeader yield monitor and was pre-processed and extrapolated to yield maps using the Achiever software. Soil was sampled on the paddock, analysed and maps of potassium, organic carbon content and nitrate release were made using Inverse Distance Weighting interpolation in ArcView. In addition a Normalized Difference Vegetation Index (NDVI) image for mid-August 2000 and a soil map were also available for the paddock. The soil type map was used to estimate deep drainage based on a pedotransfer function developed using the DSSAT model (Zhang and Wong 2002). Proximal sensing was used to map gamma-emission from ^{40}K.

Weighted Linear Combination of Yield and Gross Margin Evidence

Yield varied spatially and from year to year according to seasonal conditions, type of crop grown and the match between the land capability and its use. In spite of these changes, common themes occurred on the yield and gross margins maps (Fig. 1). The dependence of yield on available water reflects the underlying relationship between water availability and soil types and topographic location in the landscape. Although soil types and topographic locations are fixed, the spatial pattern of yield variability changes every year. This introduces a spatial ambiguity regarding the boundary between the good and poor performing areas. The conversion of the yield maps into fuzzy sets allows us to overcome this ambiguity (Zadeh, 1965). A monotonically increasing sigmoid membership function was used to derive fuzzy sets from the gross margins evidence. The results is not whether an area is suitable or not for reassignment of land use since such areas are changing all the time, but the degree to which the area is suitable. The fuzzy gross margin maps show that the poor performing parts of the paddocks were consistently operating at a loss each year irrespective of the crop grown.

Fig. 1: Allocation of gross margin maps to fuzzy sets of degree of suitability for cropping. Dark areas are less suitable and green areas most suitable. The maps are for 1998 (left) to 2000.

The fuzzy sets for 1998 to 2000 were overlayed in IDRISI using the Weighted Linear Combination technique. The weights were derived by pair wise comparisons of the fuzzy sets ranked according to how close the seasonal rainfall was to the long-term average. The Eigenvector derived from the comparison table provides the weights to be used for each fuzzy set (Saaty, 1977). Figure 2 shows the Weighted Linear Combination of the three fuzzy sets obtained by specifying that we want to remove a third of the land from production. This figure was trimmed to remove areas less than 2 ha since it would be impractical to manage such areas individually.

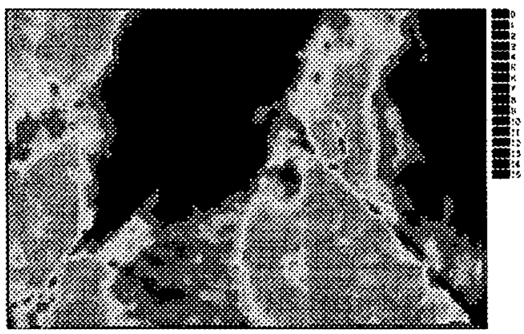


Fig. 2: Management zones derived from Weighted Linear Combination of fuzzy sets of gross margins for 1998-00 for an average risk strategy. The dark areas have a greater degree of unsuitability for cropping.

Multi-Criteria Evaluation using Dempster-Shafer Weight-of-Evidence method

Past yield performance is not a full indicator of future performance. Considering additional evidence layers would decrease the risk faced by the decision maker. Some of the poor performing areas may simply be suffering from a simple chemical limitation such as local soil acidity or nutrient deficiency that can easily be ameliorated cost effectively. Other zones such as areas of deep poor water holding sands would be uneconomic to improve. Such areas would be best reassigned to alternative use. The lines of evidence used to assess suitability for cropping were:

1. Fuzzy sets derived from the gross margin maps for 1998 to 2000.
2. Fuzzy sets derived from soil potassium map: In the strongly weathered soils of WA, the majority of topsoil potassium is in the exchangeable form. The amount of potassium increases with the clay content, which in turn gives rise to better water holding characteristics.
3. Fuzzy sets derived from soil organic matter content: It is assumed that soil organic matter content is a controlling variable for soil fertility. Increased organic matter content increases suitability for cropping.
4. Fuzzy sets derived from NDVI maps: It is assumed that higher biomass content is related to more suitable cropping sites since crops operate within a narrow harvest index range under normal seasonal conditions.
5. Fuzzy sets derived from soil type maps: Some soil types for example, deep grey sands are inherently unproductive.
6. Fuzzy sets derived from deep drainage maps: Highly leaky areas are deemed less suitable for current use.

7. Fuzzy sets derived from gamma-emission from K-40. This map is similar to that of topsoil potassium but is cheaper.

The expert with input from the farmer and/or agronomist must decide where the understanding lies about the relationship between the evidence and the hypothesis for each line of evidence. The Dempster-Shafer method allows us to overlay each of the basic probability assignment to produce a map of degree of suitability for cropping (Fig. 3). In this case, the different lines of evidence for good and poor performing areas were coherent and the potential cropping zones are identified with little ambiguity. This work is being extended to other paddocks where the balance of evidence is more complex since some of the lowest yield zones were recorded when good to high yields were expected based on independent evidence.

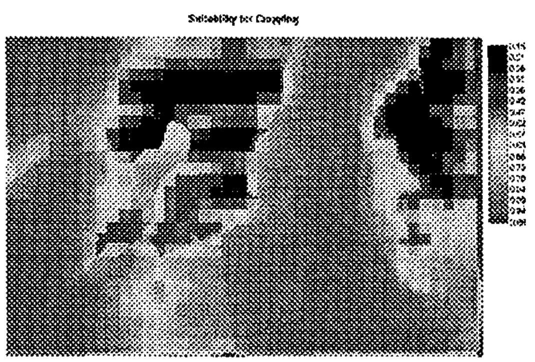


Fig. 3: Land use zones derived from the Weight of Evidence model. Green areas have a greater suitability for cropping.

Conclusion

The use of fuzzy sets and weight-of-evidence modelling are powerful tools for rational land use assignment, which minimises the decision risk made by farmers. The method developed here can be extended to include knowledge from more experts and more disciplines. At this stage, land use decision can be made based on best available knowledge and evidence. This is important since we cannot afford to wait until we have a complete understanding of causal factors inducing within paddock variability to act against our pressing salinity problem.

References

Zhang H. and Wong M. T. F. 2002. J. Expe. Agric. (In review).

Lee N.S., Grize, Y.L. and Dehnad K. (1987). Int. J. Int. Sys. 2, 15-38.

Pracilio, G , S. Asseng, S.E. Cook, G. Hodgson, M.T.F. Wong, M.L. Adams and T.J. Hatton 2002. Aust. J. Expt. Agric. (Submitted).

Saaty, T. L. 1977. J. Math. Psychol. 15, 234-281.

Zadeh, L. A., 1965. Info. Ctrl 8, 338-353.

Acknowledgement

This work is part of a research co-investment with the GRDC.

Evidence-based zone management of paddock variability to improve profits and environmental outcomes

M.T.F. Wong[A], D. Patabendige[B], G. Lyle[A] and K. Wittwer[A]
[A]CSIRO Land and Water, PO Box 5, Wembley WA 6913
[B]Department of Agriculture Western Australia, Northam WA 6401

KEY MESSAGE

- Yield mapping for more than five years in WA shows large spatial variability with grain yield ranging typically from 0.4 to 4.0 t/ha within the paddock.
- The historical data show that some areas of the paddock perform consistently poorly and lower the overall financial performance of the paddock.
- In order to improve profits and environmental benefits, the poor performing areas should be either: (1) ameliorated where economically feasible; or (2) re-assigned to a more suitable land use.
- Weight of evidence modelling uses spatial data derived from paddock/farm information. These include yield and soil property maps, remote and proximal sensed data, on-farm response experiments and expert knowledge to determine zones in the paddock that: (1) perform well, (2) can be ameliorated economically; and (3) should be considered for reassignment for an alternative land use.
- The amount of data collected for each paddock by yield mapping and from other spatial information sources is huge and potentially confusing. A new tool developed by CSIRO Land and Water (as part of CSO 213) allows the cataloguing and management of this data in a logical manner.

AIMS

- Improve the financial and environmental efficiency of farm operations by zone farming to ensure that inputs are not used uniformly and indiscriminately over the paddock irrespective of site-specific land capability.
- To develop a tool to manage the huge amount of spatial data the precision agriculture generates.

METHODS

The case study is based on a 70 ha paddock in Three Springs using a 3-year wheat-lupin-wheat rotation. Soil was sampled and analysed. Maps of potassium, organic carbon content and nitrate release were made using Inverse Distance Weighting interpolation in ArcView. In addition, an NDVI image for mid-August 2000 and a soil type map for the paddock were also attained. A potash and nitrogen trial was also set up in 2000 in order to determine the current year and residual fertiliser response.

In order to manage and document the data, an automated data management tool has been developed which categorises the data into the logical hierarchical structure of farm, paddock, year and operation. The tool then processes the spatial data into a useable and manageable form at either a farm or paddock level within a GIS environment.

The weight of evidence model used: 1) a map of historical performance zones based on the normalisation of the three years of yield maps by gross margin analysis; 2) soil property and soil type maps; 3) remotely sensed imagery; 4) land degradation hazards; and 5) fertiliser response. These factors were all included to form a cartographic model that identified poor performing paddock zones that: (1) can be improved in a profitable manner; or (2) can be assigned to alternative perennial vegetation to increase water use. The ambiguity introduced by temporal and spatial variability was represented by converting the spatial data into fuzzy sets that define the degree of association to a particular class.

RESULTS

The fertiliser trial showed that wheat and lupins responded to potassium fertilisers and less to nitrogen. The potassium response was marked in zones of low soil potassium test values. These zones coincided with areas of deep pale sand where crop yield was consistently poor (less than 0.8 t/ha). The poor crops resulted in high response in percentage terms but in poor response in absolute terms. The gross margin maps allow historical performance zones to be identified (Figure 1).

Figure 1. Historical performance zones derived from weighted linear combination of fuzzy sets of gross margins analysis for 1998-00 for an average risk strategy.

The dark areas have a greater degree of unsuitability for cropping.

Decision for land use change is an important long-term consideration since this commits part of the paddock for decades in an alternative land use. This decision should therefore be soundly based with evidence from as many independent sources as possible and should use the best available knowledge and experience. Our model allowed these sources of evidence and knowledge to be evaluated mathematically. The output is shown in Figure 2.

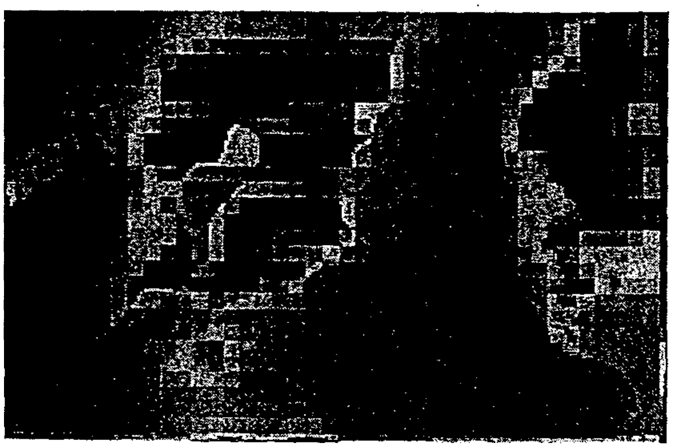


Figure 2. Land use zones based on evidence provided by maps of gross margin analysis, soil properties, nvdi, fertiliser response and expert knowledge.

The green areas represent a greater degree of suitability for cropping.

CONCLUSIONS

The application of the data management tool provided a logical and connivent way to organise large historical data sets available for this analysis.

The broad similarity between Figures 1 and 2 is due to the consistency of all the layers of evidence in this particular case study. The application of fertilisers improved yield in the poor performing areas but not to a level that was economically viable. However, other inputs such as claying could and the economic and environmental benefits for this approach compared to changes in land use should be assessed.

GRDC Project Nos: CSO 205 and CSO 213

Aust. J. Soil Res., 2002, **40**, 1357–1369

Mineral sources of potassium to plants for seven soils from south-western Australia

Y. Pal[A], *R. J. Gilkes*[A], *and M. T. F. Wong*[AB]

[A]Department of Soil Science and Plant Nutrition, The University of Western Australia, Nedlands, WA 6009, Australia.
[B]CSIRO Land and Water, Private Bag PO, Wembley, WA 6014, Australia.

Abstract

This investigation was conducted with surface horizon samples from 7 south-western Australian soils and their 3 size fractions (sand, silt, and clay). The K release of these materials was measured for several extractants; the highest amounts of K were released from the clay (<2 μm) fraction. The presence of sand-size feldspars and incomplete removal of attached organic matter resulted in sand releasing significant amounts of K. The proportions of total K released in boiling 1 M HNO_3 by the sand, silt, and clay fractions ranged from 0.4 to 3.4%, 2.6 to 36.3%, and 11.2 to 51.4%, respectively, and from 2.0% to 22.9% for the whole soils. Cumulative K uptake by 6 harvests of ryegrass over 260 days ranged from 0.26 to 1.23 cmol/kg soil.

The clay fraction released higher proportions of total K to acid compared with the sand and silt size fractions because of the high specific surface area of the clay and because it contained proportionately higher amounts of illite, which releases K by both ion exchange and dissolution, whereas K release from feldspars requires congruent dissolution of the silicate structure. The differences in contents of StepK (relatively available fraction of the non-exchangeable K) and CRK (constant rate K) for 1 M HNO_3 dissolution of these soils and size fractions reflect differences in mineralogical composition between the soils and size fractions. The low contents of StepK for the sand fraction indicated that K was strongly retained by feldspars. The soils with high CRK values had significant amounts of illite in the clay fraction. Values of CRK were positively related to cumulative K uptake and cumulative dry matter yield of ryegrass.

Additional keywords: HNO_3 extractable K, non-exchangeable K, ryegrass, K uptake, StepK, CRK.

Introduction

An important consideration influencing the availability to plants of non-exchangeable K (K_{nex}) in soils is the rate of release of this form of K to exchangeable and dissolved K pools (Feigenbaum *et al.* 1981). Particle size, mineral species, degree of weathering, and amounts of structural K are important factors that regulate the release of mineral K to soil solution and its availability to plants. Soil environment factors including soil acidity, soil water content, temperature, and the concentration of K and other ions in soil solution also affect the release of non-exchangeable K to plants (Martin and Sparks 1985; Kirkman *et al.* 1994). For highly weathered soils where the mineralogy is dominated by quartz, sesquioxides, and kaolin, K release from non-exchangeable K forms is relatively minor. For such soils exchangeable K is the major source of K available to plants (Sharpley 1989; Pal *et al.* 2001). Exhaustive cropping or grazing may exhaust exchangeable K so that release of non-exchangeable K or external addition of K are required to maintain plant growth in these soils.

Poor relationships between exchangeable K (K_{ex}) and plant response to K fertiliser have been reported (MacLean 1961; Kirkman *et al.* 1994), and may be due to K release of non-exchangeable K. Much emphasis has been placed on the clay fraction (<2 μm) as the source of non-exchangeable K (Smith and Mathews 1957; MacLean 1961; Al-Kanani *et al.*

 10.1071/SR02014 0004-9573/02/081357

Table 1. Some properties of the soils used in this investigation

Sample	Classification[A]	Texture	pH (H_2O) (1:5)	EC (1:5) (mS/m)	OC	Sand (%)	Silt	Clay	CEC [cmol(+)/kg]
KO 2A	Ultic Haploxeralf	SL	5.6	5	4.5	81	8	11	6
MRA 1	Calcic Natric Palexeralf	L	5.9	4	2.6	72	12	16	7
GTN 4	Dystric Eutrochrept	SL	6.0	5	0.9	89	8	3	4
GTN 11	Typic Palexeroll	SCL	6.4	1	1.2	80	4	16	5
KELL 4	Typic Xerorthent	LS	5.8	1	0.8	89	6	5	3
KELL 9	Typic Calcixeroll	L	8.3	16	1.5	71	17	12	16
KTG 7	Petroferric Hapludox	SL	5.2	5	2.6	87	5	8	3

[A] Soil Survey Staff (1987).

1984; Richards and Bates 1988). However, non-exchangeable K in soils is also present in various K-bearing minerals that may occur throughout the whole range of particle sizes (Jean-Francois *et al.* 1993). An earlier study of highly weathered Western Australian soils by Pal *et al.* (1999) indicated that various forms of extractable K were not statistically related to the clay and sand content in soil, but were positively related to silt content. The relevance of these results to soil testing and fertiliser recommendations needs to be evaluated. The present investigation was conducted to determine the relative contributions of soil size fractions and mineral K forms to K uptake by plants for representative Western Australian soils.

Material and methods

This investigation was conducted on the whole soil and sand, silt, and clay size fractions of surface (0–10 cm) horizons of 7 soils (Table 1). These soils are representative of the major sandy soil types of the agricultural region of south-western Australia, being taken from both ancient highly weathered and younger landscapes. Consequently the soils represent the full diversity of soil mineral suites for the region (McArthur 1991). Bulk samples were air-dried and passed through a 2-mm sieve for use in this study. Soil pH and EC were measured in H_2O using a 1:5 soil to solution ratio, after the soil suspension had been equilibrated at 25 ± 1°C for 1 h on an end-over-end shaker (Rayment and Higginson 1992). These highly leached soils contain little free salt; consequently, no pretreatments were given to remove soluble salts.

For soil fractionation into size fractions, soils were treated with H_2O_2 (~30%) to remove organic matter and dispersed by shaking in deionised water. It is recognised that some K in soils is associated with organic matter but this study is concerned with the mineral forms of K. The sand (53–2000 μm) was separated by sieving and the dispersed silt (2–53 μm) was separated from the clay (<2 mm) by repeated sedimentation and decantation (Gee and Bauder 1986). Organic carbon (OC) was determined by combustion with a high frequency induction furnace (LECO instrument) after standardising the instrument with an EDTA salt. Cation exchange capacity (CEC) was determined by single extraction of 0.5 g air-dry soil with 20 mL unbuffered 0.01 M silver thiourea $(AgTU)^+$ for 16 h with end-over-end shaking, followed by centrifugation (Rayment and Higginson 1992), and analysis of the extract for Ag using atomic absorption spectrophotometry (AAS). Soil properties and classifications are shown in Table 1.

Water-soluble K (K_{H2O}) was determined by extraction of 4000 mg soil, 4000 mg sand, 1000 mg silt, or 400 mg clay with 20 mL deionised water and 1 h of end-over-end shaking at 25°C. Exchangeable K (K_{ex}) was determined by extraction of 500 mg soil, 2000 mg sand, 500 mg silt, or 200 mg clay with 20 mL of unbuffered 0.01 M silver thiourea $(AgTU)^+$ for 16 h with end-over-end shaking followed by centrifugation. Values of K_{ex} were adjusted to correct for the contribution of water-soluble K (Rayment and Higginson 1992). Potassium concentrations in extracts were determined by atomic absorption spectrophotometry (AAS) in the presence of 4 mM Cs. Total K was determined using X-ray fluorescence spectrometry (Norrish and Chappell 1967). For total K analysis of whole soil and the sand fraction, about 10-g pellets of finely ground material were prepared using alvenol as a binder. For the silt and clay, pellets were prepared by depositing a thin layer of sample over boric acid pellets by applying a pressure of ~0.5 t/cm^2. Analyses were carried out by reference to calibration lines derived from geochemical standards prepared in the same manner.

For determination of non-exchangeable K, 2000 mg of whole soil, 2000 mg of sand, 500 mg of silt, or 200 mg of clay was repeatedly extracted with 20 mL of boiling 1 M HNO_3 at 113°C for 25 min (Metson *et al.* 1956). A correction was applied for the K in residual solution in the flask after each extraction. Six successive extractions were made with boiling 1 M HNO_3. A constant extraction rate being achieved after several extractions (Metson *et al.* 1956). In the present research the constant rate (K_c) of K release was calculated by taking the average amount extracted by the last 2 extractions. Haylock (1956) had termed the sum of the constant amount of K released in several successive HNO_3 extractions as 'constant rate K' (CRK). In this paper CRK has been calculated by multiplying the K_c value by the number of extractions: CRK = 6 × K_c. Much more K than K_c was released in the first extraction and this increment is described by Haylock (1956) as StepK, which he considered to be a relatively available fraction of the non-exchangeable K, StepK was calculated from the formula:

$$\text{StepK} = \text{Total K extracted in the 6 extractions} - (\text{AgTU})^{+}\text{K} - \text{CRK}$$

Note that $(AgTU)^{+}K$ consists of water-soluble K plus exchangeable K and also that StepK is an operational definition of non-exchangeable K that does not coincide with some other published definitions.

A glasshouse experiment was conducted using 1 kg soil samples of the <2 mm soils to assess their K supply capacities before and after exhaustive K depletion using a regularly harvested stand of perennial ryegrass (*Lolium perenne* cv. Roper). To ensure that general nutrient supply did not limit plant growth, a basal nutrient application consisting of (mg/kg soil) $MgSO_4.7H_2O$ 23, $MnSO_4.4H_2O$ 15, $ZnSO_4.7H_2O$ 9, $CuSO_4.5H_2O$ 4, H_3BO_3 0.8, $CoSO_4.7H_2O$ 0.4, $NaMoO_4.2H_2O$ 0.7, $NH_4H_2PO_4$ 148.4, and NH_4NO_3 105 (Jarvis and Robson 1983) was applied initially and after each harvest. A second application of the same amount of NH_4NO_3 only was given 20 days after each harvest. The first basal dose was given before initiation of the experiment and soils were allowed to equilibrate for a week at field capacity. Thirty ryegrass seeds were sown in each pot and thinned to 20 uniform plants after emergence. The first two attempts to establish a satisfactory density of ryegrass were unsuccessful due to variable germination but a third attempt succeeded. Seeds contained 0.18% K; thus, on average 5.32 mg K was added to each pot in seeds (i.e. from the 3 sowings) and data have been corrected for this K input.

Soils were watered daily to field capacity with deionised water, watering twice daily during hot weather, to prevent serious water stress. Visual assessment of plant stress was the main criterion for watering. Ryegrass was harvested 6 times consecutively at approximately 5–6-week intervals at about 1.5 cm above the soil surface and plant dry matter weight was determined after 24 h drying at 70°C in a forced-air oven. Entire harvested plant samples were ground for K determination. For K analysis, plant material was digested in a 3:1 nitric:perchloric acid mixture and the K concentration of the plant digest was determined by flame photometry. The experiment was terminated 260 days after sowing when there was no further plant growth in any pot due to K depletion. About 50 g soil was collected from each pot using a tube auger, this sample was used for the chemical determination of various K forms.

Results and discussion

These soils are duplex, gravely yellow earth and brown calcareous soils with loamy sand to sandy clay loam textures in topsoils (McArthur 1991). The low silt content is a characteristic of many Western Australian soils (Table 1), partly a consequence of the dominantly coarse textured granitic parent materials, and the mineralogical maturity of these soils (Singh 1992). X-ray diffraction analysis of random powders of the sand, silt, and clay fractions, and the basally oriented clay, indicated that only a few mineral species occur in these soils. The sand and silt fractions are dominated by quartz but most soils do contain significant amounts of K-feldspars (Fig. 1).

Kaolin is the dominant mineral in the clay fraction for all the soils and also occurs in the sand and silt fractions in partly altered feldspars and mica grains and is also present as strongly attached coatings on quartz grains. The XRD patterns of random powders of the silt and clay of KELL 9 indicate the presence of some calcite, which is consistent with the high pH of this soil. The clay fraction of soil KTG 7 contained some inhibited vermiculite and gibbsite (Fig. 1). The XRD patterns of random powders of the clay fractions indicate that feldspar is absent from KO 2A and KTG 7 clay but small amounts are present in the

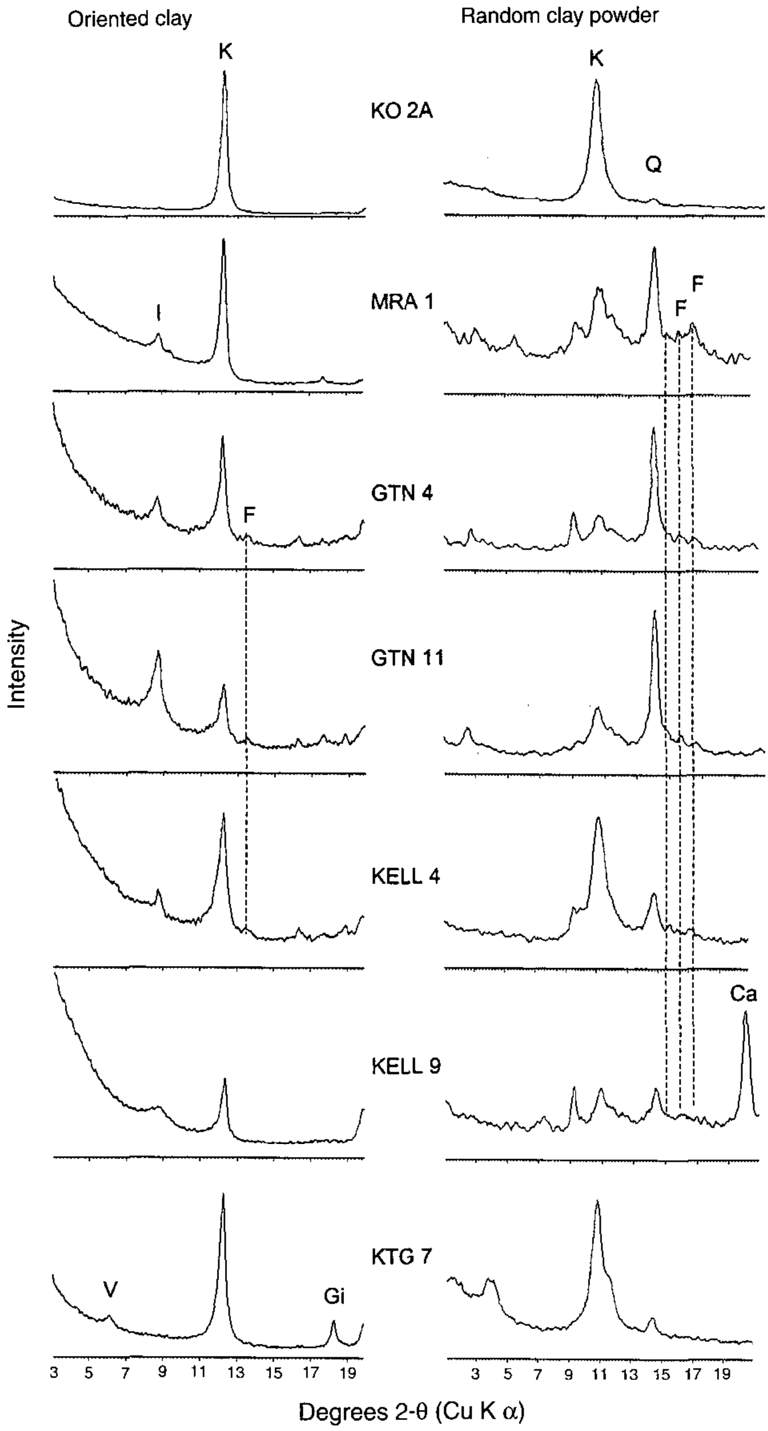


Fig. 2. XRD diffraction patterns of basally and randomly oriented powders of the clay fraction for the seven soils from Western Australia. Quartz (Q), kaolinite (K), feldspar (F), illite (I), inhibited vermiculite (V), calcite (Ca) and gibbsite (G).

Table 2. Concentrations of exchangeable K (K_{ex}) and total K both as (cmol/kg) in whole soil and size fractions

Values in parentheses are expressed as a percentage of total K in soil

Sample	Total K	K_{ex}	K_{H_2O}[A]	Total K				K_{ex}			
	Whole soil <2 mm			Sand 2000–53 μm	Silt 53–2 μm	Clay <2 μm	Calculated total K for all fractions[B]	Sand 2000–53 μm	Silt 53–2 μm	Clay <2 μm	Calculated K_{ex} for all fractions[B]
KO 2A	20.8	0.12	0.11	22.96 (89)	19.7 (8)	5.99 (3)	20.8	0.05 (0.19)	0.04 (0.02)	1.02 (0.55)	0.16
MRA 1	27.9	0.58	0.07	23.9 (61)	47.5 (21)	32.44 (18)	28.2	0.05 (0.14)	0.17 (0.07)	2.12 (1.19)	0.39
GTN 4	67.8	0.26	0.07	67.44 (89)	82.32 (10)	39.25 (1)	67.5	0.08 (0.10)	0.18 (0.02)	2.46 (0.09)	0.15
GTN 11	32.4	0.12	0.09	27.71 (62)	62.75 (6)	69.93 (32)	35.7	0.04 (0.09)	0.19 (0.02)	1.46 (0.72)	0.27
KELL 4	71.4	0.17	0.03	75.38 (94)	51.43 (4)	24.67 (2)	71.5	0.07 (0.08)	0.20 (0.02)	2.12 (0.15)	0.18
KELL 9	53.8	1.18	0.12	52.45 (69)	58.85 (19)	54.53 (12)	53.8	0.12 (0.15)	0.51 (0.16)	4.42 (1.01)	0.71
KTG 7	7.3	0.13	0.06	6.75 (81)	21.47 (15)	4.02 (4)	7.3	0.01 (0.12)	0.03 (0.02)	0.51 (0.56)	0.05

[A]Determined for whole soils only. [B]Weighted sum of K in size fractions; note that fractions had been treated with hydrogen peroxide.

Table 3. Semiquantitative mineralogy of whole soils, amounts of K extracted by 6 sequential 1 M HNO_3 extractions for soils and their size fractions, and data expressed as % of K in fraction dissolved

Soil	Whole soil mineralogy (%)							HNO_3 K (6 extracts) (cmol/kg)				% Total K in fraction dissolved			
	Kaolinite	Mica/Illite	Vermiculite[A]	Gibbsite	Calcite	Quartz	Feldspar	Soil[B]	Sand	Silt	Clay	Soil	Sand	Silt	Clay
KO 2A	10	—	—	—	—	85	5	0.7	0.1	0.5	0.7	3.4	0.4	2.7	11.2
MRA 1	15	trace	—	—	—	80	5	2.2	0.4	1.7	10.3	7.8	1.5	3.6	31.6
GTN 4	5	trace	—	—	—	85	10	2.2	0.5	3.7	15.3	3.3	0.8	4.5	39.1
GTN 11	10	10	—	—	—	75	5	2.7	0.6	4.3	23.4	8.4	2.3	6.8	33.4
KELL 4	5	trace	—	—	—	85	10	1.5	0.5	2.3	7.8	2.0	0.6	4.4	31.4
KELL 9	10	5	—	—	trace	75	10	12.3	1.8	21.4	28.0	22.9	3.4	36.3	51.4
KTG 7	10	—	trace	trace	—	85	5	0.5	0.1	0.6	0.6	6.5	0.8	2.6	15.9

[A]Inhibited vermiculite. [B]Acid extractable K includes H_2O-K and Ex-K for whole soil data only.

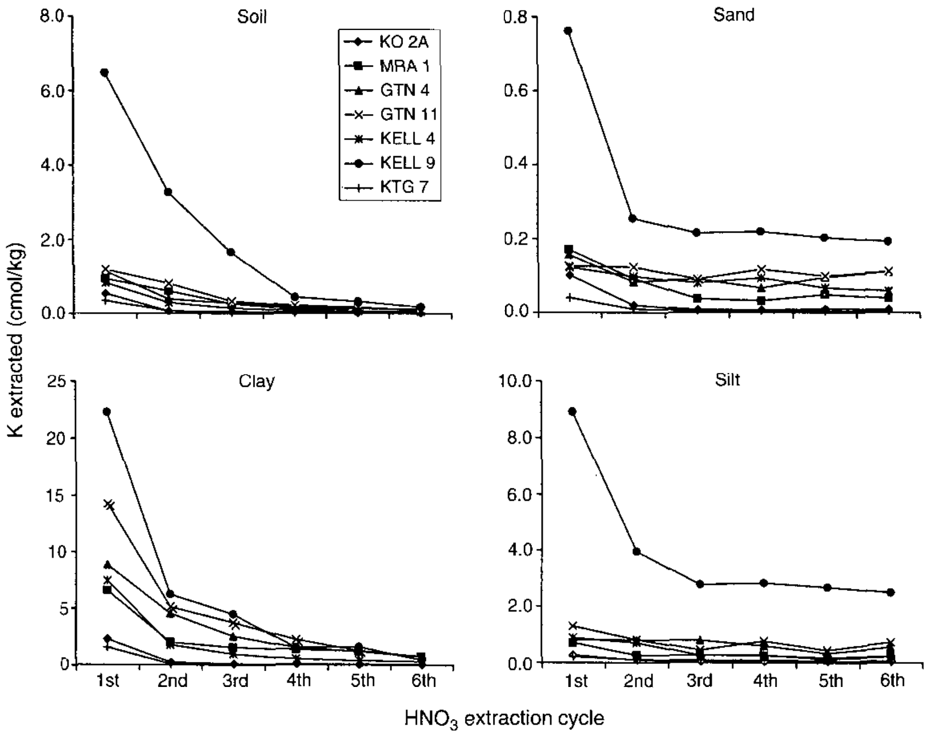


Fig. 3. Amounts of K released by seven Western Australian soils and soil size fractions by six extraction cycles with 1 M HNO_3.

Table 4. Amounts (cmol/kg) of the rapidly acid-soluble form of K (StepK) and constant dissolution rate K (CRK) for soils and their size fractions

Soil	CRK				StepK			
	Soil	Sand	Silt	Clay	Soil	Sand	Silt	Clay
KO 2A	0.11	0.06	0.38	0.25	0.38	0.03	0.16	0.42
MRA 1	0.76	0.27	1.25	5.88	0.77	0.08	0.47	4.38
GTN 4	0.77	0.63	2.65	5.76	1.13	−0.10	1.04	9.58
GTN 11	0.78	0.64	3.51	6.63	1.82	−0.01	0.77	17.68
KELL 4	0.34	0.38	1.02	2.04	0.92	0.07	1.24	5.71
KELL 9	1.49	1.20	15.4	6.06	9.51	0.48	7.59	23.95
KTG 7	0.07	0.03	0.28	0.41	0.22	0.03	0.28	0.23

the increased abundance of micaceous clay minerals and decreased abundance of 1 : 1 layer clay minerals and oxides/oxyhydroxides in the clay fraction of soils (Metson and Lee 1977; Metson 1980).

The data for calcareous soil KELL 9 will have been influenced by acid consumption by calcite and have not been included in the statistical analyses to avoid outlier effects. The statistical analysis of the data for whole soils indicated that soil pH had a significant positive relationship with StepK and CRK values. StepK represents the potentially available fraction of the non-exchangeable K in soil, and as StepK was not related to %clay content, the availability of this non-exchangeable K to plants cannot be predicted from the

Table 5. Stepwise multiple regression equations showing the most predictive soil properties for StepK and CRK for whole soil

StepK	R^2
StepK = 0.94 K_{ex} (Silt) – 1.60	0.88
StepK = 0.53 K_{ex} (Silt) + 0.49 CEC – 2.22	0.95
StepK = 0.38 K_{ex} (Silt) + 0.86 CEC + 0.30 Sand – 14.06	0.98
CRK	
CRK = 0.93 K_{ex} (Silt) + 0.07	0.85
CRK = 0.71 K_{ex} (Silt) + 0.32 Total K (Clay) – 0.21	0.92
CRK = 0.23 K_{ex} (Silt) + 0.56 Total K (Clay) + 0.44 Silt – 0.31	0.98

texture class of these soils (Richards and Bates 1988). If we exclude the pH and EC as variables, stepwise multiple regression analysis revealed that 88% of variation in values of StepK is predicted by the exchangeable K content of the silt fraction (+), and with addition of CEC (+) and %sand (+) to the equation, prediction improved to 98% of the variation. For CRK in the whole soil, 85% of the variation is predicted by the exchangeable K content of the silt fraction (+), with addition of total K (+) and %silt (+) to the equation improving prediction to explain 98% of the variation in CRK values (Table 5).

Glasshouse investigation

The different soils supported large differences in K uptake by ryegrass, and for all soils plants died from K deficiency after the fifth or sixth harvests (Table 6). Since adequate levels of all the basal nutrients except K were added, these variations in plant K uptake were not a consequence of general nutrient deficiency but were due to variations in K supply by the soils (Table 1). Note that K uptake values are expressed as cmol/kg soil to enable easy comparison of K uptake by plants with chemical measures of K forms in soils. The estimates of cumulative K uptake are lower than the actual amounts of K taken up by the plants, since the harvested material did not include plant roots.

The cumulative dry matter yield from the 6 harvests of ryegrass ranged from 11.4 to 20.1 g/kg soil, and cumulative K uptake ranged from 0.26 to 1.23 cmol/kg soil. The K concentration in the first harvest herbage ranged from 2.9 to 6.0%, which may be regarded as sufficient concentrations (Reuter *et al.* 1997), and K concentration decreased substantially for subsequent harvests. Potassium uptake (K content) values for the final harvest for the different soils ranged from 0.01 to 0.08 cmol K/kg soil with corresponding K concentration ranges from 0.3 to 1.6%. The final harvest occurred after the fifth or sixth cutting when no further growth occurred. The low tissue %K concentrations for the final harvest may be partly due to the presence of dead plant material that might have lost some of its K by leaching (Fergus *et al.* 1972; MacKay and Russell 1975), although care was taken during watering to avoid wetting plant material. A critical value of 0.8 %K had been suggested for healthy growth of ryegrass (Reuter *et al.* 1997).

For control soils that had not had plants, the total amount of K extracted in the 6 sequential extractions with boiling 1 M HNO_3 ranged from 0.47 to 12.3 cmol/kg soil, with much of this K being released to the first extraction (Table 6). The corresponding values of K extracted from soils taken after ryegrass growth ranged from 0.32 to 9.01 cmol/kg soil. Growth of ryegrass had markedly reduced the amount of K that was extracted in the first 3 extractions for most of the cropped soils in comparison to the control soils. Note that the higher amounts of K in the first extraction were largely due to water-soluble K and exchangeable K, and this had been substantially depleted by the ryegrass by the time of the

Table 6. **The amounts of K extracted (cmol/kg soil) by boiling 1 M HNO_3 from soil samples before and after six taken harvests of ryegrass**

Soil	Sample time	K extracted by successive 1 m HNO_3 treatments 1st[C]	2nd	3rd	4th	5th	6th	Total	CRK	StepK	K_{H_2O}	K_{ex}	Plant K uptake
KO 2A	Pre[A]	0.533	0.066	0.047	0.032	0.019	0.017	0.71	0.11	0.38	0.11	0.12	
	Post[B]	0.210	0.069	0.049	0.033	0.020	0.018	0.40	0.11	0.20	0.01	0.07	
	Decrease	0.323	−0.003	−0.002	−0.001	−0.001	0.000	0.32	0.00	0.18	0.10	0.05	0.35
MRA 1	Pre	0.933	0.608	0.257	0.127	0.126	0.127	2.18	0.76	0.77	0.07	0.58	
	Post	0.626	0.424	0.206	0.121	0.125	0.117	1.82	0.73	0.77	0.02	0.10	
	Decrease	0.308	0.184	0.051	0.006	0.002	0.009	0.36	0.03	0.00	0.05	0.48	0.66
GTN 4	Pre	1.133	0.385	0.271	0.186	0.128	0.129	2.23	0.77	1.13	0.07	0.26	
	Post	0.851	0.381	0.192	0.124	0.123	0.119	1.79	0.73	1.02	0.03	0.02	
	Decrease	0.282	0.004	0.080	0.062	0.005	0.010	0.44	0.04	0.11	0.04	0.24	0.49
GTN 11	Pre	1.182	0.808	0.334	0.219	0.172	0.087	2.80	0.78	1.82	0.09	0.12	
	Post	1.113	0.776	0.333	0.192	0.165	0.089	2.67	0.76	1.82	0.09	0.00	
	Decrease	0.069	0.032	0.000	0.027	0.007	−0.002	0.13	0.02	0.00	0.00	0.12	0.47
KELL 4	Pre	0.826	0.288	0.144	0.083	0.061	0.050	1.45	0.34	0.92	0.03	0.17	
	Post	0.456	0.279	0.133	0.077	0.060	0.050	1.06	0.33	0.67	0.02	0.04	
	Decrease	0.369	0.009	0.011	0.006	0.001	0.000	0.40	0.01	0.25	0.01	0.13	0.29
KELL 9	Pre	6.456	3.265	1.649	0.435	0.325	0.173	12.30	1.49	9.51	0.12	1.18	
	Post	4.467	2.350	1.294	0.431	0.289	0.176	9.01	1.40	7.43	0.01	0.17	
	Decrease	1.990	0.915	0.355	0.004	0.036	−0.003	3.30	0.09	2.08	0.11	1.01	1.23
KTG 7	Pre	0.338	0.074	0.024	0.013	0.011	0.011	0.47	0.07	0.22	0.06	0.13	
	Post	0.215	0.043	0.026	0.016	0.012	0.012	0.32	0.07	0.21	0.01	0.03	
	Decrease	0.123	0.031	−0.002	−0.003	−0.001	0.000	0.15	0.00	0.01	0.04	0.10	0.26

[A]Samples taken at start of greenhouse experiment.

[B]Samples taken after six harvests of ryegrass.

[C]Contains K_{H2O} and K_{ex}.

final harvest. The K extracted by 1 M HNO_3 from cropped soils declined relative to the original soils until the third or fourth extraction for soils KO 2A, MRA 1, and KTG 7 and thereafter remained nearly equal for subsequent extractions for both original and cropped soils. This trend conforms to the findings of other workers on diverse soil types (Haylock 1956; MacLean 1961; Metson 1968; Richards and Bates 1988; Manjaiah *et al.* 1997).

For soils GTN 4, GTN 11, KELL 4, and KELL 9, the amounts of K extracted by 1 M HNO_3 systematically decreased with extraction number until the fifth or sixth extraction. These soils contain much feldspar in addition to illite (Fig. 2) in the clay fraction. On other hand, soils KO 2A and KTG 7 contain no illite or mica and little feldspar in the clay fraction, and consequently released the lowest total amounts of K in 1 M HNO_3 acid with quite constant amounts of K being released to each of the later extractions. This result is consistent with most of the HNO_3-soluble K from these 2 soils being present in sand and silt size feldspar (Fig. 1). Ignoring the data for KELL 9, the outlier calcareous soil, the total amount of K extracted by 1 M HNO_3 from control soils had a significant positive relationship ($r = +0.73$) with the cumulative K uptake by ryegrass.

Values of StepK varied from 0.22 to 9.51 cmol K/kg for controls and from 0.20 to 7.43 cmol/kg for soil samples taken after ryegrass growth. StepK is the fraction of K that is rapidly dissolved in boiling 1 M HNO_3 and much of the K utilised by ryegrass is derived from StepK, which includes water-soluble K and exchangeable K, which are the 2 main sources of K to plants (Pal *et al.* 2001). CRK represents *inter alia* exchange of interlayer structural K in mica/illite and congruent dissolution of mica/illite and K feldspar (Haylock 1956; Richards and Bates 1988) and was relatively little affected by ryegrass growth. The values of CRK for the control soils ranged from 0.07 to 1.49 cmol/kg soil, and for soils after ryegrass growth, the values were very similar, ranging from 0.07 to 1.40 cmol/kg soil, indicating that plants obtained little K from this fraction.

The CRK values for control soils had highly significant positive relationships with plant K uptake for harvest 6 ($r = +0.97^{***}$, $P < 0.001$), which presumably reflects the importance of this form of K once the readily available K had been depleted. CRK also had significant positive relationships with cumulative K uptake ($r = +0.84^{*}$) and cumulative dry matter yield ($r = +0.74^{*}$ $P < 0.05$). On the other hand StepK, which represents the sum of a number of more readily available forms of K, had only weak positive relationship with plant K uptake for harvest 1 ($r = +0.45$) and a stronger relationship for harvest 6 ($r = +0.83^{*}$). Therefore, we may consider that after the initially available K becomes depleted, the CRK and StepK forms of K are increasingly utilised.

CRK value for the clay fraction had significant positive relationships with cumulative K uptake ($r = +0.83^{*}$) and K uptake for harvest 6 ($r = +0.99^{***}$). CRK for the sand and silt fractions had significant positive relationships ($r = +0.79^{*}$ and $r = +0.84^{*}$, respectively) with K uptake for harvest 6 only. StepK for the clay fraction had a positive significant relationship with plant K uptake ($r = +0.81^{*}$) for harvest 6; on the other hand, StepK for the sand and silt fractions was not statistically related to plant K uptake. These results indicate that non-exchangeable K as indicated by CRK is partly available to plants, and presumably becomes an important source of K to plants as the readily available K (StepK) is depleted. Note, however, that plant growth and K uptake decreased greatly and plant mortality occurred due to K-deficiency as the soils became depleted in StepK.

Conclusions

This work has indicated that for some common soils of south-western Australia with quartz, sesquioxides and kaolin as dominant minerals, most of the K exists in resistant sand and silt size particles of feldspar and mica, which release K too slowly to match plant demand. Amounts of the CRK and StepK forms of K in the soil reflect the soil mineralogy, which can therefore be used to give an indication of potential release of non-exchangeable K. StepK for whole soil, which is the more available fraction of non-exchangeable K, was not significantly related to CEC, K_{ex}, silt content, and clay content. Thus, it appears that the potential availability of non-exchangeable K to plants from these soils cannot be deduced from soil texture. Both CRK and StepK were unable to provide K to plants at a rate that prevented development of K deficiency and eventual mortality, so it appears inevitable that farmers using these soils will eventually need to supply soluble K fertilisers. The time required for this situation to develop will depend on the capacity of subsoil to supply K to plants.

Acknowledgment

We gratefully acknowledge the financial support of the Grains Research and Development Corporation.

References

Al-Kanani T, MacKenzie AF, Ross GJ (1984) Potassium status of some Quebec soils: K release by nitric acid and sodium tetraphenylboron as related to particle size and mineralogy. *Canadian Journal of Soil Science* **64**, 99–106.

Feigenbaum S, Edelstein R, Shainberg I (1981) Release rate of potassium and structural cations from mica to ion exchangers in dilute solutions. *Soil Science Society of America Journal* **45**, 501–506.

Fergus IF, Martin AE, Little IP, Haydock KP (1972) Studies on soil potassium. II. The Q/I relation and other parameters compared with plant uptake of potassium. *Australian Journal of Soil Research* **10**, 95–111.

Gee GW, Bauder JW (1986) Particle size analysis. In 'Methods of soil analysis'. (Ed. A Klute) pp. 383–409. (American Society of Agronomy, Soil Science Society of America: Madison, WI)

Haylock OJ (1956) A method for estimating the availability of non-exchangeable potassium. In 'Proceedings of the 6th International Congress of Soil Science'. pp. 403–408. (ISSS: Paris)

Huang PM, Crossan LS, Rennie DA (1968) Chemical dynamics of K-release from potassium minerals common in soils. In 'Proceedings of the 9th International Congress of Soil Science'. pp. 705–712. (CSIRO: Adelaide, S. Aust.)

Jarvis SC, Robson AD (1983) The effects of nitrogen of plants on the development of acidity in Western Australian soils. 1. Effects with subterranean clover grown under leaching condition. *Australian Journal of Agricultural Research* **34**, 341–353.

Jean-Francois N, Dufey JE, Jaillard B, Hinsinger P (1993) Release of nonexchangeable potassium from different size fraction of two highly K fertilized soils in the rhizosphere of rape (*Brassica napus* cv. Drakkar). *Plant and Soil* **155/156**, 403–406.

Kirkman JH, Basker A, Surapaneni A, MacGregor AN (1994) Potassium in the soils of New Zealand—a review. *New Zealand Journal of Agricultural Research* **37**, 207–227.

Lee R (1984) The potassium status of yellow-grey earths. In 'Soil groups of New Zealand. Part 7 Yellow-grey earths'. (Ed. JG Bruce), pp. 73–76. (New Zealand Society of Soil Science: Lower Hutt, New Zealand)

McArthur WM (1991) 'Reference Soils of South-Western Australia.' pp. 1–265. (Australian Society of Soil Science, WA Branch; Department of Agriculture, Western Australia: Perth)

Martin HW, Sparks DL (1985) On the behavior of nonexchangeable potassium in soils. *Communications in Soil Science and Plant Analysis* **16**, 133–162.

MacKay DC, Russell JS (1975) Rates of growth, potassium uptake, and changes in the potassium properties of four Queensland soils during intensive cropping by buffel grass *Cenchrusc ciliaris*. *Australian Journal of Soil Research* **13**, 217–233.

MacLean AJ (1961) Potassium-supplying power of some Canadian soils. *Canadian Journal of Soil Science* **41**, 196–206.

Manjaiah KM, Datta SC, Sidhu GS, Ghosh SK (1997) Structural changes of mica dominant clay minerals as affected by extractions of non-exchangeable potassium. *Journal of Nuclear Agriculture and Biology* **26**, 147–154.

Metson AJ (1968) The long-term potassium-supplying power of New Zealand soils. In 'Proceedings of the 9th International Congress of Soil Science'. pp. 621–630. (CSIRO: Adelaide, S. Aust.)

Metson AJ (1980) Potassium in New Zealand soils. New Zealand Soil Bureau Scientific Report No. 38, pp. 1–61.

Metson AJ, Arbuckle RH, Saunders ML (1956) The potassium-supplying power of New Zealand soils as determined by modified normal-nitric-acid method. In 'Proceedings of the 6th International Congress Soil Science'. pp. 619–627. (ISSS: Paris)

Metson AJ, Lee R (1977) Soil chemistry in relation to the New Zealand genetic soil classification. *Soil Science* **123**, 347–352.

Munn DA, Wilding LP, McLean EO (1976) Potassium release from sand, silt, and clay soil separates. *Soil Science Society of America Journal* **40**, 364–366.

Norrish K, Chappell BW (1967) X-Ray fluorescence spectrography. In 'Physical methods of determinative mineralogy'. (Ed. J Zussman) pp. 161–214. (Academic Press: New York)

Pal Y, Wong MTF, Gilkes RJ (1999) Forms of potassium in some south-western Australian agricultural soils. *Australian Journal of Soil Research* **37**, 695–709.

Pal Y, Gilkes RJ, Wong MTF (2001) Soil factors affecting the availability of K to plants for West Australian soils: a glasshouse study. *Australian Journal of Soil Research* **39**, 611–625.

Rayment GE, Higginson FR (1992) 'Australian laboratory handbook of soil and water chemical methods.' pp 1–330. (Inkata Press: Melbourne)

Reuter DJ, Edwards DG, Wilhelm NS (1997) Temperate and tropical crops. In 'Plant analysis: an interpretation manual'. (Eds DJ Reuter, JB Robinson) pp. 81–279. (CSIRO Publishing: Melbourne)

Richards JE, Bates TE (1988) Studies on the potassium-supplying capacities of southern Ontario soils. II. Nitric acid extraction of nonexchangeable K and its availability to crops. *Canadian Journal of Soil Science* **68**, 199–208.

Sharpley AN (1989) Relationship between soil potassium forms and mineralogy. *Soil Science Society of America Journal* **53**, 1023–1028.

Singh B (1992) Mineralogical and chemical characteristics of soils from south-western Australia. PhD thesis, The University of Western Australia, Australia.

Smith JA, Mathews BC (1957) Release of potassium by 18 Ontario soils during continuous cropping in the greenhouse. *Canadian Journal of Soil Science* **37**, 1–10.

Soil Survey Staff (1987) 'Keys to soil taxonomy.' 3rd edn. SMSS Technical Monograph No. 6 (USDA: Ithaca, NY)

Manuscript received 18 January 2002, accepted 27 May 2002

Australian Journal of Experimental Agriculture, 2001, **41**, 655–661

A decision support system for mapping the site-specific potassium requirement of wheat in the field

M. T. F. Wong[AB], *R. J. Corner*[AC] *and S. E. Cook*[AD]

[A]CSIRO Land and Water, Private Bag, PO Wembley, WA 6014, Australia.
[B]Soil Science and Plant Nutrition, The University of Western Australia, Nedlands, WA 6907, Australia.
[C]Present address: Department of Spatial Sciences, Curtin University, Bentley, WA 6102, Australia.
[D]Present address: Centro Internacional de Agricultura Tropical, Cali, Columbia.
[E]Author for correspondence; e-mail: m.wong@ccmar.csiro.au

Abstract. The intensely weathered nature of Western Australian cropping soils and the long history of potassium depletion by the farming system has resulted in increased incidence of potassium deficiency in wheat. There is currently no scientifically based method for potassium recommendation in Western Australia. This paper describes the use of site-specific plot-scale field trials carried out in 1995–98 and a crop response model to develop a generally applicable potassium recommendation system. Geographic information system technology was used to extend the uniform potassium recommendation system into a system for mapping spatially variable potassium requirement that takes account of crop demand and soil available potassium. The field trials were carried out on a range of soil types and showed that wheat response to potassium can be described by the Mitscherlich equation. The size of the response was dependent on the soil test value for plant available potassium and the yield of the crop. The latter is mainly dependent on rainfall in the water-limited Mediterranean environment of Western Australia. The relationships between the maximum achievable yield, crop response and soil available potassium values were quantified in order to allow the decision support system to be developed for uniform whole-paddock fertiliser recommendation. Both soil available potassium and yield are very spatially variable in Western Australia and for wheat, the coefficient of variation of yield within the paddock is often of the order of 30%. Soil property variation can be of a similar order. Maps of soil available potassium values and of spatially variable target yield determined either from (i) farmer's estimate, (ii) yield monitors and (iii) remotely sensed normalised difference vegetation index measurements allow this decision system to map spatially variable potassium requirement. Comparison of the map of potassium requirement with measured spatially variable response to potassium showed that the decision support system performed satisfactorily.

Additional keywords: fertiliser, recommendation, precision agriculture.

Introduction

Potassium deficiency is an increasing risk in soils of the Western Australian wheat belt. These soils are intensely weathered and quartz and kaolinite dominate their mineralogy. The content of potassium (K)-bearing minerals such as illite is typically very low. Non-exchangeable K content is also very low due to the virtual absence of 2:1 layer clay minerals (Pal *et al.* 1999). Total plant K uptake is therefore limited in these soils to the exchangeable K content, which represents the total amount of available K (Pal *et al.* 2001). Although exchangeable K may accumulate in the clayey subsoil of some of these soils, this K source contributes little to uptake by wheat because of low root density (Wong *et al.* 2000). These low K soils are being driven to produce ever-greater yields resulting in K depletion. While simply applying chemical fertiliser can correct K deficiency, there is currently no published method for K recommendation in Western Australia. Uncertainty about the specific benefit of application impedes efficient fertiliser use. This uncertainty is caused by 2 sources. First, soil available K is highly heterogeneous locally. Available K is measured in Western Australia on the 0–10-cm sample by extraction with sodium bicarbonate using the Colwell K test (Rayment and Higginson 1992). These test values vary by an order of magnitude within paddocks (Wong and Harper 1999). Second, the demand for K is mainly dependent on crop growth and yield. This also varies widely, as indicated by detailed wheat yield maps, which routinely show ranges of between 0.5 and >4 t/ha within a single paddock (Cook and Bramley 2000). The causes of this variability include a number of biophysical factors, including water and nutrient availability and the incidence of weeds, pests and diseases. The farmers can identify consistently poor and well-performing areas within the paddock.

 10.1071/EA00191 0816-1089/01/050655

This paper describes an improved method of decision support to reduce this uncertainty. It provides not only whole-paddock recommendations but also site-specific recommendations, given basic estimates of achievable crop yield and soil K.

The A, B, C estimates for potassium recommendation

This decision support system (DSS) uses the results of plot-scale field experiments undertaken over 4 years (1995–98) in the 350–500-mm rainfall region of the Western Australian wheat belt. These experiments, which have been described elsewhere (Wong *et al.* 2000), show that the response of wheat yield (Y) to K fertiliser application can be described by the Mitscherlich equation (Edwards 1997):

$$Y = A - B\exp(-CR), \tag{1}$$

where A is the maximum achievable yield with optimal K fertiliser (kg/ha), B is the maximum response (kg/ha), C is the curvature of the Mitscherlich curve and R is the rate of K applied (kg/ha). The magnitude of the crop response term is dependent on the K supply at a site. This can be expressed as the ratio of the yield of the untreated control plots relative to the maximum yield achievable with K. This ratio can also be described as a function of soil test values for K using the Mitscherlich equation (Wong *et al.* 2000).

Fertiliser recommendations

Fertiliser recommendations may be made using an inverted form of the Mitscherlich equation (equation 2):

$$R = -1/C \times \ln[(Y_t - A)/-B]. \tag{2}$$

For any given target yield (Y_t), this model requires estimates of A, B and C. These will be considered in turn.

Estimating A: the maximum achievable yield

The decision support system requires an estimate of the target yield for which fertiliser is being applied since larger crops obviously require more K. Within the Mediterranean-type environment of the Western Australian wheat belt, the prime limitation to yield is water availability (Passioura 1977). In this environment, the French and Shultz (1984) equation provides a convenient and pragmatic method of estimating the achievable yield of wheat based on the sum of the growing season rainfall and the amount of water stored from the previous summer rain:

$$\text{Maximum achievable yield (kg/ha)} = [\text{soil stored water (mm)} + \text{season rainfall (mm)} - 110] \times 20. \tag{3}$$

The maximum water-use efficiency for wheat yield, as defined by equation 3 is 20 kg/ha.mm (French and Shultz 1984; Turner and Whan 1995). The other constant (110) in the equation refers to water loss by soil evaporation (Perry 1987). The maximum achievable yield, or a scaled value derived from it, is used in traditional agronomy to estimate the rate of uniform fertiliser application for the paddock.

Estimating B: the maximum response to potassium

The maximum response of a site (B) depends on both the water-limited yield (A) and the inherent capability of the soil to supply K. Predicted maximum response is estimated as:

$$B = A(1 - K_{supply}). \tag{4}$$

Potassium supply is estimated by dividing the yield of the K control plots with the maximum yield achievable with K fertiliser at the site. A statistical relationship between K supply and soil Colwell K, was developed from field experimental data reported in Wong *et al.* (2000):

$$K_{supply} = 0.95 - 2.60\exp(-0.095K_0)\ (r^2 = 0.77), \tag{5}$$

where K_0 is Colwell K. Soils with lower Colwell-K values result in larger values of response, B.

The data used to produce equation 5 are pooled from all experimental sites and years (Wong *et al.* 2000). While this approach ignores the effect of other soil variables, it is justified by results from field experiments at 180 sites in Victoria, which showed that little was gained by using separate regression equations to take account of different soil types (Gourley 1989).

Estimating C: the curvature of the Mitscherlich response curve

The Mitscherlich coefficient (C) describes the shape of the response curve between minimum and maximum values of K. Larger values of C result in steeper curves and in the maximum yield being reached with less fertiliser. Field experiments in Western Australia showed that the curvature of the Mitscherlich curve is sensitive to the variety of wheat used. Calculations from published data (Edwards 1997) give values of C ranging from 0.03 to 0.04 for a soft wheat variety and from 0.015 to 0.011 for an Australian standard wheat (ASW). These tests were carried out at Nyabing and Katanning using broadcast application of K applied as KCl. The data from these sites also suggest that soil type has little effect on the value of C. A similar low sensitivity of C to soil type was observed for pasture response to K in Victoria, where an average value of C = 0.025 was derived from 36 field experiments (Gourley 1989). This low sensitivity to soil type would suggest that K reacts in a similar fashion with different soils and in Western Australia, a survey of wheat belt soils shows that the dominant pool of total plant available K is exchangeable K (Pal 1999; Pal *et al.* 1999; Wong and Harper 1999).

Simple fertiliser recommendation

The relationships described so far and based on the results of recent field experiments in Western Australia allow values to be determined for A, B and C. These results are presented as nomographs in Figure 1. Knowing the yield target, soil K and wheat variety, farmers and advisers can use them to estimate K fertiliser requirements.

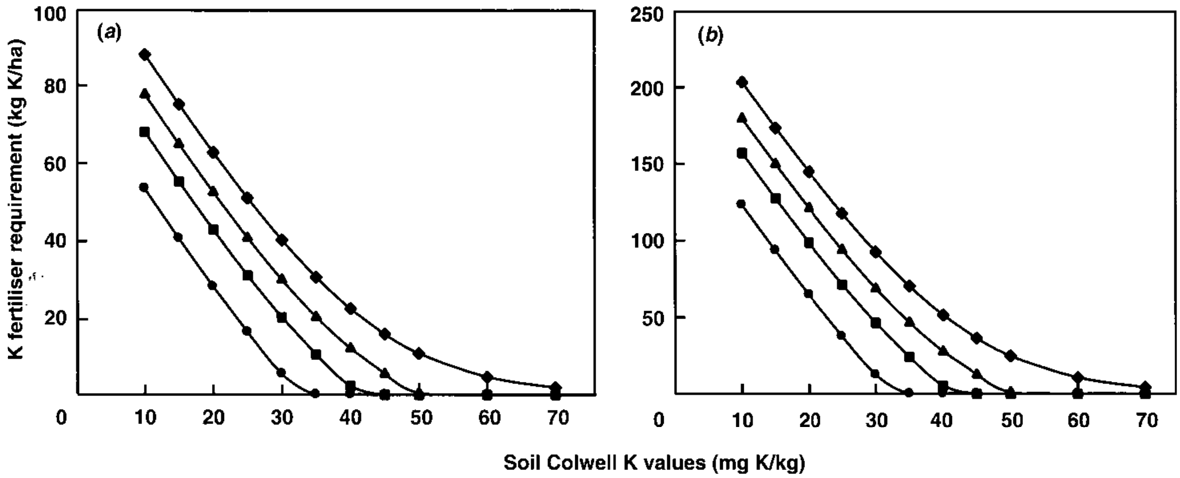


Figure 1: Effect of soil available K on K fertiliser requirement for different achievable yields (● 1.5 t/ha crop; ■ 2.5 t/ha crop; ▲ 3.5 t/ha crop; ◆ 5.0 t/ha crop) and for the curvature of the Mitscherlich curve (C) values of (a) 0.03 (soft wheat) and (b) 0.015 (Australian standard wheat).

Site-specific fertiliser recommendation

As pointed out in the introduction, the actual benefit of K fertiliser can be highly uncertain because of spatial variation of K supply and demand across a field. This can be reduced by providing information to qualify estimates of A and B, from which site-specific fertiliser recommendations can be made. In effect, equation 2 is solved, for Y_t, for each pixel in a raster data layer in a geographic information system (GIS).

The first stage of this process is to generate layers map representing the variables A and B. The curvature C of the Mitscherlich curve is assumed to be a constant for any particular crop variety.

Spatially variable estimates of A

An estimate of mean maximum achievable yield for the whole paddock can be determined using equation 3. Farmers know that this represents only the mean value and that achievable yield will differ substantially within the paddock, due primarily (in the absence of weeds or disease and similar transient factors) to the effect of soil moisture retention and topography on the available water. In the absence of a more formal measure of variability, a sketch by the farmer showing relative yield performances provides a basic framework to map the spatial distribution of the achievable yield in the paddock. Where a history, however brief, of yield mapping is available, this provides more detailed and accurately geo-located estimates of yield variability.

A further source of historical spatial data about yield variation is satellite imagery. Mid season normalised difference vegetation index (NDVI) has been used for some time to make estimates, at regional scale, of grain yield (Smith *et al.* 1995). While the relationship between mid season NDVI and grain yield breaks down unfortunately at paddock and subpaddock scale (Corner *et al.* 1998), the relationship between mid season NDVI and biomass is relatively stable (Smith *et al.* 1993). Since biomass production is the main driver of K demand and uptake, NDVI imagery may therefore be regarded as a reasonable indicator of nutrient demand within the area. For both yield maps and NDVI estimates, data from a number of years may be accumulated by normalising and averaging the spatial data.

The final stage in preparing a map of A is to normalise it to produce an estimate with a mean value equal to the estimate from French and Schultz (1984) and a variance equal to that from measured wheat paddocks within the region. This assumption is based on a study of a number of representative wheat paddocks throughout the Western Australian wheat belt, which showed that the spatial distribution of wheat yield is normally distributed and that the coefficient of variation (CV) lies between 20 and 50% with 29% being a regional mean. The spatial DSS uses this CV and mean value to produce a map of achievable yield. Based on experience, historical yield maps or remotely sensed data, the user can adjust the CV to represent paddocks that are more or less variable than the regional mean.

Spatial determination of B

The maximum expected response, B, is estimated by solving equations 4 and 5, using the map of A with the method described above, and an estimate of K supply. The latter can be estimated from spatially interpolated soil test values. Recent work suggests that it should soon be possible to estimate K supply from a soil map combined with other spatial attributes such as natural gamma-ray emission from ^{40}K and a digital terrain model (Corner and Wong 1999).

Determination of site-specific fertiliser requirements

Target yields less than A must be set for the paddock to allow equation 2 to be solved spatially. For practical

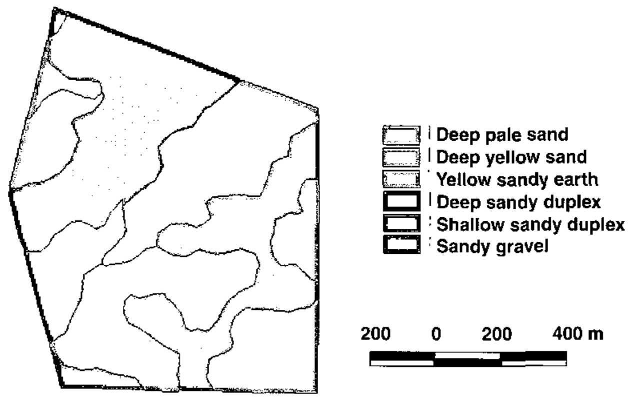


Figure 2. Distribution of soils in the 80-ha experimental paddock.

illustration purposes, a typical value of 95% is used. The spatial DSS determines the target yield map using the following formula:

$$Y_t = A - 0.05A, \tag{6}$$

where A is the mean value of achievable yield for the paddock as a whole. Once this has been determined, equation 2 may be solved and a map of recommended K rates produced.

Application of the decision support system to a spatially variable paddock

The method is demonstrated with data from a field trial carried out in 1997 on an 80-ha paddock at Corrigin, Western Australia (Wong *et al.* 1998). The paddock received nitrogen and phosphorus fertilisers and micronutrients. Spatial variables from that paddock are used here to illustrate the operation of the DSS. The distribution of soils observed on the paddock is shown in Figure 2.

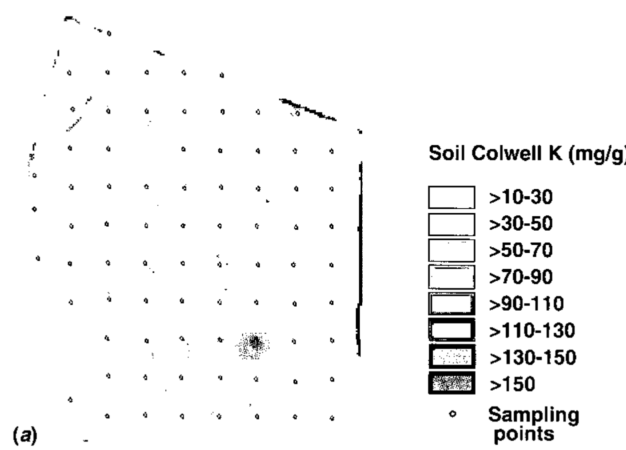
Summer rainfall in December 1996–March 1997 was only 15 mm and likely to have been lost quickly by soil evaporation. Furthermore, this rainfall was low compared with the rainfall recorded in the growing season and the stored water term is therefore ignored in equation 2. The growing season rainfall for April–October 1997 was 284 mm, giving a water-limited maximum achievable wheat yield of 3480 kg/ha, assuming that 110 mm water was lost by soil evaporation. The measured mean yield for the experimental paddock in 1997 was 2685 kg/ha, which is 77% of the maximum mean water-limited yield.

The soils in the paddock were sampled in a regular 100 by 100 m grid and a map of Colwell-K values was created from the test results using an inverse distance weighting interpolator (Fig. 3*a*). While geostatistical estimation would have been preferred, the density of samples was insufficient to compute an experimental variogram that looked meaningful.

The mean soil test value for the paddock was 64 mg K/kg and, based on Figure 1, no fertiliser K would be recommended for the paddock as a whole for immediate yield response. In the longer term, maintenance application of K would be beneficial in order to avoid the K depletion mentioned earlier.

Two maps of achievable yield for the paddock were derived using the method described above, one as a map of relative yield potential drawn by the farmer and the other from an NDVI composite. The NDVI composite was created from images collected in 1990, 1993, 1995 and 1996. These input maps are shown in Figure 4 and the resulting maps of achievable yield (A) are shown in Figure 5. The farmer and NDVI-derived maps are broadly similar and we shall demonstrate the operation of the DSS based on the farmer's map.

Equations 4 and 5 were used to create a map of B from the map of Colwell K. Spatially variable target yield was calculated using equation 6.



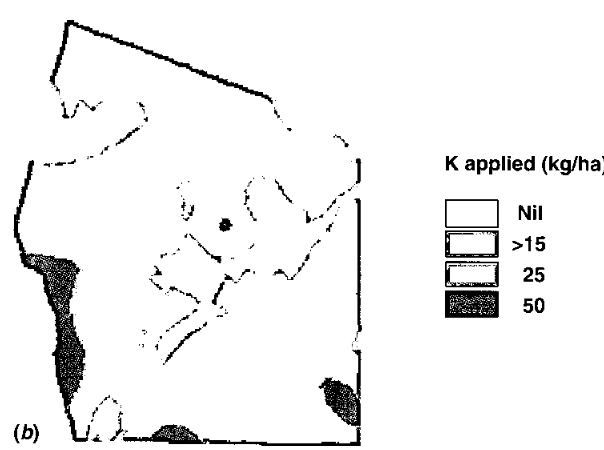
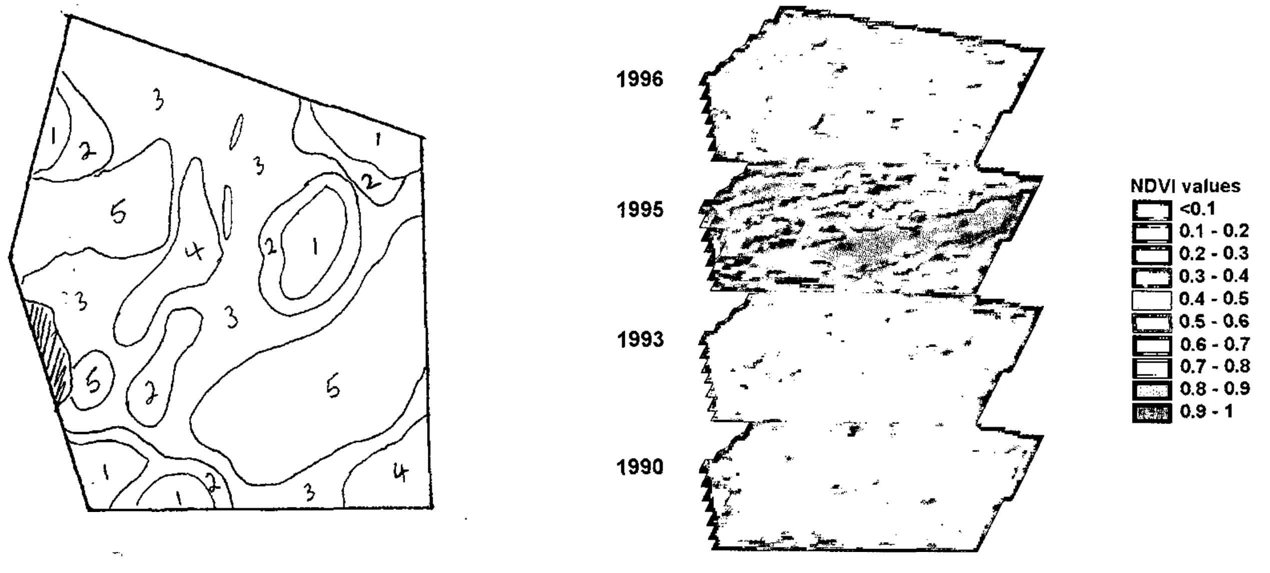


Figure 3. Distribution of (*a*) soil K concentration and (*b*) recommended K application rates (spatially variable) in the trial paddock.



(a) (b)

Figure 4. Inputs to achievable yield mapping (*a*) farmer's sketch map of scaled wheat yield performance and (*b*) 4 years of (NDVI) data.

Equation 2 was then used to calculate the site-specific K fertiliser recommendation (R) from the spatially variable target yield (Y_t), maximum achievable yield (A) and maximum response to K (B). Figure 6 shows recommended fertiliser rates for the trial paddock. This application map has been simplified to show 3 application rates.

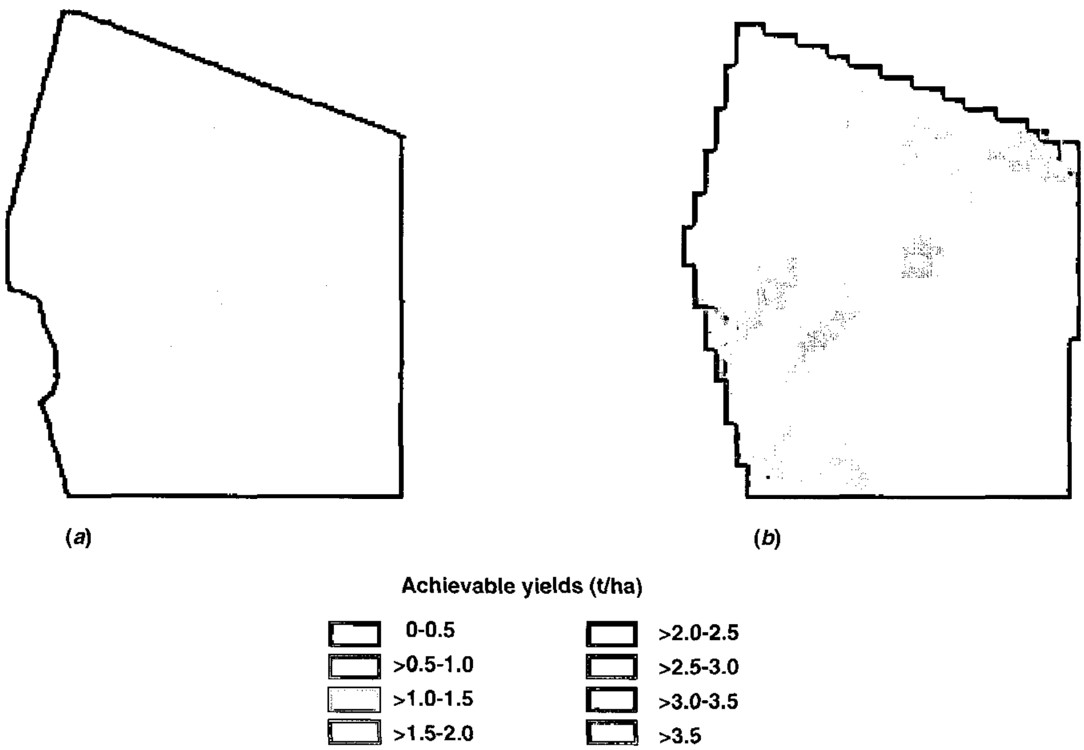


Figure 5. Achievable yield maps derived from (*a*) farmer's map and from (*b*) normalised difference vegetation index (NDVI) values.

Table 1. Response to 50 kg potassium/ha in areas for which variable recommendations were made

Mean response values followed by the same letter are not significantly different at $P = 0.05$

Recommended rate (kg K/ha)	Paddock area (ha)	Mean response (t grain/ha)
0	53	0.097a
25	10	0.305b
50	1.2	0.201c

Comparing the detailed recommendations with paddock results

The map in Figure 3*b* simplifies the variable rate recommendation into 3 classes of recommended K application rates to enable comparison with results from a large-scale trial in which K was added at rates of 0, 25 and 50 kg K/ha. Details of the field trial can be found in Wong *et al.* (1998). The accuracy of site-specific recommendation was assessed by comparing the measured yield response to 50 kg, at randomly located points taken from the map shown in Figure 3*b*. Where the recommendation was to apply high rates of K, the measured response should be large. Where the recommendation was to apply low rates, the response should be small.

Table 1 shows the response to 50 kg K/ha at sites where recommendations were for 0, 25 and 50 kg K/ha, respectively. As expected, when the recommendation was to apply no fertiliser, the response to an addition of 50 kg K/ha was negligible. This recommendation correctly identified 83% of the paddock area that required no K for immediate crop response. When the recommendation was to apply 25 kg K/ha, application of K resulted in a 0.3 t/ha increase in grain yield. This recommendation applied to 16% of the paddock area. Although 5% of the entire paddock was identified as requiring 50 kg/ha, only 2% of the K-treated experimental area fell into this category. The results for the higher application rate are therefore problematic and the apparent anomaly shown in Table 1, where response to K was less in sites predicted to require more K can be attributed to the very small number of points. This is a shortcoming of the paddock that was operating at 77% of its water limited yield potential and where the soil K status is now known to be generally adequate following the availability of results of soil test calibration trials (Wong *et al.* 2000).

Discussion

The average soil test value (64 mg K/kg) for the Corrigin paddock suggests that it required no K application for immediate crop response. A more detailed knowledge of variation of both K status and achievable yield indicated that 16% of the paddock area (13 ha) required 25 kg K/ha and gave a response of 0.3 t/ha. The cost of fertiliser to treat that area is A\$150 (25 kg K/ha × \$0.6/kg K × 10 ha) and the increased grain revenue is \$450 (0.3 t grain/ha × \$150/t grain × 10 ha). While this result indicates the benefit from a site-specific recommendation, it overlooks the cost of intensive soil sampling, which, at up to \$12/ha, may wipe out any potential gains. One option to reduce this cost is to estimate soil K from its relationship with attributes that can be acquired more cheaply. For example, in the eastern and southern parts of the Western Australian wheat belt, a strong relationship can occur between the gamma-ray signal for ^{40}K and Colwell K, in which case gamma-ray spectrometry would provide a cheaper alternative for mapping soil K (Wong and Harper 1999).

As an alternative to targeting a specific yield, a map of the most profitable K rate to be applied can be calculated from the predicted response and the cost of applying K. Maximum profit is achieved when the curve for the marginal return from fertiliser intersects that of the marginal cost of the fertiliser. The predicted most profitable rate is dependant on the ratio (P_r) of the price of a unit of fertiliser to the price of a unit of grain. This economic analysis of the data is being developed as an extension to the DSS.

Conclusions

This work provides the basic relationships required for a soundly based K recommendation system for the Western Australian wheat belt. The DSS deals with spatial variability of both soil available K, which is a measure of supply, and achievable yield, which is a measure of the crop demand for K. It uses the Mitscherlich equation to match the supply of fertiliser with the crop demand. Initial test shows a good performance of the DSS in its spatial mode in identifying variable K requirement. Development of this DSS is aimed at improving our estimate of crop demand and at developing cheaper methods for mapping soil K supply.

Acknowledgments

This work is part of GRDC funded project CSO 205 WR. Soil sampling was performed by Precision Agriculture, Australia and analysed by Wesfarmers-CSBP. We are grateful to the farmer, Mr Richard Barrett, and to Mr Daya Patabendige (Agriculture WA) for implementing and managing the paddock-scale experiment, and to Canpotex for additional financial support. Satellite imagery was made available through the AgImage project. This is an initiative of Agriculture WA and Remote Sensing Services, Department of Land Administration, Western Australia.

References

Cook SE, Bramley RGV (2000) Coping with variability in agricultural production — implications for soil testing and fertilizer management. *Communications in Soil Science and Plant Analysis* **31**, 1531–1551.

Corner RJ, Wong MTF (1999) Predicting the spatial distribution of potassium in the landscape at regional and field scales using a knowledge based method. In 'Precision agriculture 99'. (Ed. JV Stanford) pp. 605–614. (SCI Press: UK)

Corner RJ, Cook SE, Wheaton GA, Caccetta PA (1998) The effect of scale on the utility of remotely sensed grain yield estimates. In 'Proceedings of the conference of the Australian Society of Remote Sensing'. (Sydney, Australia)

Edwards NK (1997) Potassium fertiliser improves wheat yield and grain quality on duplex soils. In 'Proceedings of the first workshop on potassium in Australian agriculture'. (Eds MTF Wong, Y Pal, NK Edwards) pp. 85–91. (UWA Press: WA)

French RJ, Shultz JE (1984) Water-use efficiency of wheat in a Mediterranean-type environment. II. Some limitation to efficiency. *Australian Journal of Agricultural Research* **35**, 765–775.

Gourley CJP (1989) Predicting the responsiveness of pasture to potassium fertiliser in Victoria. *Australian Journal of Experimental Agriculture* **29**, 377–382.

Pal Y (1999) Potassium mineralogy, chemistry and availability in sandplain and duplex soils of the south-western of Western Australia. PhD Thesis, University of Western Australia.

Pal Y, Wong MTF, Gilkes RJ (1999) The forms of potassium and potassium adsorption in some virgin soils from south-western Australia. *Australian Journal of Soil Research* **37**, 695–709.

Pal Y, Wong MTF, Gilkes RJ (2001) Soil factors affecting the availability of K to plants for western Australian soils: a glasshouse study. *Australian Journal of Soil Research* **39**, 611–625.

Passioura JB (1977) Grain yield, harvest index and water use of wheat. *The Journal of the Australian Institute of Agricultural Science* September/December 1977, 117–120.

Perry MW (1987) Water use efficiency of non-irrigated field crops. In Agronomy 1987 — responding to change. In 'Proceedings of the 4th Australian agronomy conference'. (Ed. TG Reeves) pp. 83–89. (Australian Society of Agronomy: Parkville, Vic.)

Rayment GE and Higginson FR (1992) 'Australian laboratory handbook of soil and water chemical methods.' Australian soil and land survey handbook. (Inkata Press: Melbourne)

Smith RCG, Wallace JF, Hick PT, Gilmour RF, Belford RK, Portman PA, Regan KL, Turner NC (1993) Potential of using field spectroscopy during early growth for ranking biomass in cereal breeding trials. *Australian Journal of Agricultural Research* **44**, 1713–1730.

Smith RCG, Adams J, Stephens DJ, Hick PT (1995) Forecasting wheat yield in a Mediterranean-type environment from the NOAA satellite. *Australian Journal of Agricultural Research* **46**, 113–125.

Turner NC, Whan BR (1995) Strategies for increasing productivity from water-limited areas through genetic means. In 'Genetic research and education: current trends and the next fifty years'. (Ed. B Sharma) pp. 545–557. (Indian Society of Genetics and Plant Breeding: New Delhi)

Wong MTF, Harper RJ (1999) Use of on-ground gamma-ray spectrometry to measure plant-available potassium and other topsoil attributes. *Australian Journal of Soil Research* **37**, 267–277.

Wong MTF, Patabendige D, Barret R, Corner RJ, Mills D. (1998) Improving the efficiency of potassium and nitrogen use by wheat in precision agriculture. In 'Highlights of cereal research and development in Western Australia'. pp. 80–81. (GRDC)

Wong MTF, Edwards NK, Barrow NJ (2000) Accessibility of subsoil potassium to wheat grown on duplex soils in the south-west of Western Australia. *Australian Journal of Soil Research* **38**, 745–751.

Received 3 December 2000, accepted 7 March 2001

Plant and Soil 234: 131–142, 2001.

Potassium nutrition effects on seed alkaloid concentrations, yield and mineral content of lupins (*Lupinus angustifolius*)

P. Gremigni[1,7], M. T. F. Wong[2,3], N. K. Edwards[4], D. Harris[5] & J. Hamblin[1,6]

*[1]Centre for Legumes in Mediterranean Agriculture, University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia; [2]CSIRO Land and Water, Private Bag PO, Wembley WA 6014, Australia; [3]Soil Science and Plant Nutrition, University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia; [4]Agriculture Western Australia, Baron-Hay Court, South Perth WA 6151, Australia; [5]Chemistry Centre (WA), 125 Hay Street, East Perth WA 6004, Australia; [6]Export Grains Centre Ltd, 219 Canning Hwy, South Perth WA 6151, Australia. [7]Corresponding author**

Received 20 September 2000. Accepted in revised form 30 April 2001

Key words: K deficiency, *Lupinus angustifolius*, 13-hydroxylupanine, lupanine, quinolizidine alkaloid

Abstract

To ensure that narrow-leafed lupin (*Lupinus angustifolius* L.) meets feed quality standards, the concentration of alkaloids must be kept under the maximum acceptable limit of 200 mg kg^{-1} DM. One of the factors that may affect seed alkaloid concentration is soil nutrient deficiency. In this paper, we report the results of glasshouse and field experiments that tested the effect of potassium (K) deficiency on seed alkaloid concentrations. In the glasshouse, seed alkaloid concentrations increased by 385, 400 and 205% under severe K deficiency in sweet varieties (Danja, Gungurru and Yorrel, respectively) of *L. angustifolius*. The concentration of alkaloids in Fest, the bitter variety, was always high regardless of soil K status. At all levels of applied K (0–240 mg kg^{-1} soil), lupanine was the predominant alkaloid in sweet varieties, whereas 13-hydroxylupanine prevailed in the bitter variety. Seed yield of all varieties increased exponentially with increasing amounts of applied K, reaching a maximum at 60 mg K kg^{-1} soil. In the field, application of K to deficient soils decreased seed alkaloid concentration at Badgingarra, Western Australia (WA) but not at Nyabing, WA, in 1996. In both field trials, seed yield and mineral content were not affected by the amounts of K fertiliser applied. These findings highlighted the need for adequate K fertilisation of deficient soils in WA to avoid the risk of producing low quality lupin seed with high alkaloid concentrations. K deficiency is involved in stimulating alkaloid production in sweet varieties of *L. angustifolius*.

Introduction

Lupinus angustifolius L. (hereafter narrow-leafed lupin) growing areas are mainly on the earthy sands and yellow earths of the northern wheatbelt, and extend to the duplex soils of the central and southern wheatbelt of Western Australia (WA) (Thomson and Perry, 1995). Many soils of WA are characterized by low potassium (K) concentrations (< 40 mg K kg^{-1} soil) in the surface (0–10 cm depth) and at these concentrations lupins often show yield increases to applied K (Cox, 1978). Both native K and fertiliser K are easily leached from the soil surface, particularly on sandy soils in medium and high rainfall areas, and become less available to crops if leached beyond the rooting depth of the lupin crop (Cox, 1978; Edwards, 1993, 1995). Also, soil K reserves are being continuously removed in grain; on average 1 tonne of lupin grain contains about 8.5–9 kg of K (Cox, 1978; Wong et al., 2000a, b). Lupin grain is a highly nutritious component of animal feed, due mainly to its mineral composition, high protein and fibre concentrations (Petterson et al., 1997). Quinolizidine alkaloids are the main antinutritional factors that confer unpalatability and toxicity to lupin seed as an-

* FAX No: +61-8-9380-1140.
E-mail: pgrem@cyllene.uwa.edu.au

imal feed. These cyclic secondary metabolites[1], which contain one or more atoms of N in the molecule, are synthesised in the leaves and accumulated in the seed (Rana and Robins, 1985; Robins, 1987; Wink, 1987; Wink and Hartmann, 1982). The seed alkaloids of narrow-leafed lupin in order of abundance are lupanine, 13-hydroxylupanine, angustifoline and α-isolupanine (Allen et al., 1990; Harborne and Baxter, 1993).

The so-called 'bitter' and 'sweet' varieties have high ($\geq$ 10000 mg kg^{-1} DM) and low ($\leq$ 500 mg kg^{-1} DM) seed alkaloid concentrations (Culvenor and Petterson, 1986; Walton and Francis, 1975). Strict limits are imposed on seed alkaloid concentration of new varieties, so that the average concentration is <200 mg kg^{-1} DM (Culvenor and Petterson, 1986). However, seed alkaloid concentrations may fluctuate depending both on genotype and environment (Harris, 1994) and this unpredictable variability is a potential hindrance to the wider use of lupins for human consumption (Lowen et al., 1995).

It is well known that narrow-leafed lupin is susceptible to K deficiency (Gladstones, 1970) and it has been suggested that K deficiency may induce elevated alkaloid concentrations in lupins (Gremigni et al., 1997, 1998, 1999; Waller and Nowacki, 1978). Scibor-Marchocka (1970) found that K deficiency enhanced the concentration of quinolizidine alkaloids in the seed of bitter and sweet varieties of *L. albus*, whilst it did not affect alkaloid production in the vegetative portions of the plant. In *L. albus*, the bitter variety had seed alkaloid concentrations higher than the sweet variety, because of a more efficient mechanism of alkaloid translocation from the vegetative parts to the seed (Scibor-Marchochka, 1970). Waller and Nowacki (1978) observed that K-deficient lupins (species unknown) had higher alkaloid concentrations than adequately supplied plants. K is well known to stimulate the biosynthesis of proteins, rather than that of secondary metabolites, in plants (Marschner, 1995).

The aim of this research was to investigate the response of sweet and bitter varieties of *L. angustifolius* to K supply and in particular the response of seed alkaloid concentrations, yield and mineral content. It is hypothesised that K deficiency in narrow-leafed lupin increases seed alkaloid concentrations and reduces grain yields.

[1] Secondary metabolites are low molecular weight compounds. They include N-free and N-containing compounds (Wink, 2000a, b) and are synthesised in living organisms from precursors produced from basic metabolic pathways such as glycolysis, Krebs cycle or the shikimate pathway (Wink, 2000a). Secondary metabolites are unique and diverse for each plant species and, although they are not essential for growth and development, they are indispensable for survival (Croteau et al., 2000; Hartmann, 1981).

Materials and methods

Glasshouse experiment

A glasshouse experiment was carried out at the University of Western Australia, Perth (31° 57′ 05 S, 115° 05′ 02 E), Western Australia (WA) in 1996.

A virgin[2] soil was collected from Lancelin (31° 01′ 00 S, 115° 20′ 00 E), WA in March 1996. The Lancelin soil is classified as brown sand (Uc4.22) (Northcote, 1971), with pH 5.2 (1:5 soil:0.01 M $CaCl_2$, w/v) and 8.6 g kg^{-1} organic carbon (C) (Walkley and Black, 1934). The sand contained 28 mg K ($NaHCO_3$-extractable) kg^{-1} soil (Rayment and Higginson, 1992) and the concentration of other nutrients (mg kg^{-1}) was: 2, P ($NaHCO_3$-extractable); 2, NO_3 (H_2O-extractable); 7, NH_4 (KCl-extractable); 275, reactive Fe. The sand was air-dried, sieved through a 2 mm stainless steel sieve and thoroughly mixed. Six kg of soil were weighed into undrained pots (19 cm height × 19.5 cm diameter) lined with polythene bags. Basal nutrients were applied using AR grade salts in deionized water and added in solution to each pot at the following rates (mg kg^{-1} soil): $MgCl_2 \cdot 6H_2O$ (17), $Ca(H_2PO_4)_2 \cdot H_2O$ (133), $MnSO_4 \cdot 7H_2O$ (10), $ZnSO_4 \cdot 7H_2O$ (10), $CuSO_4 \cdot 5H_2O$ (1.5), H_3BO_3 (0.7), $CoSO_4 \cdot 7H_2O$ (0.3), $Na_2MoO_4 \cdot 2H_2O$ (0.17). The $Ca(H_2PO_4)_2$ H_2O (solubility 1.8 g 100 mL^{-1} water) was dissolved in water acidified with 2 ml of concentrated HCl. Different amounts of K (0, 15, 60, 240 mg K kg^{-1} soil) were added as K_2SO_4 solution. The adequate level of K for lupin growth was 60 mg kg^{-1} soil (Tang, 1998). After drying, solid $CaSO_4$(100) (solubility 0.209 g 100 mL^{-1} water) was added to the soil and all the nutrients were thoroughly mixed throughout the soil by shaking the soil of each pot in a plastic jar. No N was applied. Soil was watered to field capacity (11% oven dried soil weight) and allowed to settle, for 3 days before sowing, in root-cooling units with temperature maintained at 20±2 °C.

[2] For several years, the source of soil for most glasshouse experiments of plant nutrition at the University of Western Australia has been a sand pit at Lancelin, WA. This topsoil is extremely low in nutrients and is *virgin*, because it comes from an area covered by native vegetation and never altered by the application of fertilisers, herbicides and pesticides.

Table 1. Description of *L. angustifolius* varieties

	Sweet			Bitter
	Yorrel	Gungurru	Danja	Fest
Relative maturity	Very early	Early	Early	Late
Alkaloid genotype[a]	*iuc*	*iuc*	*iuc*	*Iuc*
Seed total alkaloids (mg kg^{-1} DM)[b]	70	170	200	15000

[a] *iucundus* is the gene for low alkaloids, recessive (*iuc*) in sweet and dominant (*Iuc*) in bitter varieties.
[b] Measured prior to planting.

Four cultivars of *L. angustifolius* were grown (Fest, Danja, Gungurru and Yorrel, details given in Table 1).

Pots were arranged in a randomised block design with four replicates. Lupin seeds were sieved to 5.5 mm, surface-sterilised in 0.1% (v/v) sodium hypochlorite (NaOCl) for 1–2 min and rinsed four times with deionised water. Ten seeds were sown in each pot on 29 May 1996. Each seed was inoculated with 1 ml Rhizobia suspension of *Bradyrhizobium* sp. (*Lupinus*) WU425. About 3 weeks after sowing, plants were thinned to three plants per pot. The soil surface of each pot was covered with alkathene beads to limit soil water evaporation, and watered daily to field capacity. Throughout the experiment, all pots were re-randomized once a week to minimise possible effects of location of the pots in the cooling units.

At flowering, one plant from each pot was removed for detailed growth analysis, while the remaining two plants were grown to maturity. At harvest (146 days after sowing for Yorrel, 150 for Danja and Gungurru, and 180 for Fest), plants were cut at ground level and air-dried in the glasshouse (max. temperature 60°C) for 6 days. Pods and seeds from main stem and uppermost branches (Dracup and Kirby, 1996) were collected separately and air-dried in the glasshouse for 6 days. The dry weight and number of pods and seeds, as well as dry weight of remainder of the plant parts above ground were recorded. The loss of leaves due to plant defoliation at harvest was similar in all treatments and was not considered in the dry weight of plant above ground parts.

Field experiments

Badgingarra experiment

A randomised block design experiment was conducted at Badgingarra (31° 48′ 94 S, 115° 45′ 18 E), WA in 1996, on a deep sandy soil classified as siliceous sand (Uc5.11) (Northcote, 1971). Soil pH was 5.0 (1:5 soil:0.01 M $CaCl_2$, w/v) in the 0–15 cm layer and 4.8 in the 15–50 cm layer. The soil had 9.4 g kg^{-1} organic C, low P (0–10 cm, 7.0 mg kg^{-1}) and K levels (0–60 cm, 21 mg K kg^{-1} soil; 60–100 cm, 34 mg K kg^{-1} soil) measured before the experiment began. The annual rainfall in 1996 was 594 mm with 490 mm falling in the May–October growing season. In the previous year (1995), seven levels of K (0–12.5–25–50–75–100–200 kg ha^{-1}) were applied to wheat. Plot size was 7.75 × 45 m for each main plot except the nil-K applied plot, which was 15.5 × 45 m. The nil-K plot was a different size because it would be split into five sub-plots to be fertilised with five K levels in the following year (1996).

In 1996, lupins were grown on all plots. The experiment in 1996 tested: (a) The effect of residual K from the 1995 wheat experiment on seed yield, alkaloid concentration and mineral content of lupins grown in 1996. (b) The effect of K application in 1996 to the plot that received nil K in 1995 on seed yield, alkaloid concentration and mineral content of lupins grown in 1996.

The plots of the nil-K treatment from 1995 were split for five K levels (0–12.5–25–50–75 kg ha^{-1}), each applied in 1996 to an area of 3.875 × 15 m of the original nil-K treatments.

Nyabing experiment

A randomised block design experiment was conducted at Nyabing (33° 32′ 04 S, 118° 08′ 08 E), WA in 1996. The soil at the site is classified as a yellow duplex soil (Dy) (Northcote, 1971). The 0–10 cm layer had pH 4.57 (1:5 soil:0.01 M $CaCl_2$, w/v), 7.7 mg kg^{-1} organic C and 18.3 mg kg^{-1} P. The corresponding values in the 10–40 cm layer were pH 5.21, 2.0 mg kg^{-1} organic C and 6.6 mg kg^{-1} P. The soil had low K levels (0–40 cm, 29 mg K kg^{-1} soil) measured before the experiment began. The annual rainfall in 1996 was 405 mm with 230 mm falling in the May-October growing season. In 1996, five levels of K (0–12.5–25–50–75 kg ha^{-1}) were applied to plots 7.75 × 45 m for the K fertilised plots and 15.5 × 45 m for the nil-K plots. The nil-K plot had a different size because it would to be split into five sub-plots to be fertilised with five K levels in the following year (1997), when wheat was grown.

Narrow-leafed lupin (cv. Gungurru) was sown at 120 kg ha^{-1} on 21 May 1996 at Badgingarra and on 26 June 1996 at Nyabing. Adequate phosphorus (P) fertiliser (Super Phosphate 120 kg ha^{-1} soil) containing basal Cu, Zn, Mn, B, Co and S, was drilled with the seed. The amounts of K were applied as KCl to the soil surface by hand 3 weeks after seeding. The herbicides applied to lupins were glyphosate as *Roundup* CT ® prior to seeding, diflufenican as *Brodal*® and fluazifop-P-butyl as *Fusilade*® after seeding. Insects were not controlled. Flowering times of lupin at Badgingarra and Nyabing were 22 August and 1 October and harvest times were 3 December and 11 December 1996, respectively. Grain was harvested at maturity using a plot harvester and yield was recorded.

Chemical analysis of the lupins

Seed samples were analysed for alkaloids and minerals (N, K, Ca, Mg, P, S) concentrations at the Chemistry Centre (WA). All chemicals used in the analysis were AR grade and organic solvents were re-distilled.

The seed was milled through a Newport grinder to pass through a 1 mm screen before chemical analysis.

Nitrogen

Total nitrogen (N) concentrations were measured on a Leco, FP-428, using the Dumas combustion technique (AOAC, 1999).

Mineral composition

The ground material was dissolved in concentrated nitric/perchloric acid in a block digestor (200–210°C). After cooling, the extracts were diluted with deionized water and analysed for minerals (K, Ca, Mg, P, S) by ICP-AES (McQuaker et al., 1979).

Alkaloids

Quinolizidine alkaloids were extracted by shaking ground seed in 5% trichloroacetic acid (TCA) for 2 h. After centrifugation at 3500 RPM, an aliquot of supernatant of each extract was transferred to separating funnels, made basic with 10 M sodium hydroxide (NaOH) and extracted with methylene chloride (CH_2Cl_2) (Harris and Wilson, 1988). The extracts were analysed by capillary gas chromatography (GC) (Priddis, 1983), with a Hewlett Packard (HP) 5890 GC equipped with a flame ionisation detector (FID) and a 25 m HP Ultra 1 dimethyl-polysiloxane column (0.32 mm inner diameter and 0.17 μm film thickness). Individual alkaloids were identified by comparison with authentic standard materials, and verified by Gas Chromatography/Mass Spectrometry (GC/MS), using a mass selective detector and the capillary column described for GC.

Table 2. Glasshouse experiment. Parameter values of curves fitted on square-root transformed data of total and individual alkaloids (mg kg^{-1} DM) of main stem seed of *L. angustifolius* varieties (cv. Fest, Danja, Gungurru and Yorrel), grown at different levels of applied K

L. angustifolius variety	a Asymptote	b Range	$a+b$ Intercept	k Rate	r^2 Correlation coefficient
			Total alkaloids		
Fest	175	3.4	178	2.68	0.02^{NS}
Danja	48	68	116	2.63	0.88^{***}
Gungurru	25	53	78	2.64	0.81^{***}
Yorrel	12	47	59	2.69	0.85^{***}
			Angustifoline		
Fest	69	1.8	71	2.68	0.02^{NS}
Danja	19	20	39	2.60	0.83^{***}
Gungurru	9	15	24	2.66	0.69^{**}
Yorrel	0.4	17	17	2.70	0.72^{**}
			13-Hydroxylupanine		
Fest	121	$0.66e^{-15}$	121	3.21	0.15^{NS}
Danja	32	28	60	2.58	0.86^{***}
Gungurru	17	23	40	2.56	0.72^{***}
Yorrel	2.9	23	26	2.70	0.76^{**}
			Lupanine		
Fest	113	−5.3	107	2.73	0.47^{NS}
Danja	30	60	91	2.65	0.88^{***}
Gungurru	17	45	62	2.64	0.85^{***}
Yorrel	10	40	50	2.68	0.85^{***}

***P <0.001.
**P <0.01.
*P <0.05.
^{NS}Not Significant.

Statistical analysis

The data were analysed using the Genstat 5.41 statistical software (Genstat 5 Committee, 1993). Alkaloid concentrations, seed yield and mineral concentrations were analysed by ANOVA to determine the effects of genotype, K concentration and their interactions. The relationship between grain yield or alkaloid concentration and level of K applied to the soil was modelled by the standard asymptotic curve

$$y = a + b \cdot e^{kx}$$

(Tables 2 and 3), where y represents either grain yield or seed alkaloid concentration, x is the level of K applied to the soil, a is the asymptote, b is the range, $a+b$ is the intercept, and k is the rate parameter of the fitted curve (Table 2). Comparisons between means are based on the standard error of the difference (SED).

Data were square-root transformed when necessary to normalize residuals, in which case SED applied only to transformed data. Transformed data were

Table 3. Glasshouse experiment. Relative proportions (% of total) of individual alkaloids in seed from the main stem of *L. angustifolius* cv. Fest, Danja, Gungurru and Yorrel grown at different levels of applied K

L. angustifolius variety	Applied K (mg K kg^{-1} soil)	Angustifoline	Lupanine (% of total)	13-Hydroxylupanine
Fest	0	15	36	47
	15	16	36	45
	60	16	36	46
	240	16	30	52
Danja	0	11	60	26
	15	11	63	24
	60	13	53	32
	240	16	40	42
Gungurru	0	10	65	24
	15	10	63	24
	60	13	54	31
	240	14	47	38
Yorrel	0	9	71	18
	15	9	67	22
	60	13	59	25
	240	8	59	31
$LSD_{0.05}$				
Applied K		1.9	4.7	3.0
Variety		1.9	4.7	3.0
Applied K × variety		3.8	9.4	6.1

back transformed where necessary for presentation of ordinary means in the results.

Results

Glasshouse experiment

Total alkaloids

Alkaloid concentrations had similar trends in seed from the main stem and uppermost branches. In the sweet varieties, Danja, Gungurru and Yorrel, total alkaloid concentrations (Figures 1a and 2a) fell with increasing amounts of applied K ($p<0.001$). Total seed alkaloid concentrations varied also among varieties ($p<0.001$), depending on their inherent alkaloid concentrations. By contrast, seed alkaloid concentrations in the bitter variety Fest were not affected by the application of K fertiliser. This contrasting response is the reason for the significant interaction ($p<0.005$) between variety and applied K fertiliser for alkaloid concentrations.

Seed alkaloid concentrations in sweet varieties were significantly higher than the maximum acceptable limit for release of new varieties in Western Australia (Culvenor and Petterson, 1986) and also higher than in the seed that was sown (Table 1). For example, the values for Danja ranged from 2300 to 13600 mg kg^{-1}DM in main stem seed and from 2600 to 13700 mg kg^{-1}DM in uppermost branch seed. Under K deficiency, seed alkaloid concentrations reached the highest value in Danja (Table 2, intercept). At adequate levels of K applied, the minimum value for seed alkaloid concentrations was observed in Yorrel (Table 2, asymptote).

The average alkaloid level in the bitter variety Fest was very high (30 700 mg kg^{-1}DM in main stem seed and 29 800 mg kg^{-1}DM in uppermost branch seed), independent of levels of K applied (Figures 1a and 2a)

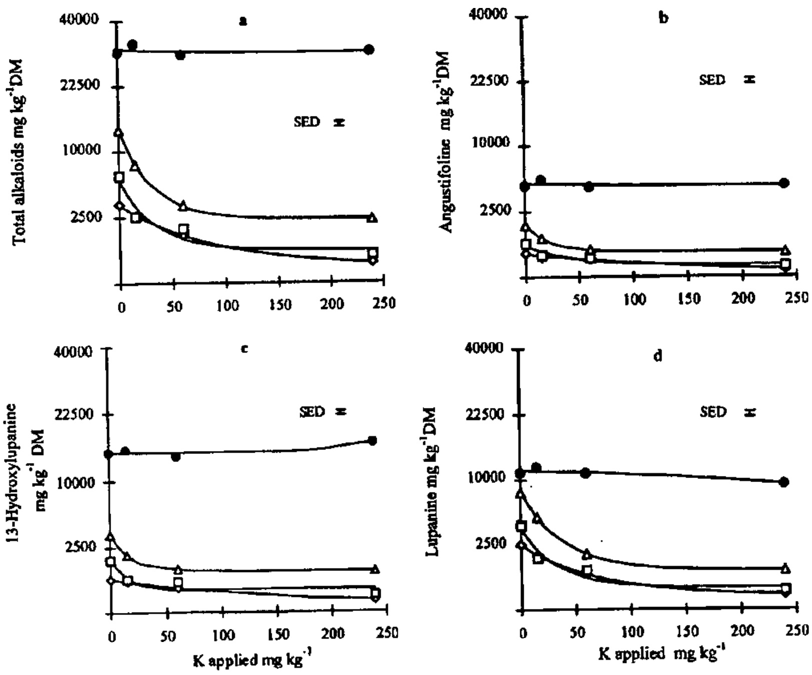


Figure 1. Glasshouse experiment. Total (a) and individual (b, c, d) alkaloid concentrations (mg kg^{-1} DM) in seed from the main stem of *L. angustifolius* cv. Fest (•), Danja (△), Gungurru (□) and Yorrell (◇) grown at different levels of applied K. Values are means of three replicates. Bars are standard errors of differences between means (SED). Data were square-root transformed before analysis of variance and estimation of the SED. Data on the Y-axis are back-transformed and Y scale is not linear.

and well above the seed alkaloid concentration of the seed that was sown (Table 1).

Individual alkaloids

Angustifoline, lupanine and 13-hydroxylupanine accounted for more than 98% of total alkaloids in sweet and bitter varieties (Table 3). The alkaloids α-isolupanine and isoangustifoline together contributed only to about 2% of total alkaloids found in lupin seed.

Lupanine predominated (40–70%) in the sweet varieties, while 13-hydroxylupanine (45–52%) was the main alkaloid in the bitter variety Fest (Table 3).

In the bitter variety, Fest, angustifoline, lupanine and 13-hydroxylupanine concentrations did not alter with the amounts of K applied (Figures 1b, c, d and 2b, c, d). In the sweet varieties, the concentrations of angustifoline ($p<0.001$), lupanine ($p<0.001$) and 13-hydroxylupanine ($p<0.001$) decreased asymptotically to a constant level at the increased amounts of applied K (Figures 1b, c, d and 2b, c, d).

Table 4. Glasshouse experiment. Parameter values of curves fitted on data of total seed yield (g $plant^{-1}$) of *L. angustifolius* cv. Fest, Danja, Gungurru and Yorrel, grown at different levels of applied K

L. angustifolius variety	*a* Asymptote	*b* Range	*a* + *b* Intercept	*k* Rate	r^2 Correlation coefficient
Fest	2.52	−0.56	1.96	2.52	0.38*
Danja	4.12	−1.32	2.80	2.50	0.47**
Gungurru	4.49	−2.09	2.39	2.68	0.86***
Yorrel	3.90	−1.98	1.92	2.60	0.88***

*** $P<0.001$.
**$P<0.01$.
*$P<0.05$.

Seed yield

Total yield (main stem and upper branch seed) of sweet and bitter genotypes increased significantly ($p<0.001$) with increasing amounts of applied K fertiliser (Figure 3a, Table 4). Although the yield plateau for the relationship between yield and K applied was reached at 60 mg K kg^{-1} soil for all varieties, there

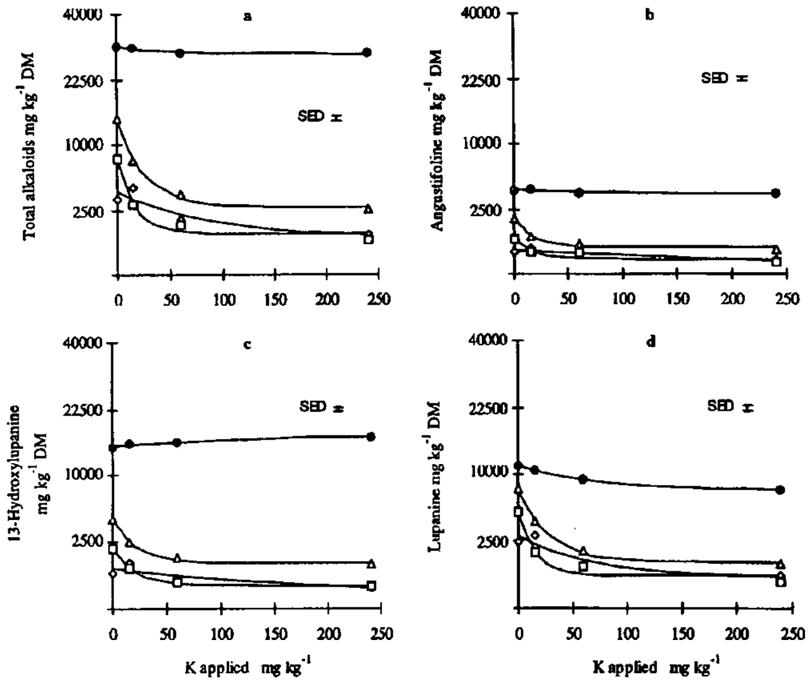


Figure 2. Glasshouse experiment. Total (a) and individual (b, c, d) alkaloid concentrations (mg kg^{-1} DM) in seed from the uppermost branches of *L. angustifolius* cv. Fest (•), Danja (△), Gungurru (□) and Yorrell (◇) grown at different levels of applied K. Values are means of three replicates. Bars are standard errors of differences between means (SED). Data were square-root transformed before analysis of variance and estimation of the SED. Data on the Y-axis are back transformed and Y scale is not linear.

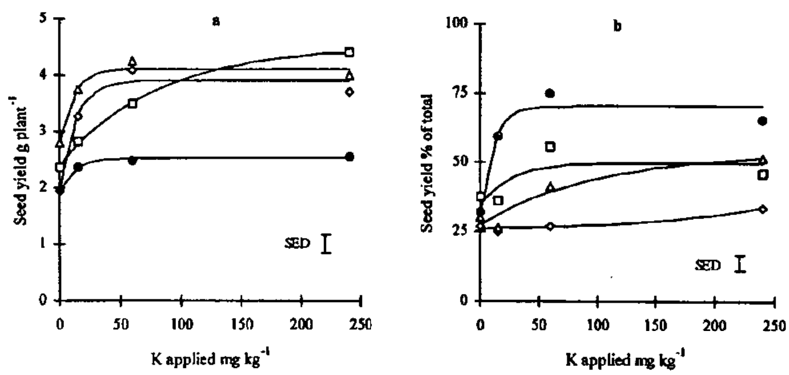


Figure 3. Glasshouse experiment. Seed yield (g plant^{-1}) (a) and contribution of main stem seed to seed yield (b) in *L. angustifolius* cv. Fest (•), Danja (△), Gungurru (□) and Yorrell (◇) grown at different levels of applied K. Values are means of three replicates. Bars are standard errors of differences between means (SED).

were significant differences (p<0.001) in seed yield among varieties.

Under severe and mild K deficiency, the main stem seed of the sweet varieties contributed only 26–35% (Figure 3b) to total seed yield. In the sweet varieties, Danja and Gungurru, when adequate and abundant amounts of K were applied, seed from both main stem and uppermost branches contributed about 50% of total seed yield (Figure 3b). In Yorrel, the highest percentage of seed yield (about 74%) was observed from the uppermost branches, independent of the amounts of K applied (Figure 3b).

Table 5. Glasshouse experiment. Total concentrations of N, K, Ca, Mg, P and S in seed from both main stem and uppermost branches of *L. angustifolius* cv. Fest, Danja, Gungurru and Yorrel grown at different levels of applied K

L. angustifolius variety	Applied K ($mg\ K\ kg^{-1}$ soil)	Mineral concentration ($g\ kg^{-1}$ DM) N	K	Ca	Mg	P	S
Fest	0	56	4.6	2.5	1.4	2.8	3.5
	15	55	5.8	3.0	1.7	2.8	4.2
	60	51	4.9	2.4	1.4	2.1	3.5
	240	51	5.3	2.3	1.4	1.9	3.5
Danja	0	56	6.4	3.2	1.5	3.8	3.2
	15	56	6.5	2.9	1.4	2.8	3.2
	60	57	8.2	2.7	1.5	2.7	3.7
	240	51	9.0	2.5	1.8	2.3	3.8
Gungurru	0	59	6.2	3.1	1.5	3.7	2.6
	15	56	6.9	2.9	1.5	3.1	2.7
	60	57	7.5	2.9	1.3	3.0	3.7
	240	58	9.4	2.4	1.8	2.4	3.5
Yorrel	0	61	8.0	3.3	1.7	4.6	3.8
	15	59	7.6	3.3	1.6	3.4	3.5
	60	59	8.0	3.2	1.7	3.2	3.4
	240	57	9.2	2.7	2.0	2.7	3.2
$LSD_{0.05}$							
Applied K		1.7	0.65	0.34	0.21	0.36	0.48
Variety		1.7	0.65	0.34	0.21	0.36	0.48
Applied K × variety		3.4	1.30	0.69	0.43	0.73	0.95

In the bitter variety, Fest, the main stem seed contributed 32% of total yield under severe K deficiency, whilst it was the major contributor (60–75%) to total yield when K was applied (Figure 3b).

Mineral composition

As amounts of applied K fertiliser increased, so did the concentrations of K and Mg in the seed from both main stem and upper branches of sweet varieties. Concentrations of Ca and P decreased with increased amounts of applied K in the sweet varieties, but did not change in the bitter variety Fest (Table 5). Concentrations of S in seed of all varieties were not affected by K supply. Only in the sweet varieties did the concentrations of N increase at adequate K levels, due to the significant effect of K applied (p=0.003) and variety (p<0.001) (Table 5).

Field experiments

Total alkaloids

Results for the two field trials relating K nutrition of lupins to total seed alkaloid concentrations are shown in Figure 4a.

Badgingarra experiment

There was a significant (p <0.05) reduction in the level of alkaloids where K fertilizer was applied in the current year. Total seed alkaloid concentrations decreased significantly (p<0.05) with increasing amounts of K applied in 1996 (Figure 4a). Although the residual effect of K applied in 1995 was not significant on total alkaloid concentration of seed harvested in 1996, the trend was for lower alkaloid concentrations at high rates of applied K (Figure 4a).

Nyabing experiment

Total alkaloid concentrations in the seed were not affected significantly by the amounts of K fertiliser applied (Figure 4a).

Alkaloid concentrations were significantly (p<0.001) lower in seed from Nyabing than in that from Badgingarra.

Individual alkaloids

Badgingarra experiment

The predominant alkaloids in the lupin seeds were angustifoline, lupanine, and 13-hydroxylupanine. The concentrations of angustifoline, lupanine and 13-hydroxylupanine decreased significantly (p<0.05, p<0.001 and p<0.05, respectively) with increased applied K levels only when plots were fertilised in 1996 (Figure 4b, c, d). However, the relative proportions of seed individual alkaloids (% of total) did not vary with increased amounts of K applied (data not shown).

Nyabing experiment

Angustifoline was not detectable in the seed and the concentrations of lupanine and 13-hydroxylupanine were not affected by applied K rates (Figure 4b, c).

Seed yield

Seed yield at both sites was not significantly affected by amounts of K applied (Table 6).

Seed yield was significantly higher at Nyabing than at Badgingarra (p<0.01) (Table 6).

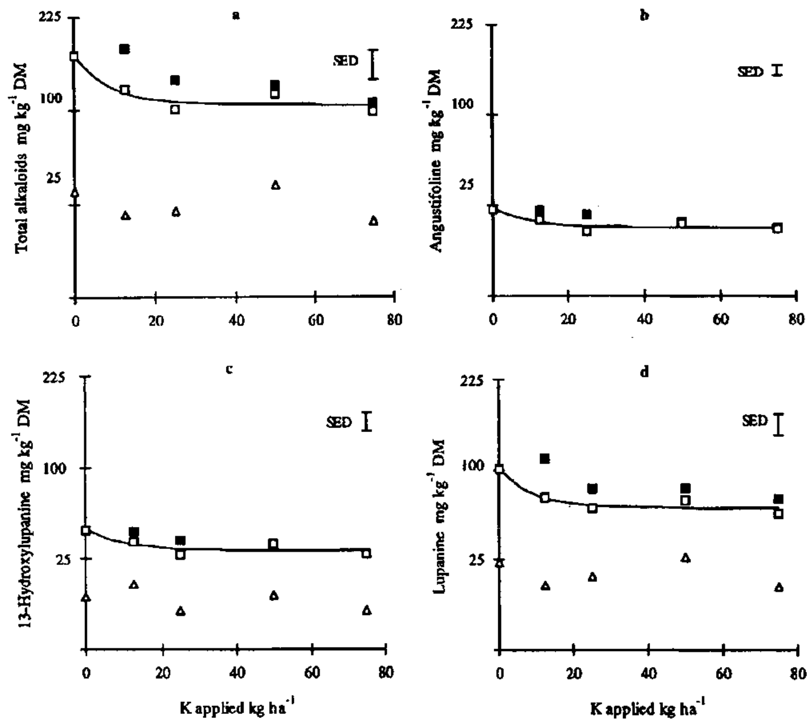


Figure 4. Field experiments. Total (a) and individual (b, c, d) alkaloid concentrations (mg kg^{-1} DM) in seed of *L. angustifolius* cv. Gungurru grown on plots with different levels of applied K at Badgingarra (K applied either in 1995 ■ or in 1996 □) and at Nyabing (K applied in 1996 △), WA. Values are means of two replicates. Bars are standard errors of differences between means (SED). Data were square-root transformed before analysis of variance and estimation of the SED. Data on the Y-axis are back-transformed and Y scale is not linear.

Table 6. Field experiments. Seed yield of *L. angustifolius* cv. Gungurru from plots fertilized with different levels of K applied at Badgingarra in 1995 and 1996, and Nyabing in 1996

Applied K (kg ha^{-1})	Seed yield (kg ha^{-1})		
	Badgingarra		Nyabing
	1995	1996	1996
0	1421	1421	1575
12.5	1419	987	1685
25	1427	1141	1491
50	1377	1129	1494
75	1403	983	1612
ANOVA *F* ratio			
Applied K	0.368^{NS}	0.472^{NS}	0.455^{NS}
Location	0.009^{**}		
Applied K × location	0.620^{NS}		

Mineral composition

For both sites, there were no significant trends of applied K on mineral concentration of seed (data not shown). Seed K, Mg and P concentrations were always significantly higher and Ca concentrations lower at Nyabing than at Badgingarra ($p<0.005$).

Discussion

Total alkaloids

Potassium deficiency increases seed alkaloid concentrations and may depress seed yield in the sweet varieties (Danja, Gungurru, Yorrel) of *L. angustifolius*. In these varieties, the concentration of seed alkaloids increased with K deficiency both in the glasshouse and in the field experiment at Badgingarra. The decrease of seed alkaloids to applied K was similar to an exponential decay curve that reached its minimum value when K supply was adequate. The plateau for the alkaloid concentration at adequate K varied greatly from the glasshouse to the field, and from variety to variety. The shape of the decay curve was also subject to genotype × environment interactions, with the bitter variety Fest showing no increase in seed alkaloid concentrations under K deficiency.

Similarly, Scibor-Marchocka (1970) found that in *L. albus* seed alkaloid concentrations decreased in the sweet variety but did not vary in the bitter variety, with increased amounts of applied K fertiliser. The reasons for this difference between bitter and sweet varieties in their response to applied K and level of alkaloid expression are not known.

In the field, at Nyabing, the *L. angustifolius* sweet variety Gungurru showed no reduction in the concentration of alkaloids with increasing rates of applied K, despite a low level of soil K in the top 40 cm. The site was on a duplex soil characterised by a sandy textured topsoil overlying clay. Lupin roots would have rapidly reached the 40 cm depth to the clay layer where they were likely to have sufficient K available to be non-responsive to K both for grain yield and alkaloid concentrations.

Individual alkaloids

The proportion of lupanine was greater in the sweet varieties (40–70%), whereas in the bitter variety Fest the most abundant alkaloid was 13-hydroxylupanine (45–52%). Scibor-Marchocka (1970) reported higher lupanine than 13-hydroxylupanine concentrations in both sweet and bitter varieties of *L. albus*. Our contrasting results of the percentage of alkaloid in sweet and bitter *L. angustifolius* varieties may be explained by species differences (Nowacki and Waller, 1970).

An unexpected result was the high alkaloid levels of seed of both sweet and bitter lupins grown in the glasshouse, compared with seeds produced in the field experiments. This may be due to the synergistic effect of other environmental stresses, such as high light energy and air temperatures in a glasshouse (Connellan, 1996), together with the limited rooting space available in the pots (Bar-Tal, 1999). It is well known that plants grown on K-deficient soils are more susceptible to a range of environmental stresses (Marschner, 1995) and in the case reported here may respond by increasing the production of alkaloids.

Seed yield

Grain yield responded to K application in the glasshouse and yield per plant reached a maximum with the addition of 60 mg K kg^{-1}, equivalent to 90 kg K ha^{-1}.

Interestingly, the main stem seed contributed only one third of total yield under K deficiency in both bitter and sweet varieties. At adequate and abundant levels of K applied seed yield on main stem increased but overall, the upper branches were the main contributors to yield in all sweet varieties. This is a typical feature of narrow-leafed lupins (Dracup and Kirby, 1996).

The lack of yield response by lupin to applied K fertiliser at both Badgingarra and Nyabing was not expected, as soil K levels in the upper layer of soil at both sites was well below the 40 mg K kg^{-1} soil, usually considered to be critical levels to achieve a K response in lupin (Cox, 1978).

The higher yield at Nyabing was most probably due to a high K concentration on the clay close to the surface (40 cm depth) to be well within reach of lupin roots. This situation is in contrast to that at Badgingarra, where the trial site was on a deep sand. However, this study showed that the level of soil K was increasing with depth (0–60 cm 21 $\mu g\ g^{-1}$ soil, 60–100 cm 35 $\mu g\ g^{-1}$ soil). Lupin roots grow to about 2 m in the deep sands of WA and can access a greater volume of soil with higher K levels (Dracup and Kirby, 1996; Hamblin and Hamblin, 1985; Rowland et al., 1986). Lupin roots can extract K from a greater depth of soil than other crop plants (Perry et al., 1998; Rowland et al., 1986). Even when grown on K-deficient Australian sandplain soils, narrow-leafed lupins may increase the K levels of the surface 10 cm of soil without showing seed yield response to added K fertilisers (Rowland et al., 1986). On the duplex soil at Nyabing, lupin roots may have obtained sufficient K to suppress a yield response to applied K. This different response to soil K status of grain yield and alkaloid concentrations deserves further research since the critical soil concentrations are different in these two cases.

Seed mineral composition

There were significant variations in the seed mineral concentrations with applied K when narrow-leafed lupins were grown in the glasshouse. There were no effects of applied K on the mineral concentrations of the seed in the field experiments, although there were differences in the total levels of different minerals between sites (K, P and mg were higher at Nyabing whereas Ca was higher at Badgingarra).

These results clearly illustrate the difficulties of obtaining a clear-cut response in a stratified heterogenous soil in the field, as compared to the controlled situation in the glasshouse.

Conclusion

K deficiency stimulates seed alkaloid accumulation and may depress seed yield in the sweet genotypes of *L. angustifolius*. Although the same amounts of K applied may have different effects on different soil types, regular and adequate application of K fertiliser to K-deficient soils in the lupin growing areas of WA is essential to keep the seed alkaloid concentration under the current maximum acceptable level of 200 mg kg^{-1} DM (Culvenor and Petterson, 1986).

Further research is needed to understand the effect of other environmental factors stimulating alkaloid production in *L. angustifolius*, including high light energy and air temperature, such as it may occur in a glasshouse environment.

Acknowledgements

We acknowledge the Grains Research and Development Corporation (GRDC) for funding the two projects (UWA 168 and CSO 148). We gratefully acknowledge also Prof. W. Cowling, Dr N. Galwey, Prof. Z. Rengel and Dr C. Tang for critically reviewing the manuscript.

References

Allen D G, Greirson B N, Harris D J and Spadek Z E 1990 Alkaloid profiles of various lupin species. Chemistry Centre Western Australia, Occasional Report No. 89B28804-55, Perth, WA. 13 p.

AOAC 1999 Official Methods of Analysis of AOAC International. 16th Edition, 5th revision, Method 4.2.04 (968.06). Ed. P Cunniff. p 13. AOAC International, Gaithersburg, MA, USA.

Bar-Tal A 1999 The significance of root size for plant nutrition in intensive horticulture. *In* Mineral Nutrition of Crops – Fundamental Mechanisms and Implications. Ed. Z Rengel. pp 115–139. Food Product Press®, The Haworth Press Inc, Birghmanton, N Y.

Connellan G 1996 The pursuit of optimum environments in Australian greenhouses. Eds. C Kubota, K Fujiwara, Y Ibaraki and S Sase. pp 159–164. Proceedings of the International Symposium on Plant production in closed ecosystems. Acta Hort. 440, August 1996. ISHS, Tokyo, Japan.

Cox W J 1978 Potassium deficiency in lupins – identification, rates, times and method of application. J. Agric. West. Aust.19, 27–31.

Croteau R, Kutchan T M and Lewis N G 2000 Natural products (secondary metabolites). *In* Biochemistry and Molecular Biology of Plants. Eds. B Buchanan, W Gruissem and R Jones. pp 1250–1318. American Society of Plant Physiologists, Rockville, MD USA

Culvenor C C J and Petterson D S 1986 Lupin toxins – alkaloids and phomopsins. pp. 188–198. Proceedings of the 4th International Lupin Conference, August 1986. Dept Agric.WA, Perth, WA.

Dracup M and Kirby E J M 1996 Lupin development guide. U W A Press, Perth, WA, Australia. 97 p.

Edwards N K 1993 Distribution of potassium in the soil profile of a sandplain soil under pasture species. Plant Soil 155, 407–410.

Edwards N K 1995 Potassium nutrition of lupins in the sandplain soils of Western Australia. Final Rep. Plant Ind. Div., Dept Agric.WA, Perth, WA. 13 p.

Genstat 5 Committee 1993 Genstat 3 Reference Manual, Clarendon Press, Oxford, UK. 796 p.

Gladstones J S 1970 Lupins as crop plants. Field Crop Abs. 23, 2, 123–148.

Gremigni P, Hamblin J and Harris D 1997 Alkaloid level in lupin seed is affected by nutritional stresses. Proceedings of the International Food Legume Research Conference III, September 1997. Adelaide, SA. 143 p.

Gremigni P, Gazey C, Hamblin J and Harris D 1998 Soil nutritional status affects alkaloid levels in Australian sweet lupin. Proceedings of the 3rd European Conference on Grain Legumes, November 1998. AEP, Paris, France. 179 p.

Gremigni P, Hamblin J and Harris D 1999 Genotype × environment interactions and lupin alkaloids. Eds. E Van Santen, M Wink, S Weissman and P Romer. pp 362–365. Lupin – An ancient crop for the new millennium. Proceedings of the 9th International Lupin Conference, June 1999. Klink-Müritz, Germany.

Hamblin A P and Hamblin J 1985 Root characteristics of some temperate legume species and varieties on deep, free-draining entisols. Aust. J. Agric. Res. 36, 63–72.

Harborne J B and Baxter H 1993 Phytochemical Dictionary. Eds. Taylor & Francis. pp 284–289. London, UK.

Harris D J 1994 Quality production and breeding. Eds. M Dracup and J Palta. pp 98–105. Proceedings of the 1st Australian Lupin Technical Symposium, October 1994. Dept Agric.WA, Perth, WA.

Harris D and Wilson P E 1988 A rapid manual method of lupin alkaloid analysis. Ed. T Twardowski. pp 598–601. Proceedings of the 5th International Lupin Conference, July 1988. Poznan, Poland.

Hartmann T 1988 Secondary metabolism of lupins: biosynthesis, translocation and accumulation of the quinolizidine alkaloids. Ed. T Twardowski. pp 64–78. Proceedings of the 5th International Lupin Conference. Poznan, Poland.

Lowen R, Alam F K A and Edgar J A 1995 Lupin bean toxicity. Med. J. Aust. 162, 256–257.

McQuaker N R, Brown D F and Fluckner P D 1979 Digestion of environmental materials for analysis by inductively coupled plasma - atomic emission spectrometry. Anal. Chem. 51, 1082–1084.

Marschner H 1995 Functions of mineral nutrients: macronutrients. *In* Mineral Nutrition of Higher Plants. Ed. H Marschner. pp 299–312. Academic Press, London, UK.

Northcote K H 1971 A factual key for the recognition of the Australian soils. Rellim Glenside, S A. 123 p.

Nowacki E K and Waller G R 1970 Quinolizidine alkaloids from Leguminosae. Rev. Latinoamer. Qufm. 8, 49–56.

Perry M W, Dracup M, Nelson P, Jarvis R, Rowland I and French R J 1998 Agronomy and farming systems. *In* Lupins as Crop Plants: Biology, Production and Utilisation. Eds. JS Gladstones, CA Atkins and J Hamblin. pp 291–338. CAB International, Wallingford, UK.

Petterson D S, Sipsas S and Mackintosh J B 1997 The chemical composition and nutritional value of Australian pulses. pp 7–9. Grains Research & Development Corporation, Canberra, ACT.

Priddis C R 1983 Capillary gas chromatography of lupin alkaloids. J. Chrom. 261, 95–101.

Rana J and Robins D J 1985 Biosynthesis of quinolizidine alkaloids, incorporation of [1-amino-^{15}N,1-^{13}C] cadaverine into lupanine, 13-hydroxylupanine, and angustifoline. J. Chem. Res. (S), 196–197.

Rayment G E and Higginson F R 1992 Australian laboratory handbook for soil and water chemical methods. Australian soil and land survey handbook. Inkata Press, Melbourne, VIC, Australia. 330 p.

Robins D J 1987 Synthesis of [1,2-$^{13}C_2$] cadaverine and its incorporation into five quinolizidine alkaloids. J. Chem. Res. (S), 256–257.

Rowland I C, Mason M G and Hamblin J 1986 Effects of lupins on soil fertility. pp 96–111. Proceedings of the 4th International Lupin Conference, August 1986. Dept Agric.WA, Perth, WA.

Scibor-Marchocka A 1970 Comparative studies on the homologous types of bitter and fodder white lupine. Acta Agrobot. 23(1), 23–38.

Tang C 1998 Factors affecting soil acidification under legumes I. Effect of potassium supply. Plant Soil 199, 275–282.

Thomson B D and Perry M W 1995 A guide to selecting grain legumes for your soil. pp 1–8. CLIMA, Perth, WA.

Walkley A and Black I A 1934 an examination of the Degtjareffe method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29–38.

Waller G R and Nowacki E K 1978 Alkaloid biology and metabolism in plants. Plenum Press, New York. 294 p.

Walton G H and Francis C M 1975 Genetic influences on the split seed disorder in *Lupinus angustifolius* L. Aust. J. Agric. Res. 26, 641–646.

Wink M 1987 Quinolizidine alkaloids: Biochemistry, metabolism and function in plants and cell suspension cultures. Planta Med. 53, 509–514.

Wink M 2000a Functions of plant secondary metabolites and their exploitation in biotechnology. Vol. 3 of Annual Plant Reviews, Sheffield Academic Press. 362 p.

Wink M and Hartmann T 1982 Localisation of the enzymes of quinolizidine alkaloid biosynthesis in leaf chloroplasts of *Lupinus polyphyllus*. Plant Physiol. 70, 74–77.

Wong M T F, Edwards N K and Barrow N J 2000a Accessibility of subsoil potassium to wheat grown on duplex soils in the southwest of Western Australia. Aust. J. Agric. Res. 38, 745–751.

Wong M T F, Gilkes R J, Edwards N K and Pal Y 2000b Using recently acquired knowledge to manage potassium sustainability in the wheatbelt. pp 86–93. Proceedings of Soils 2000, Muresk Institute of Agriculture, July 2000. Northam, WA, Australian Society of Soil Science Inc. (WA Branch).

Section editor: F.R. Minchin

Aust. J. Soil Res., 2001, **39**, 611–625

Soil factors affecting the availability of potassium to plants for Western Australian soils: a glasshouse study

Y. Pal[A], *R. J. Gilkes*[A], *and M. T. F. Wong*[B]

[A]Department of Soil Science and Plant Nutrition, The University of Western Australia, Nedlands, WA 6009, Australia.
[B]CSIRO Land and Water, Private Bag PO, Wembley, WA 6014, Australia.

Abstract

A glasshouse experiment was conducted with 41 surface and 8 subsurface soils to measure their potassium (K) supply capacities and K depletion of soils by ryegrass growth for 260 days and harvesting at ~40-day intervals. Dry matter yield ranged from 0.22 g to 25.4 g/kg soil, cumulative K uptake ranged from 0.006 to 1.49 cmol/kg soil, and values of K concentration (%) in the first cut herbage ranged from 0.40% to 5.97%. Some of the light-textured soils were so impoverished in K that symptoms of K deficiency appeared during the first growth period. Water-soluble K + exchangeable K accounted for 43–100% of cumulative K uptake by the ryegrass. Multiple regression analysis indicated that 68% of the variation in dry matter yield and 90% of the variation in K uptake may be predicted by the exchangeable K content of these soils. The 6 harvests of ryegrass extracted only 0.21–12.07% of total K from these soils, which was not sufficient to cause discernible mineralogical changes in most soils. For some soils vermiculite was formed at the expense of illite/mica by K release to plants. For soils containing vermiculite but no other K-bearing clay minerals, vermiculite peaks broadened on K depletion by plants. Major proportions of total K in these soils are present in silicate minerals, yet only minor amounts are released to plants by very slow weathering processes. For soils that do not contain any K bearing clay minerals, very minor amounts of feldspar may have dissolved to release K.

Additional keywords: feldspar, vermiculite, illite, exchangeable-K.

Introduction

Chemical methods are commonly used to predict the potassium (K) fertility of soils, through establishing relationships between the chemical measure and K uptake by plants. Exhaustive cropping techniques combined with chemical analyses are useful in evaluating plant uptake of the various forms of soil K in soils (Martin and Sparks 1985). For particular soil–plant systems, the suitability of an extractant for predicting K supply depends on how closely the extraction of K indicates the actual uptake of K by plants. Therefore, the success of a chemical method for evaluating K supply to plants depends on its ability to predict the immediately available K, which is generally assumed to be solution K plus exchangeable K, as well as the rate of replenishment (Kirkman *et al.* 1994). Such extractants are generally dilute salt solutions or resins and do not provide an indication of the rate of replenishment of these pools from non-exchangeable K forms. In regions of low K soil fertility, and under conditions of continuous export of agricultural products, it is likely that the readily available forms of K will become depleted and need to be replenished from other forms in the absence of K fertilisation.

Potassium deficiency is common throughout the agricultural region of Western Australia (Carroll 1961; Cox 1973). Pasture legumes are particularly susceptible to K deficiency but foliar symptoms of K deficiency in cereals occur only at very low soil K levels (<40 mg/kg soil $NaHCO_3$-K, Wong and Wittwer 1997), whereas yield will be depressed at much higher levels. Muriate of potash (KCl) at 50–100 kg/ha is usually recommended to overcome potassium deficiency of cereals and pastures. Although K fertiliser usage in Western Australia has progressively increased since 1990, very little K fertiliser is applied to crops

 10.1071/SR00030 0004-9573/01/030611

(average 0.2 kg K/ha) and pastures in the low to medium rainfall region (350–650 mm/year) (Reuter *et al.* 1997*a*). Many soils of this region are very weathered and highly infertile with little exchangeable K (Robson and Gilkes 1980). The continuing export of K in primary produce is regarded as the 'mining' of the meagre K reserves of these soils. It is essential, therefore, to quantify the amounts and forms of soil K reserves, and determine if K in poorly soluble forms becomes available under conditions of extreme K depletion. There is little knowledge of K reserves and no knowledge of mineralogical changes associated with K depletion for these highly weathered soils (Norrish and Pickering 1983; McArthur 1991). To meet the above objectives, perennial ryegrass was grown on these soils in a glasshouse for 260 days to deplete the plant-available K. The depleted soils were analysed for changes in mineralogical and chemical composition.

Materials and methods

A glasshouse experiment was conducted on 41 representative surface and 8 subsurface soils from virgin sites (Table 1) to assess K supply capacities and associated mineralogical changes on exhaustive K depletion of these soils using perennial ryegrass (*Lolium perenne* cv. Roper). The soils included highly weathered lateritic material and younger, more fertile soils on alluvial and aeolian deposits. To permit rapid removal of K by cropping, a large number of plants in small containers were used (15-cm-diam. plastic pots with polyethylene liners containing 1 kg of air-dry soil per pot). To ensure that general nutrient supply did not limit plant growth, a basal nutrient application consisting of $MgSO_4.7H_2O$, 23 mg/kg soil; $MnSO_4.4H_2O$, 15 mg/kg soil; $ZnSO_4.7H_2O$, 9 mg/kg soil; $CuSO_4.5H_2O$, 4 mg/kg soil; H_3BO_3, 0.8 mg/kg soil; $CoSO_4.7H_2O$, 0.4 mg/kg soil; $NaMoO_4.2H_2O$, 0.7 mg/kg soil; $NH_4H_2PO_4$, 148.4 mg/kg soil and NH_4NO_3, 105.05 mg/kg soil (Jarvis and Robson 1983) was applied initially and after each harvest and a second application of the same amount of NH_4NO_3 only was given 20 days after each harvest. The first basal dose was given before initiation of the experiment and soils were allowed to equilibrate for a week at field capacity. Thirty ryegrass seeds were sown in each pot and thinned to 20 uniform plants after emergence. The first two attempts to establish a satisfactory density of ryegrass were unsuccessful due to variable germination but a third attempt succeeded. Seeds contained 0.18% K, thus on average 5.32 mg K was added to each pot in seeds from the 3 sowings.

Soils were watered daily to field capacity with deionised water, watering twice daily during hot weather, to prevent serious water stress. Visual estimation of plant stress became the main criterion for watering. Ryegrass was harvested 6 times consecutively at approximately 5–6-week intervals at about 1.5 cm above the soil surface and plant dry matter weight was determined after 24 h drying at 70°C in a forced-air oven. Entire plant samples were ground for K determination. For K analysis, plant material was digested in a 3:1 nitric:perchloric acid mixture and the K concentration of the plant digest was determined by flame photometry. The plant roots could not be included in this investigation because plants ceased to grow at different times, resulting in decay of roots by the time of the final harvest and collection of the soil. The experiment was terminated 260 days after sowing when there was no further plant growth in any pot (except for the GTN 9 and MER 2 soils) due to severe K deficiency. A 50-g sample of soil was collected from each pot using a tube auger; this soil was used for the chemical determination of various K forms.

Water-soluble K was determined by extraction of 4 g soil with 20 mL deionised water for 1 h end-over-end shaking. Exchangeable K was determined by extraction of 0.5 g soil with 20 mL of unbuffered 0.01 M silver thiourea $(AgTU)^+$ for 16 h with end-over-end shaking followed by centrifugation (Rayment and Higginson 1992) and values were adjusted for the water-soluble K form. One molar HNO_3-extractable K (HNO_3-K) was determined by boiling 2 g of soil in 20 mL 1 M HNO_3 at 113°C for 25 min, followed by washing with 0.1 M HNO_3 and making the final volume to 100 mL with deionised water (Pratt 1965). A measure of potentially available K defined as non-exchangeable K was determined as the difference between HNO_3-K and $(AgTU)^+$-K (water-soluble K + exchangeable K). Total K in soils was determined using X-ray fluorescence spectrometry (Norrish and Chappell 1967).

Results and discussion

Dry matter yield, tissue %K concentration, and K uptake of ryegrass

Representative plots for 6 ryegrass harvests dry matter yield, tissue %K concentration, and K uptake for 6 surface and subsurface soils are shown in Fig. 1. These plots show that there

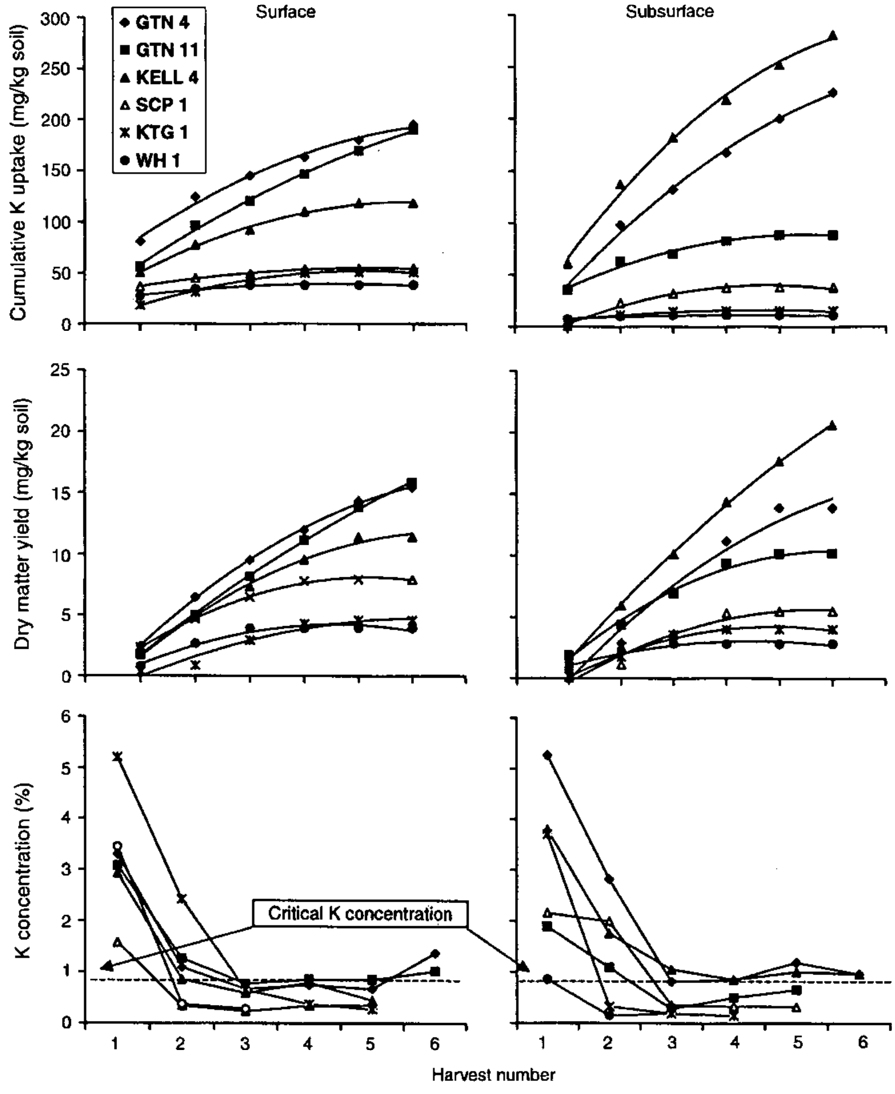


Fig. 1. Representative plots of ryegrass dry matter yield, %K concentration, and K uptake at various harvests for 6 surface and subsurface horizon soils.

are large variations in the dry matter yield and K uptake by ryegrass. Since adequate levels of all the basal nutrients except K were added, these variations in plant growth response and K uptake are due to differences in properties of these soils (Table 1).

For soils MRA 5, MRA 6, MRA 8, and GTN 10, plants died immediately after the first harvest, and for soils SCP 11 and MER 1, plants died after the second harvest. All the mentioned soils were highly weathered, nutrient-deficient siliceous sands. For soils

Table 1. Classification, parent material, and physical and chemical properties of the surface and subsurface (b) soil horizons

Note location, classification, parent material, and field texture are as described in 'Reference soils of south-western Australia' (McArthur 1991). EXK, exchangeable K; NEK, non-exchangeable K; H_2O-K, water-soluble K; OC, organic carbon

Location	Classification	Parent material	Texture	pH (H_2O) (1:5)	EC (mS/m)	OC (%)	Clay (%)	CEC	H_2O-K [cmol(+)/kg soil]	EXK [cmol(+)/kg soil]	NEK [cmol(+)/kg soil]	HNO_3-K [cmol(+)/kg soil]	$NaHCO_3$-K [cmol(+)/kg soil]	Total K [cmol(+)/kg soil]
SCP 1	Typic Haploxerult	Weathered granite and laterite on Darling Plateau	LS	5.5	3	1.4	7	2	0.07	0.13	0.09	0.29	0.07	43.77
SCP 1b			SC	5.5	2	0.1	31	4	0.02	0.11	0.05	0.18	0.06	30.26
SCP 5	(Plinthic) Eutrudox	Alluvium from Darling Plateau	L	5.6	4	3.3	21	9	0.06	0.34	0.34	0.74	0.22	19.32
SCP 6	Typic Eutrudox	Alluvium from Darling Plateau	Si L	5.9	4	7.0	20	17	0.16	0.93	0.88	1.97	1.02	28.16
SCP 11	Dystric Xeropsamment	Siliceous sand	LS	5.8	1	1.2	1	6	0.01	0.03	0.00	0.05	0.03	3.09
KO 1	Natric Abruptic Durixeralf	Alluvium from Beaufort River	LS	5.7	5	0.7	4	2	0.04	0.10	0.16	0.30	0.09	52.20
KO 2	Typic Palexeralf	Weathered granite	SL	5.8	11	4.6	33	11	0.04	0.18	0.09	0.31	0.10	5.84
KO 2A	Ultic Haploxeralf	Weathered dolerite	SL	5.6	5	4.5	11	6	0.11	0.12	0.22	0.45	0.19	20.83
MRA 1	Calcic Natric Palexeralf	Riverine alluvium from Moore River	L	5.9	4	2.6	16	7	0.07	0.58	0.60	1.25	0.30	27.85
MRA 5	Dystric Xeropsamment	Cretaceous sandstones	S	6.0	1	0.3	1	1	0.01	0.02	0.00	0.03	0.01	0.44
MRA 6	Dystric Xeropsamment	Cretaceous sandstones	S	5.3	1	0.4	1	1	0.01	0.03	0.00	0.04	0.06	0.74
MRA 8	(Pale)xeralf	Cretaceous sandstones and shales	LS	5.4	1	0.5	4	2	0.01	0.05	0.00	0.06	0.05	1.22
MRA 9	Typic Xeropsamment	Cretaceous sandstones and shales	LS	6.1	1	0.4	6	1	0.01	0.06	0.01	0.08	0.06	1.28
WH 1	Ultic Haploxeralf	Colluvium from weathered granite	SL	5.8	1	1.0	11	2	0.01	0.11	0.07	0.19	0.08	18.93
WH 1b			LC	5.7	15	0.3	40	4	0.00	0.04	0.09	0.13	0.06	11.79
WH 2	Calcic Ultic Haploxeralf	Weathered dolerite	SL	5.8	2	0.7	4	1	0.03	0.09	0.02	0.14	0.08	6.13
WH 3	Aquic Eutrudox	Siliceous residue from weathered granite	LS	5.5	1	0.3	5	1	0.01	0.07	0.04	0.12	0.08	4.12
GTN 4	Dystric Eutrochrept	Alluvium from Chapman River	SL	6.0	5	0.9	3	4	0.07	0.26	0.66	0.99	0.19	67.78
GNT 4b			SC	6.6	3	0.1	30	6	0.01	0.62	1.25	1.88	0.41	60.00
GTN 5	Xanthic Eutrudox	Jurrasic sediments—sandstones and shales	S	6.3	1	0.3	5	1	0.02	0.07	0.00	0.09	0.07	1.66

(Continued)

Table 1. (Continued)

Location	Classification	Parent material	Texture	pH (H_2O) (1:5)	EC (mS/m)	OC (%)	Clay (%)	CEC	H_2O-K [cmol(+)/kg soil]	EXK	NEK	HNO_3-K	$NaHCO_3$-K	Total K
GTN 6	Dystric Durochrept	Alluvium from sheet flooding	SL	6.0	2	0.7	10	4	0.04	0.46	0.39	0.89	0.29	54.65
GTN 7	Lithic Petrocalcic Xerochrept	Tamala Limestone	LS	6.5	2	1.1	2	3	0.06	0.18	0.38	0.62	0.11	18.17
GTN 9	Typic Palexeroll	Alluvium from Greenough River	SCL	6.4	1	1.2	16	5	0.11	0.84	0.85	1.80	0.64	31.44
GTN 10	Xanthic Eutrudox	Lateritic material formed on Archean granite	S	5.8	1	0.3	3	1	0.02	0.05	0.01	0.08	0.09	2.48
GTN 11	Mollic Natric Palexeralf	Riverine alluvium	LS	5.9	1	0.8	5	2	0.09	0.12	0.79	1.00	0.17	32.42
GTN 11b			MC	7.2	30	0.2	36	7	0.12	0.43	1.42	1.97	0.24	44.62
GTN 13	Dystric Durochrept	Alluvium	SL	5.9	1	0.4	8	3	0.04	0.35	0.44	0.83	0.21	34.33
KELL 2	Palexerult	Precambrian granite and dolerite	LS	5.9	1	0.6	5	2	0.02	0.12	0.03	0.17	0.08	6.04
KELL 3	Palexeralf	Precambrian granite and dolerite	LS	5.9	2	1.3	6	3	0.03	0.15	0.16	0.34	0.10	24.81
KELL 4	Typic Xerorthent	Precambrian granite	LS	5.8	1	0.8	5	3	0.03	0.17	0.47	0.67	0.16	71.41
KELL 4b			LS	8.5	8	0.3	29	10	0.03	0.64	1.40	2.07	0.40	58.72
KELL 5	Ultic Palexeralf	Alluvium-colluvium from weathered granite	LS	5.8	1	0.7	5	2	0.02	0.15	0.21	0.38	0.11	35.12
KELL 6	Haploxeralf	Precambrian dolerite	C	6.7	13	1.5	11	17	0.11	1.77	3.17	5.05	1.31	49.06
KELL 7	Haploxeralf	Alluvium from weathering of granite and dolerite	SL	6.9	3	1.0	13	10	0.08	0.68	1.35	2.11	0.46	37.30
KELL 7A	*Calcic Haploxeralf*	*Alluvium from weathering of granite and* dolerite	SL	6.8	4	0.7	7	6	0.08	0.47	0.97	1.51	0.40	37.84
KELL 9	Xanthic Eutrudox	Calcareous clay blown from adjacent salt lakes	L	8.3	16	1.5	12	16	0.12	1.18	4.78	6.08	1.43	53.79
MER 1	Aquic Hapludox	Siliceous residue from weathered granite	LS	5.8	1	0.7	11	2	0.01	0.04	0.06	0.11	0.07	2.08
MER 2	Typic Kanhapludalf	Alluvium from granite and dolerite	L	7.0	3	1.2	25	13	0.07	1.09	3.24	4.40	0.65	26.69
KTG 1	Typic Kanhapludalf	Alluvium from breakdown of granite and laterite	SL	6.4	2	1.4	5	4	0.03	0.11	0.18	0.32	0.09	7.23
KTG 1b			LC	6.4	8	0.1	35	6	0.01	0.03	0.15	0.19	0.06	4.10
KTG 2	Typic Chromudert	Alluvium deposited in lacustrine condition	C	6.5	408	0.9	32	15	0.13	0.52	0.65	1.30	0.28	12.75
KTG 4	Typic Kanhapludalf	Alluvium from breakdown of granite and laterite	LS	6.1	2	1.1	2	3	0.01	0.07	0.03	0.11	0.06	3.72
KTG 4b			MC	6.5	61	0.1	29	6	0.00	0.02	0.09	0.11	0.05	5.90
KTG 5	Fluventic Xerochrept	Precambrian dolerite	SL	5.1	12	2.7	6	5	0.04	0.17	0.25	0.46	0.11	18.39
KTG 6	Aquic Natrixeralf	Weathered precambrian granite	L	6.0	51	6.6	10	14	0.06	0.29	0.04	0.39	0.10	10.70
KTG 7	Petroferric Hapludox	Weathered granite	SL	5.2	5	2.6	8	3	0.06	0.13	0.17	0.36	0.11	7.26
KTG 8	Aquic Fraguidalf	Detritus from weatherd granite and laterite	SL	5.4	4	1.8	4	1	0.05	0.05	0.04	0.14	0.08	1.45
KTG 8b			SCL	6.1	32	0.1	32	5	0.01	0.07	0.11	0.19	0.05	2.82
KTG 9	Natric Mollic Palexeralf	Weathered precambrian granite with dolerite	SL	6.0	14	5.2	9	3	0.08	0.16	0.26	0.50	0.12	2.81

MRA 9, WH 1, WH 2, WH 3, GTN 5, KELL 2, KTG 4, and KTG 8, plants died after third harvest, and for soil KO 1, plants died after the fourth harvest. Soil texture for these soils varied from light sand to loamy sand. For 25 soils the plants died from K deficiency after the fifth or sixth harvests. For only 2 soils, GTN 9 and MER 2, the plants survived after the sixth harvest; both of these soils were alluvial in origin and were loam in texture.

The cumulative dry matter yield from the 6 harvests of ryegrass ranged from 0.22 to 25.4 g/kg soil with a median value of 9.38 g/kg soil, and cumulative K uptake ranged from 0.006 to 1.49 cmol/kg soil with a median value of 0.16 cmol/kg soil. Note that K uptake values are expressed as cmol/kg soil to enable easy comparison of K uptake by plants with chemical measures of K forms in soils. The tissue %K concentration in the first cut herbage ranged from 0.40 to 5.97% with a median value of 2.93%. Here, the lower value of 0.40% is below the critical value of 0.80%, identified by Reuter *et al.* (1997*b*). Consequently, ryegrass mortality started after the first cut.

For the light-textured soils, symptoms of K deficiency began to appear on older leaves as chlorosis and necrosis at the tip, while new emerging and young leaves were normal green. Potassium deficiency was severe for soils MRA 5 and MRA 6, where the plants died after the first harvest, and for soils GTN 10, MER 1, SCP 11, and MRA 8, the plants died after the second harvest. For the rest of the soils there was normal plant growth during the initial growth period but later growth and successive K depletion of soils induced symptoms of K deficiency, reduced yield, and ultimately plant death. Except for KELL 4, the comparison of data for the 2 horizons indicated that the amount of K available to plants was not markedly higher from the subsurface horizons despite their higher clay contents. Potassium uptake values for the final harvests ranged from 0.0003 to 0.156 cmol K/kg and tissue %K concentration in tops varied from 0.15 to 1.56% with the final harvest occurring after different numbers of cuttings for different soils. The low tissue %K concentrations for the final harvest may be partly due to the presence of dead plant material that might have lost some of its K by leaching (Fergus *et al.* 1972; MacKay and Russell 1975), although care was taken during watering to avoid wetting plant material.

Changes in forms of soil K

The plots of values of total K in soil versus water-soluble K, exchangeable K, non-exchangeable and 1 M HNO_3 extractable K for soils analysed before and after the sixth harvest of ryegrass are given in Fig. 2. Prior to growing ryegrass, the contents of water-soluble K ranged from 0.001 to 0.16 cmol/kg soil (median value, 0.04 cmol/kg soil), exchangeable K ranged from 0.018 to 1.77 cmol/kg soil (median value, 0.13 cmol/kg soil), non-exchangeable K ranged from 0 to 4.78 cmol/kg soil (median value, 0.17 cmol/kg soil) and HNO_3-K ranged from 0.03 to 6.08 cmol/kg soil (median value, 0.36 cmol/kg soil).

The contents of water-soluble K were variously affected by growth of ryegrass. Some soils that initially contained small amounts of water-soluble K (e.g. MRA 8, WH 1, WH 3, GTN 10, GTN 11, GTN 13, KELL 5, MER 1) gained this form of K due to ryegrass growth (Fig. 2). A possible reason for this increase may be mobilisation of other forms of soil K by plant roots, which were left in soil after plant death, and/or the dissolution of non-exchangeable K due to rhizosphere activity. MacKay and Russell (1975) reported similar increases in water-soluble K, for their experiment after 10 weeks of plant growth, and these changes were greatest for podzolic soils.

For soils WH 3, GTN 6, GTN 11, GTN 13, KELL 5, despite considerable K uptake by ryegrass the contents of water-soluble K changed little, indicating a high K buffering capacity for these soils and high K release from non-exchangeable K and exchangeable

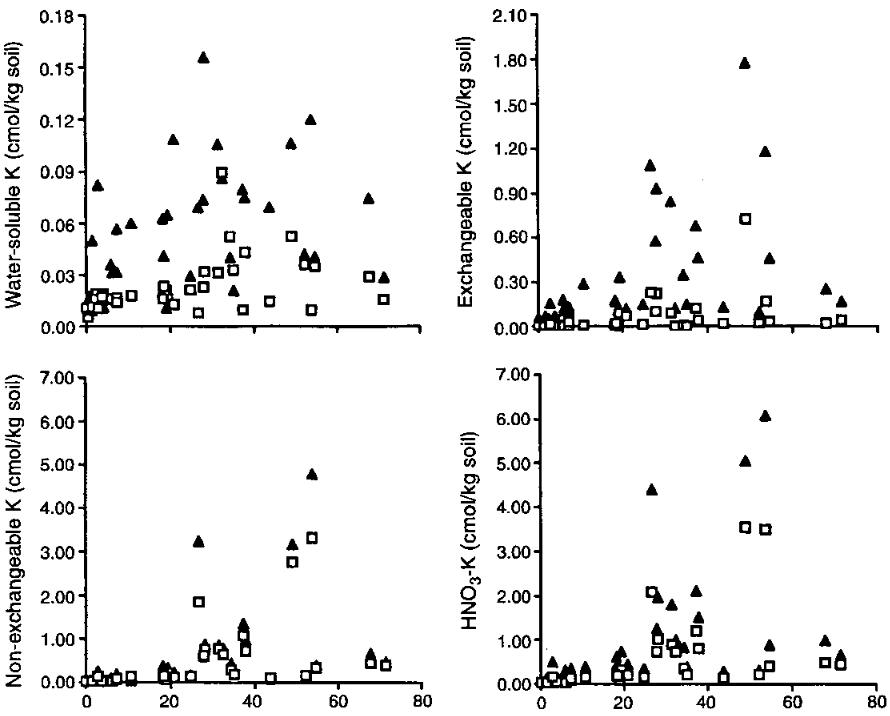


Fig. 2. Amounts of water-soluble K, exchangeable K, non-exchangeable K and 1 M HNO_3 extractable K in relation to total K content of soils for soil sampled before (▲), and after (□) plant growth.

forms to water-soluble K. For the other soils, water-soluble K was reduced considerably due to K uptake by ryegrass. After 6 cuttings, water-soluble K ranged from 0.005 to 0.10 cmol/kg soil. Cumulative K uptake by ryegrass had a significant positive relationship ($r = 0.66^{**}$, $P < 0.05$) with initial water-soluble K, which changed to a nonsignificant relationship ($r = 0.24$) for water-soluble K in soil samples taken at the end of experiment.

Exchangeable K in soils after the growth of ryegrass varied from 0 to 0.73 cmol/kg soil (median, 0.008 cmol/kg soil), and thus, exchangeable K was considerably depleted relative to initial values (median 0.13 cmol/kg soil). Water-soluble + exchangeable K appear to have been the dominant or only sources of K available to plants for most soils (e.g. SCP 11, MRA 5, MRA 6, MRA 8, etc.). Water-soluble K + exchangeable K accounted for most of cumulative K uptake by the tops of ryegrass, the major contribution (~80%) coming from exchangeable K. Plots of cumulative K uptake by ryegrass versus exchangeable K, actually the sum of water-soluble K and exchangeable K, are shown in Fig. 3. These plots show the progressive utilisation of these forms of K by the ryegrass during the experiment so that by the end of the sixth harvest when all plants had died from K depletion (except GTN 9 and MER 2) the cumulative K uptake by ryegrass was approximately equal to the water-soluble K plus exchangeable K at the commencement of the experiment. The slope of the regression line in Fig. 3 increases progressively up to about one for the sixth harvest,

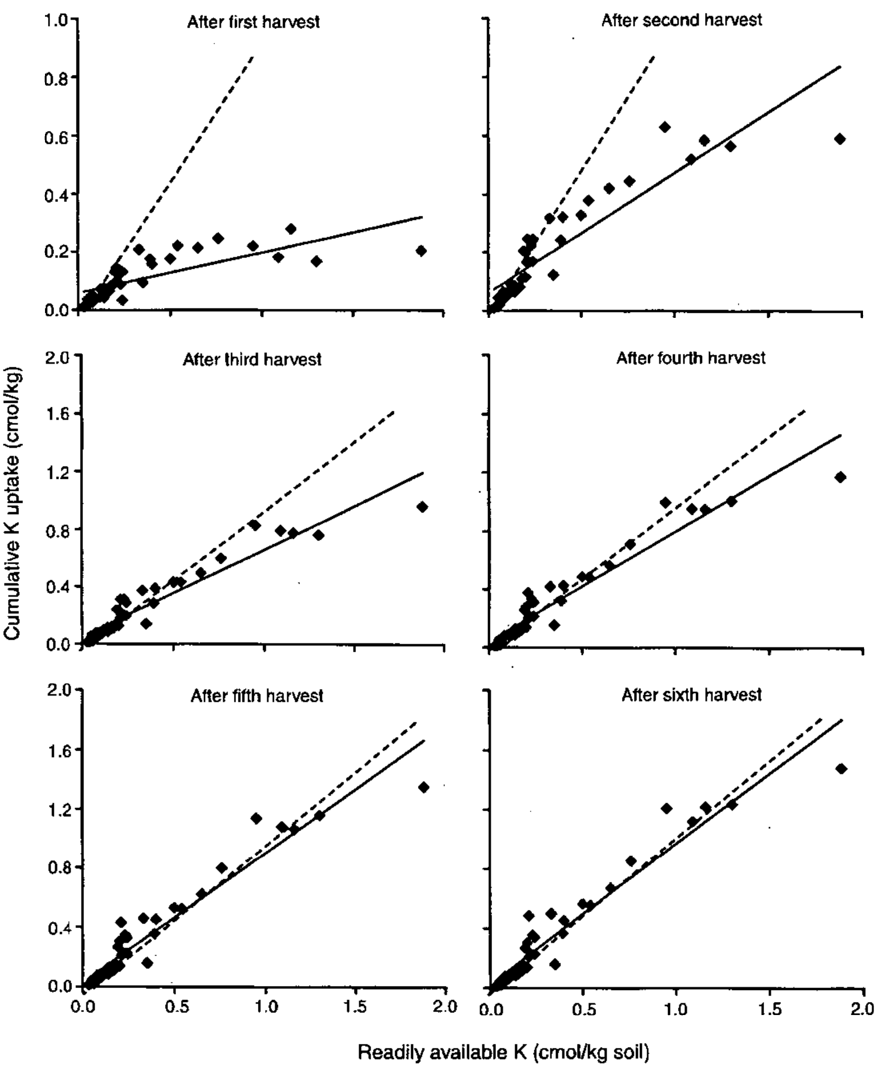


Fig. 3. Relationship between readily available K (exchangeable K + water-soluble K) and cumulative K uptake by ryegrass fpr 6 harvests. Broken lines have slope = 1

indicating that in general the plants have utilised all the water-soluble K and exchangeable K and relatively little K from other pools. The slope is not exactly 1, as some K would have remained in plant roots that were not analysed. Similar results have been reported by German (1957) and Kirkman *et al.* (1994).

For these soils, exchangeable K seems to be a robust indicator of K-supply to plants as it has a highly significant positive linear relationships with cumulative dry matter yield ($r = 0.82$), cumulative K uptake ($r = 0.95$) by the 6 harvests of ryegrass (Fig. 3) and a close relationship with tissue K concentration for the first cut (Fig. 4) (German 1957; Kirkman *et al.* 1994). Several workers have reported strong positive relationships between

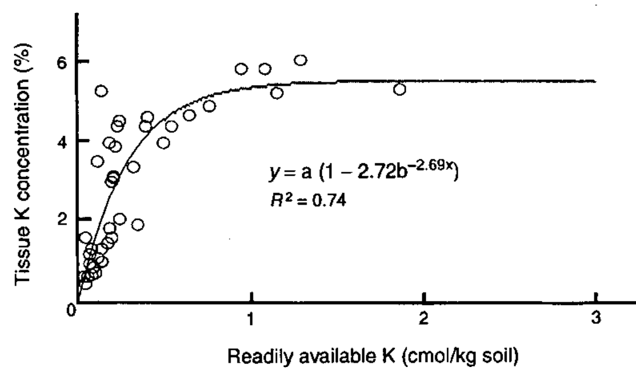


Fig. 4. Relationship between readily available K and tissue K concentration (%) of the first cut herbage of ryegrass.

exchangeable K and K uptake by plants (Rodriguez 1974; MacKay and Russell 1975; Mielniczuk and Selbach 1978; Lopez-Pineiro and Garcia 1997).

In highly weathered soils where K release from non-exchangeable forms is of minor importance and extremely slow, exchangeable K can be expected to be the most important source of K available to plants (Schmitz and Pratt 1953). Our other investigation on these soils (Pal 1999) has indicated that exchangeable K is closely and linearly related to forms of non-exchangeable K (r = 0.84 –0.90), indicating that these forms may be in equilibrium with the source of exchangeable K. However, in general the transfer of K from non-exchangeable forms to exchangeable K will be slow and may not match the demand of plants for K under exhaustive cropping conditions.

Close inspection of Fig. 3 indicates that for some soils, plants used considerably more K than could be provided by exchangeable K alone. Many of these soils exhibited a decrease in non-exchangeable K, indicating that some K was provided to plants from this pool. Out of 49 samples, 28 supplied non-exchangeable K to ryegrass. For soil samples taken after the sixth cutting of ryegrass, the contents of non-exchangeable K varied from 0.014 to 3.54 cmol/kg soil (median, 0.13 cmol/kg soil) compared with a median value of 0.17 at the start of the experiment.

Eleven mostly light-textured soils appear to have gained minor amounts of nonexchangeable K from structural K forms during ryegrass growth. For soils which released non-exchangeable K, omitting GTN 11 and KELL 9 which have relatively large contents of exchangeable K, there is a highly significant positive relationship (r = 0.92, n = *26*) between cumulative K uptake and the decrease in non-exchangeable K in the soils (Fig. 5*a*). The slope of the regression line in Fig. 5*a* shows that nonexchangeable K accounted for about 25% (0–75%) of cumulative K uptake by ryegrass. Subtraction of values of exchangeable K and water-soluble K from cumulative K uptake gave values that may indicate uptake of non-exchangeable K by the plants. These values have a close positive relationship (r = 0.97) with non-exchangeable K released by these soils (Fig. 5*b*) and the slope of the regression line is about unity (1.14), which can be taken to indicate that K uptake by plants in excess exchangeable K was wholely due to release of some non-exchangeable K.

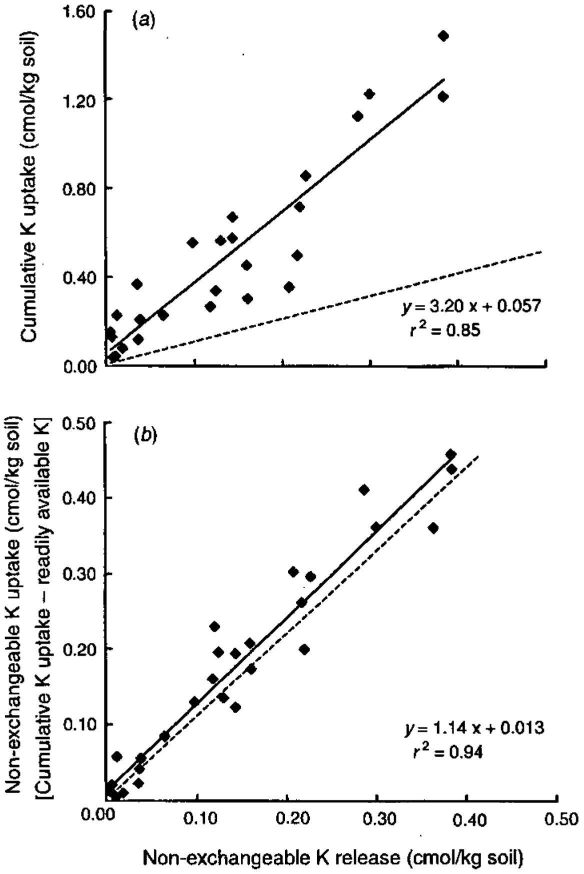


Fig. 5. (*a*) Relationship between cumulative K uptake by ryegrass and K released from non-exchangeable K forms in soil, and (*b*) relationship for plant uptake of non-exchangeable K and K released from non-exchangeable K forms. Broken lines have slope = 1.

Relationship between plant and soil parameters

The coefficients of linear relationships for cumulative K uptake, tissue %K concentration for the first cut, and cumulative dry matter yield versus soil properties including different K forms are given in Table 2. The plant parameters are significantly related to all measures of soil K for soil sampled before cropping. Water-soluble K is not adequately predictive for soil sampled after plant growth and exchangeable K is also much less predictive. In both instances this decrease is due to consumption of most of these forms of K by plants. Plant growth and consumption of K did not affect the relationship between plant parameters and both non-exchangeable K and HNO_3-extractable K. A number of other soil parameters were related to the plant parameters, with silt content being highly predictive and cation exchange capacity being moderately predictive. Stepwise multiple regression equations and coefficients of determination for the most predictive combinations of independent variables are shown in Table 3. A combination of exchangeable K plus water-soluble K is highly predictive of cumulative yield and K uptake. Silt and coarse sand contents combine to predict 68% of the variation in %K concentration of the first cut herbage.

Table 2. Correlation coefficients (r) for linear relationships between ryegrass cumulative dry matter yield, cumulative K uptake, and %K concentration in first harvest versus various forms of soil K and other soil properties

EXK, exchangeable K; NEK, non-exchangeable K; H_2O-K, water soluble K; OC, organic carbon: CS, coarse sand. **Bold** coefficients indicate significance at $P \leq 0.05$ ($n = 49$)

Variable	Cumulative dry matter yield	Cumulative K uptake	%K concentation
pH	**0.46**	**0.56**	**0.43**
Coarse sand	**–0.59**	**–0.52**	**–0.71**
Fine sand	**0.38**	0.26	**0.47**
Silt	**0.80**	**0.87**	**0.75**
Clay	0.22	0.20	**0.34**
CEC	**0.71**	**0.74**	**0.64**
%K saturation	**0.55**	**0.60**	**0.44**
Total K	**0.47**	**0.56**	**0.61**
	Analaysis of soil before ryegrass growth		
H_2O-K	**0.78**	**0.72**	**0.62**
EXK	**0.82**	**0.95**	**0.70**
NEK	**0.68**	**0.82**	**0.59**
HNO_3-K	**0.75**	**0.89**	**0.65**
	Analysis of soil after ryegrass growth		
H_2O-K	**0.34**	0.26	0.16
EXK	**0.65**	**0.78**	**0.53**
NEK	**0.70**	**0.86**	**0.62**
HNO_3-K	**0.70**	**0.86**	**0.63**

Soil plant available K depletion and mineralogical changes

The total K uptake by the 6 harvests of ryegrass as a proportion of soil total K varied from 0.21% to 12.07% for surface horizon soils. The soils which had supplied more than 3% of

Table 3. Step-wise multiple regression equations relating the most predictive soil K forms and soil properties to cumulate dry matter yield, cumulative K uptake, and %K concentration in first harvest

EXK, exchangeable K; H_2O-K, water-soluble K; OC, organic carbon; CS, coarse sand; V_K, %K saturation

Cumulative dry matter yield	R^2
Y = 0.82 EXK + 5.14	0.677
Y = 0.44 EXK + 0.54 H_2O K –2.95	0.792
XK = 0.45 H_2O K + 0.42 Total K –2.09	0.821
Y = 0.28 EXK + 0.48 H_2O K + 0.20 Total K + 0.31 OC + 1.25	0.865
Cumulative K uptake	
Y = 0.20 EXK + 0.04	0.904
Y = 0.95 EXK + 0.82 H_2O K –0.014	0.927
Y = 0.19 EXK + 0.68 H_2O K + 0.18 %Silt –0.06	0.939
%K concentration in first harvest	
Y = 0.75 %Silt + 1.14	0.568
Y = 0.41 %Silt + 0.52 %CS + 3.95	0.678
Y = 0.20 %Silt + 0.42 %CS –0.38 H_2O K + 3.60	0.702
Y = 0.14 %Silt + 0.36 %CS –0.39 H_2O K + 0.17 VK + 3.49	0.717

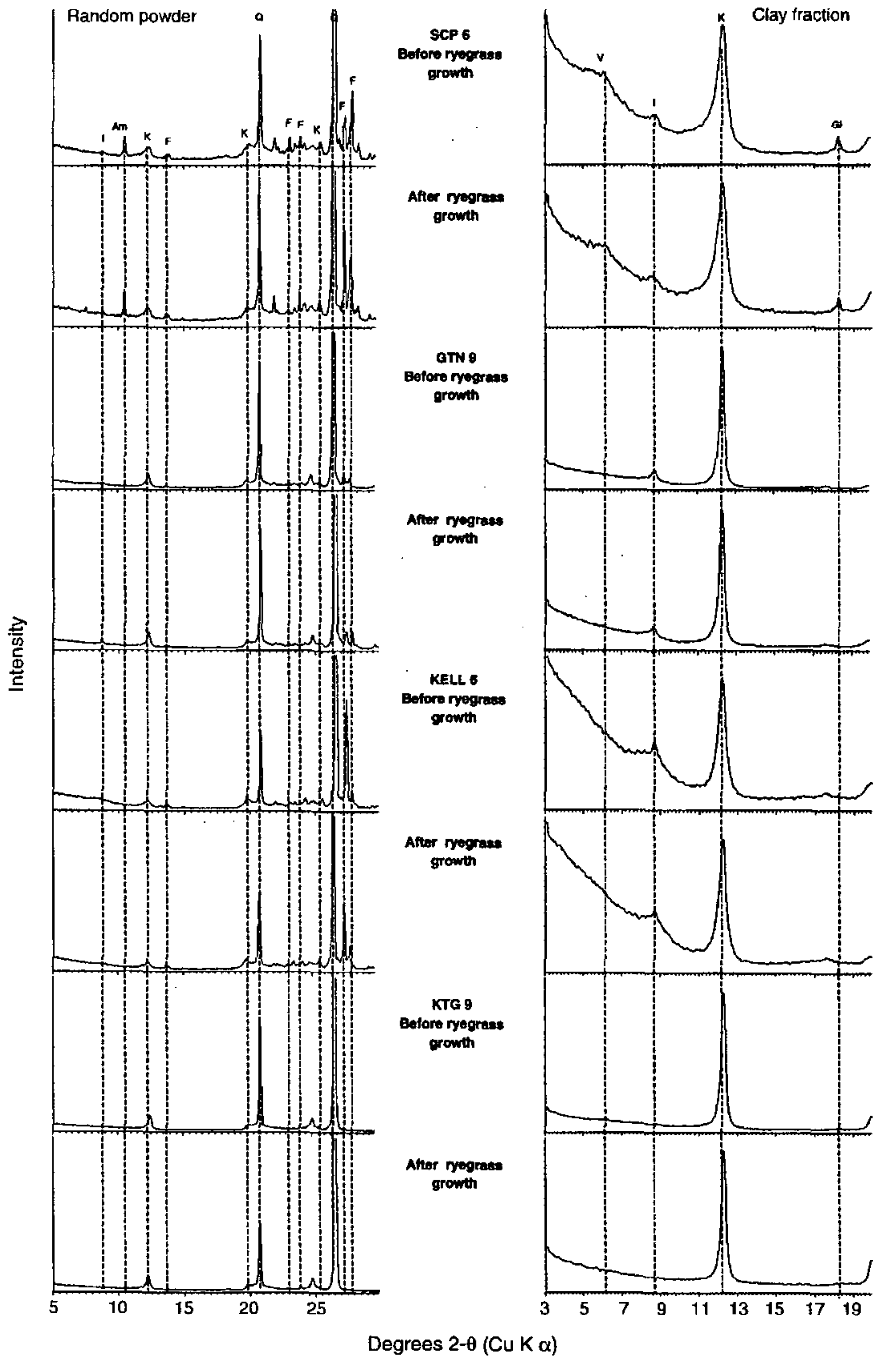


Fig. 6. X-ray diffraction patterns of random powders of soils and oriented clays before and after ryegrass growth. Quartz (Q), feldspar (F), vermiculite (V), illite (I), Kaolinite (K), gibbsite (Gi), and amphibole (Am). Cu K a radiation, Mg saturated clay fraction.

their total K towards cumulative K uptake to ryegrass growth were selected for random powder and clay fraction X-ray diffraction (XRD) analysis to determine mineralogical changes that took place upon K depletion of soils (Fig. 6). Lesser extraction of K is unlikely to have produced any discernible change in mineralogy.

XRD patterns of random powders of soils sampled before and after ryegrass growth indicate that the K-containing minerals illite, vermiculite, and feldspar occur in these soils together with quartz, amphibole, kaolinite iron oxide, and gibbsite. The intensities of some reflections, in the region of feldspar peaks at about 3.20 Å, increased (for soils SCP 6, GTN 9, KELL 6, MER 2, and KTG 7). However, this result does not indicate that feldspar crystallised during the experiment. New compounds were formed in the soils during the plant growth experiment and their reflections had masked any changes in intensity of the feldspar reflections. Bloedite [$Na_2Mg(SO_4)_2.4H_2O$], mirabilite [$NaSO_4.10H_2O$], rozenite [$Ca_3(Si_3O_8(OH)_2$], and nesquehonite ($MgCO_3$) have d-spacings between 3.20 and 3.29 Å (JCPDS 1983) and these salts had presumably formed from the basal fertilisers applied to these soils.

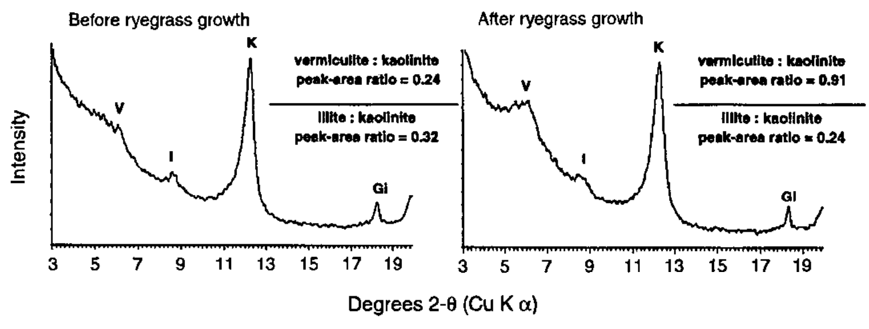


Fig. 7. Diffraction patterns of basally oriented, Mg-saturated clay from soil SCP 6 showing little or no change in relative peak heights for clay minerals but substantial changes in peak-area ratios after ryegrass growth. Vermiculite (V), illite (I), kaolinite (K), and gibbsite (Gi) are the main minerals

XRD analysis of basally oriented clay fractions of soils taken before and after ryegrass growth confirmed the presence of the K-bearing mineral illite plus vermiculite. Neither mineral was substantially affected by plant growth, as the diffraction patterns for the clay fraction from some soils before and after cropping were virtually identical. Extremely precise measurements are required to identify changes in XRD patterns. For example, the clay fraction of soil SCP 6 contained illite and vermiculite, and after ryegrass growth the illite and vermiculite peaks changed in intensity and may have broadened slightly (Fig. 7) (Arnold and Close 1961). Highly reproducible results were obtained for slow scan replicated XRD analysis for the clay of SCP 6. Using kaolinite as an internal standard indicated that when peak-area is used as a measure of intensity (Brindley 1980), there may be a slight decrease in illite (001) peak-intensity with a concomitant increase in vermiculite (001) peak-intensity due to K removal from illite by plants. These results are consistent with those of Jackson (1964), Feigenbaum and Kafkafi (1972), Hinsinger *et al.* (1992), Liu *et al.* (1997), and Singh and Goulding (1997) who reported that K-depletion resulted in a decrease in illite and an increase in interstratified clay minerals, vermiculite and smectite.

Conclusions

This research has clearly identified exchangeable K as an excellent indicator of the availability of K to plants for these Western Australian soils. The results indicate that some K may be supplied by the 'non-exchangeable K' fraction and XRD results indicate that some of this K was released from the interlayer site in illite. The exhaustion experiment involved small volumes of soil that were intensively exploited by roots and removal of plant tops ensured that there was limited recycling of K. Under field conditions plant roots can exploit much larger volume of soil and recycling occurs. Consequently, K exhaustion of soils will occur at a slower rate in the field but the present results indicate that both top soils and subsoils of many common Western Australian soil types are highly K-deficient and will eventually become fully depleted if K fertilisers are not provided.

References

Arnold PW, Close BM (1961) Potassium releasing power of soils from the agdel rotation experiment assessed by greenhouse cropping. *Journal of Agricultural Sciences* **57**, 381–386.

Brindley GW (1980) Quantitative x-ray mineral analysis of clays. In 'Crystal structures of clay minerals and their x-ray identification'. (Eds GW Brindley, G Brown) pp. 411–438. (Mineralogical Society: London)

Carroll MD (1961) Potassium deficiency in the wheat belt. *Journal of Agriculture, Western Australia* **2**, 457–458.

Cox WJ (1973) Potassium for pastures. *Journal of Agriculture, Western Australia* **14**, 215–219.

Feigenbaum S, Kafkafi U (1972) The effect of illite content of soils on the potassium supply to plants. In 'Potassium in soils. Proceedings of the 9th Congress of the International Potash Institute'. Landshut, Germany. pp. 131–138.

Fergus IF, Martin AE, Little IP, Haydock KP (1972) Studies on soil potassium. II. The Q/I relation and other parameters compared with plant uptake of potassium. *Australian Journal of Soil Research* **10**, 95–111.

German WL (1957) Potassium release characteristics of several soils from Ohio and New York. *Soil Science Society of America Proceedings* **21**, 52–58.

Hinsinger P, Jaillard B, Dufey JE (1992) Rapid weathering of a trioctahedral mic by the roots of ryegrass. *Soil Science Society of America Journal* **56**, 977–982.

Jackson ML (1964) Chemical composition of soils. In 'Chemistry of soils'. (Ed. FE Bear) pp. 87–112. (Reinhold Publishing Corp.: New York)

Jarvis SC, Robson AD (1983) The effects of nitrogen of plants on the development of acidity in Western Australian soils. 1. Effects with subterranean clover grown under leaching condition. *Australian Journal of Agricultural Research* **34**, 341–353.

JCPDS (1983) Mineral powder diffraction file. International Centre for Diffraction Data, Pennsylvania, USA.

Kirkman JH, Basker A, Surapaneni A, MacGregor AN (1994) Potassium in the soils of New Zealand—a review. *New Zealand Journal of Agricultural Research* **37**, 207–227.

Liu GuangDong, Nielsen NE, Hansen HCB, Borggaard OK (1997) Mineral changes in a Danish Alfisol caused by 30 years of potassium depletion in the field. *Acta Agriculturae Scandinavica* **47**, 1–6.

Lopez-Pineiro A, Garcia Navarro A (1997) Potassium release kinetics and availability in unfertilized Vertisols of south-western Spain. *Soil Science* **162**, 912–918.

MacKay DC, Russell JS (1975) Rates of growth, potassium uptake, and changes in the potassium properties of four Queensland soils during intensive cropping by buffel grass *Cenchrusc ciliaris*. *Australian Journal of Soil Research* **13**, 217–233.

MacLean AJ (1961) Potassium supplying power of some Canadian soils. *Canadian Journal of Soil Science* **41**, 196–206.

Martin HW, Sparks DL (1985) On the behavior of nonexchangeable potassium in soils. *Communications in Soil Science and Plant Analysis* **16**, 133–162.

McArthur WM (1991) Reference soils of south-western Australia. pp. 1–265. Australian Society of Soil Science (WA Branch); WA Department of Agriculture, Perth, WA.

Mielniczuk J, Selbach PA (1978) Potassium supplying capacity of six soils from Rio Grande do Sul, Brazil. *Revista Brasileira de Ciencia do Solo* **2**, 115–120.

Norrish K, Chappell BW (1967) In 'Physical methods of determinative mineralogy.' (Ed. J Zussman) (Academic Press: New York)

Norrish K, Pickering JG (1983) Clay minerals. In 'Soils: an Australian viewpoint'. pp. 281–308. (CSIRO: Melbourne/Academic Press: London)

Pal Y (1999) Potassium mineralogy, chemistry and availability in sandplain and duplex soils of south-western Australia. PhD thesis, The University of Western Australia.

Pratt, PF (1965) Potassium. In 'Methods of soil analysis Part 2: chemical and biological'. (Ed. CA Black) pp. 1023–1031. (American Society of Agronomy: Madison, WI)

Rayment GE, Higginson FR (1992) 'Australian laboratory handbook of soil and water chemical methods.' (Inkata Press: Melbourne)

Reuter D, Duncombe-Wall D, Judson G (1997*a*) Potassium balance in Australia's broadacre industries: a contemporary national and regional analysis. In 'Proceedings of the 1st Workshop on Potassium in Australian Agriculture'. pp. 17–24. (Australian Society of Soil Science: Perth, WA)

Reuter DJ, Edwards DG, Wilhelm NS (1997*b*) Temperate and tropical crops. In 'Plant analysis: an interpretation manual'. (Eds DJ Reuter, JB Robinson) pp. 81–279. (CSIRO Publishing: Melbourne)

Robson AD, Gilkes RJ (1980) Fertilizer responses (N, P, K, S, Micronutrients) on lateritic soils in south-western Australia— a review. In 'Lateritisation processes. Proceedings of the International Seminar on Lateritisation Processes'. Trivandrum, India. pp. 381–390. (Oxford and IBH Publishing Co.: New Delhi)

Rodriguez N (1974) Potassium supplying capacity of some Venezuelan soils. *Tropical Agriculture* **51**, 189–199.

Schmitz GW, Pratt PF (1953) Exchangeable and nonexchangeable potassium as indexes to yield increases and potassium absorption by corn in the greenhouse. *Soil Science* **76**, 345–353.

Singh B, Goulding KWT (1997) Changes with time in the potassium content and phyllosilicates in the soil of the Broadbalk continuous wheat experiment at Rothamsted. *European Journal of Soil Science* **48**, 651–659.

Wong MTF, Wittwer K (1997) Aspects of potassium impacting on the sustainability of West Australian agriculture. In 'Proceedings of the 1st Workshop on Potassium in Australian Agriculture'. pp 25–30. (Australian Society of Soil Science: Perth, WA)

Manuscript received 2 June 2000, accepted 18 October 2000

Aust. J. Soil Res., 2001, **39**, 813–822

Mineralogy and potassium release from some Western Australian soils and their size fractions

Y. Pal[A], *R. J. Gilkes*[A], *and M. T. F. Wong*[B]

[A]Department of Soil Science and Plant Nutrition, The University of Western Australia, Nedlands, WA 6009, Australia.
[B]CSIRO Land and Water, Private Bag PO, Wembley, WA 6014, Australia.

Abstract

Seven surface horizon soils and their sand, silt, and clay fractions were characterised for mineralogy, and K release by extracting samples with 1 mM $CaCl_2$ solution daily for 10 days. The low silt content is characteristic of many Western Australian soils, which may provide a partial explanation of the paucity of available K in soils that contain little silt-size primary minerals. The sand and silt fractions were dominated by quartz and contained significant amounts of K-feldspars. The clay fraction was dominated by kaolinite, and some samples contained illite/mica, inhibited vermiculite, and gibbsite. On a per unit weight basis the clay-fraction released the largest amount of K followed in sequence by the silt and sand. The contribution of size fractions to total K release by the soil ranged from 50 to 87%, 2 to 7%, and 10 to 44% for the clay, silt, and sand, respectively. Linear plots of K release versus time$^{1/2}$ for the soils, and the sand and silt fractions, indicated that a parabolic diffusion equation adequately describes the K release process. For some clay samples this diffusion controlled kinetic is not strictly obeyed during the initial period of K desorption due to rapid exchange of adsorbed K at sites on external surfaces. The Elovich equation plots show a discontinuity in slope and support the hypothesis of the multireactive nature of K exchange sites for these soils. The parabolic diffusion rate constant closely predicted K supply to plants as it has a close positive relationship (r = 0.99) with total K uptake by ryegrass for 260 days of growth.

Additional keywords: soil separates, $CaCl_2$ extractable K, exchangeable K.

Introduction

Potassium (K) uptake during plant growth is a dynamic process causing K depletion in the root-zone through removal of exchangeable K. An understanding of the nature and rate of release of soil K from different pools of adsorbed and structural K is important from a soil fertility viewpoint (Sharpley 1987). Desorption of soil K in laboratory experiments has been described by several equations, for example simple first-order rate equations were used by Munn *et al.* (1976) and Ogwada and Sparks (1986), to describe K desorption over short time periods (<1000 h). The desorption of K from soils has been shown by numerous investigators to be a diffusion controlled process (Feigenbaum and Shainberg 1975; Feigenbaum *et al.* 1981; Sparks and Jardine 1981). The modified Elovich and power-form equations have been used to describe K desorption from soils (Martin and Sparks 1983; Havlin *et al.* 1985), although their application has been limited to long time periods (>1000 h) and release of non-exchangeable K.

The amount of K in soils that contain K mainly in 2:1 clay minerals, of the illite/mica group, is high compared with the amount of K taken up by plants. The plant availability of interlayer K from micaceous minerals, and lattice K of feldspars, is not simply dependent on the quantity of K, but is more related to its release rate and mineral dissolution, which depend greatly on the type of K-bearing mineral (Sparks 1987). Some pure clay minerals such as smectite, kaolinite, and hectorite saturated with K release all of their adsorbed K very easily because mostly K exists as surface K and interlayer K in accessible interlayer

10.1071/SR00031 0004-9573/01/040813

sites (Mengel and Uhlenbecker 1993). Micaceous minerals retain most of their interlayer K against exchange, and feldspars must dissolve congruently to release their structural K (Huang *et al.* 1968; Feigenbaum *et al.* 1981).

Soils in the south-west of Western Australia are mostly ancient and highly weathered and are thus dominated by kaolinite and quartz rather than illite and feldspar. More than 50% of 114 reference soils representing the entire agricultural region were found to be deficient in K (McArthur 1991). Despite this high incidence and severity of K deficiency, the prediction of yield responses to K fertilisers applications based on soil tests for exchangeable K is of limited accuracy. In particular the forms of plant-available K in these soils are not known, and in very sandy soils some of the K obtained by plants may originate in the silt and sand fractions. This investigation was conducted to identify the contribution of size fractions and minerals to K release and plant K uptake.

Materials and methods

This investigation was conducted on 7 surface (0–10 cm) soils and 3 size fractions (sand, silt, and clay). The basic properties and classification of soils are given in Table 1 and these soils are representative of agricultural soils of south-west Western Australia with soils being from both ancient highly weathered and younger landscapes. The sand (53–2000 μm) was separated by sieving, and the clay (<2 μm) was separated from the silt (2–53 μm) by repeated sedimentation and decantation. The exchangeable K was determined by extraction of samples with 20 mL of unbuffered 0.01 M silver thiourea $(AgTU)^+$ for 16 h with end-over-end shaking followed by centrifugation (Rayment and Higginson 1992). Dissolved K was determined by flame photometry.

The K release investigations on whole soils were conducted on original soil, and Ca-saturated soil. Ca-saturated soils were obtained by multiple washing with 1 M $CaCl_2$ solution to replace the exchangeable K and soils were subsequently washed with deionised water, followed by 1:1 acetone : water mixture, until a negative test for Cl^- was obtained with $AgNO_3$ solution. For K release measurements, 2 g soil, 2 g sand, 1 g silt, and 500 mg clay were shaken for 24 h with 30 mL of 1 M $CaCl_2$ (pH 5.02) in 50-mL centrifuge bottles at 25±1°C. The K released from soils and their separates were determined by 11 successive daily extractions, changing the solution each day for 11 days (Munn *et al.* 1976). The suspension was centrifuged and supernatant was decanted for K determination.

For random powder X-ray diffraction (XRD) analysis, about 0.5 g of finely ground sample was pressed into an aluminium holder and scanned for 5 to 35° 2θ angle at a 0.02° step size, 1°/min scanning speed, and using Cu Kα radiation with Philips PW 1830/40 vertical goniometer. Quartz was present in all samples and was used as the internal standard for correcting the d-spacing using XPAS software so as to obtain highly precise and accurate values (Singh and Gilkes 1992). Basally oriented specimens of the clay fractions were prepared by placing the clay suspension on ceramic plates under suction followed by saturation with $MgCl_2$ solution and washing. For identification of the clay mineral species, samples were scanned from 3 to 20° 2θ angle at 0.02° step size and 1°/min scan speed (Brown and Brindley 1980).

A glasshouse experiment was carried out to measure the K supply capacity of soils by growing ryegrass in 1-kg pots of soil for 260 days and the plants were harvested 6 times during the growth period. For some soils plants died from K deficiency before the sixth harvest. For K analysis plant material was digested in a 3 : 1 nitric : perchloric acid mixture and the K concentration of the plant digest was determined by flame photometry Pal *et al.* (2001).

Results and discussion

The soils were chosen to be representative of the diversity of Western Australian soils. These soils are predominantly duplex, red earth, gravely yellow earth, and brown calcareous soil with loamy sand, sandy loam, and sandy clay loam surface horizons (McArthur 1991). The low silt content is characteristic of many Western Australian soils (Table 1) and this difference is a consequence of the dominantly granitic parent materials

Table 1. Some properties of the soils used in this investigation.
OC, organic carbon; CEC, cation exchange capacity (cmol/kg); SL, sandy loam; L, loam; SCL, sandy clay loam; LS, loamy sand

Sample	Classification[A]	Parent material	Texture	pH (H_2O) (1 : 5)	EC (1 : 5) (mS/m)	OC	Sand	Silt (%)	Clay	CEC
KO 2A	Ultic Haploxeralf	Weathered dolerite	SL	5.6	5	4.5	81	8	11	6
MRA 1	Calcic Natric Palexeralf	Riverine alluvium associated with Moore River	L	5.9	4	2.6	72	12	16	7
GTN 4	Dystric Eutrochrept	Alluvium from Chapman River	SL	6.0	5	0.9	89	8	3	4
GTN 9	Typic Palexeroll	Alluvium from Greenough River	SCL	6.4	1	1.2	80	4	16	5
KELL 4	Typic Xerorthent	Precambrian granite	LS	5.8	1	0.8	89	6	5	3
KELL 9	Xanthic Eutrudox	Calcareous clay blown from adjacent salt lakes	L	8.3	16	1.5	71	17	12	16
KTG 7	Petroferric Hapludox	Weathered granite	SL	5.2	5	2.6	87	5	8	3

[A] Soil Survey Staff (1987).

and the mineralogical maturity of most Western Australian soils (Singh 1992). In some young soils in the region much of the soil K is present in the silt and sand fraction as primary feldspars and mica. In contrast, the ancient Western Australian soils, which contain little K have been reported to contain little silt and few primary minerals apart from quartz (McArthur 1991). Mulcahy (1960) has reported the presence of rare residual feldspar grains in topsoils of some lateritic soils but these may represent minor amounts of aeolian addition from younger soils (Glassford 1980).

XRD analysis of random powders of the sand and silt fractions and of the oriented clay indicated that several mineral species occur in these soils. The coarser fractions are dominated by quartz but do contain significant amounts of K-feldspars. The sand and silt fractions of some of the soils also contain illite/mica (Fig. 1). In the clay fraction kaolinite is the dominant mineral for all of the soils. The clay fraction of soil KTG 7 also contained inhibited vermiculite and gibbsite. Inhibited vermiculite is a common constituent of kaolinite-dominant soils and its occurrence could be attributed to alteration of dioctahedral mica that persists in deeper horizons of these soils. In more acidic surface soil horizons, the interlayer K has been removed from mica by exchange and replaced by aluminium hydroxide polymers (Norrish and Pickering 1983; Singh 1992). Inhibited vermiculite is generally absent from relatively younger Western Australian soils where high amounts of illite/mica are present (Singh 1992). The clay fractions of soils MRA 1, GTN 4, GTN 11, KELL 4, and KELL 9 contain various amounts of illite/mica (Fig. 1). In some instances this illite/mica may be attributed to the presence of aeolian additions from illitic playa lake sediments (McArthur 1991).

The cumulative amounts of K released by the virgin soils and their different size fractions in 11 extraction cycles with 1 mM $CaCl_2$, renewing the solution every day, are given in Table 2. Among whole soils, the cumulative amounts of K released ranged from

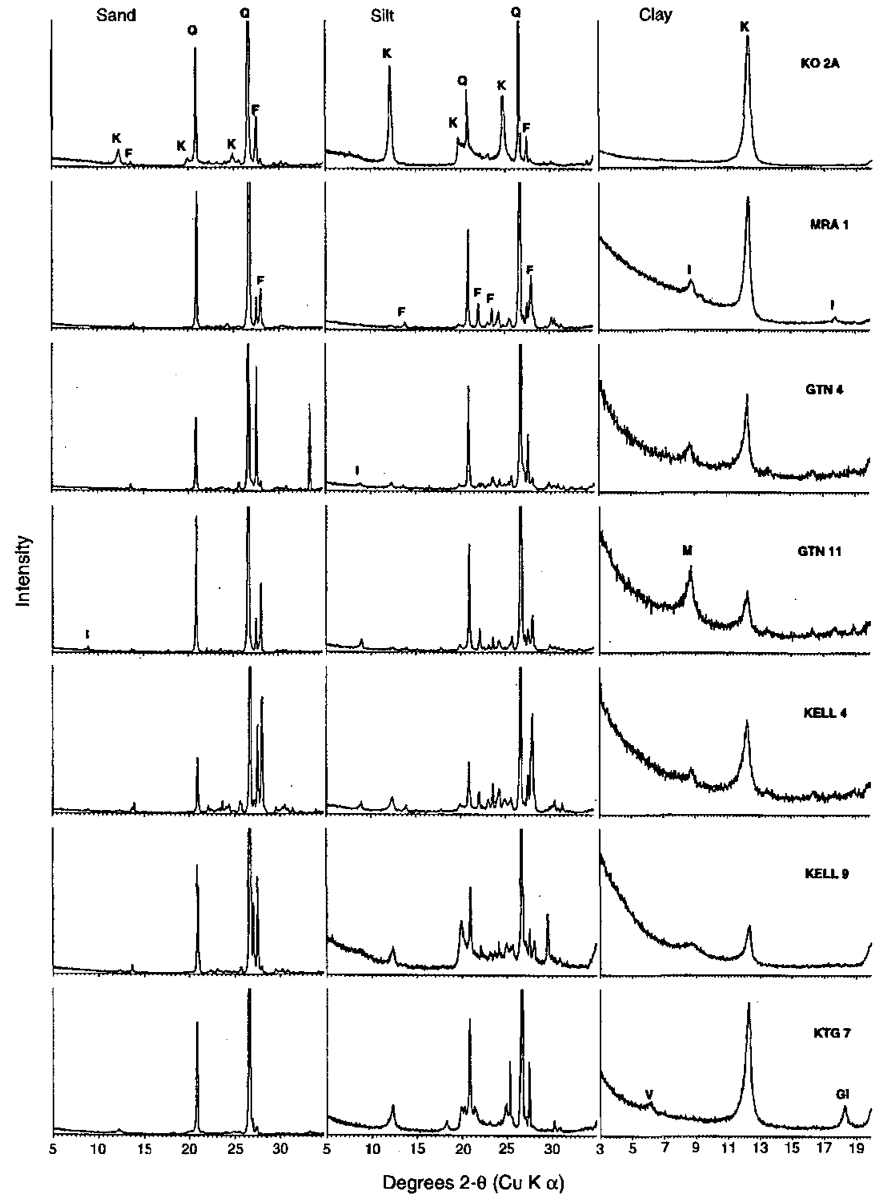


Fig. 1. XRD diffraction patterns of random powders of the sand and silt fractions and of the oriented clay for the seven soils from Western Australia. Quartz (Q), kaolinite (K), feldspar (F), illite (I), vermiculite (V), mica (M), and gibbsite (Gi).

0.27 to 1.56 cmol/kg for the original soils and 0.05 to 0.79 for the Ca-saturated soils where readily available K had been removed by the Ca-saturation procedure. Soil KTG 7 released the lowest amount of K, which is consistent with the absence of illite and the small content

Table 2. Contents of exchangeable K and cumulative amounts of K released (cmol/kg soil) in 10 sequential $CaCl_2$ extractions
The values in parentheses are percent of K released by size fractions on a whole soil basis

Sample	Exchangeable K				K released in $CaCl_2$					Computed
	Soil	Sand	Silt	Clay	Soil <2 mm		Sand	Silt	Clay	total K released
	<2 mm	2000–53 µm	53–2 µm	<2 µm	Ca saturated	Original	2000–53 µm	53–2 µm	<2 µm	by all fractions
KO 2A	0.23	0.06	0.04	2.07	0.09	0.39	0.09 (23)	0.06 (2)	2.13 (75)	0.32
MRA 1	0.65	0.07	0.17	3.10	0.39	0.83	0.10 (10)	0.16 (3)	3.71 (87)	0.67
GTN 4	0.33	0.08	0.19	3.96	0.23	0.50	0.11 (44)	0.17 (6)	4.38 (50)	0.23
GTN 11	0.21	0.05	0.20	3.12	0.25	0.61	0.07 (25)	0.16 (2)	4.47 (73)	0.28
KELL 4	0.20	0.07	0.21	3.57	0.14	0.28	0.09 (30)	0.18 (4)	3.68 (66)	0.28
KELL 9	1.3	0.17	0.54	6.42	0.79	1.56	0.32 (18)	0.55 (7)	7.62 (75)	1.26
KTG 7	0.19	0.02	0.03	1.21	0.05	0.27	0.03 (19)	0.05 (2)	1.23 (79)	0.12

of feldspar of this soil (Fig. 1). However, the cumulative K released from soils is not directly related to the contents of illite and feldspar identified by XRD results.

Among the different size fractions, on a per unit weight basis, the clay-fraction released the highest amount of K, followed in sequence by the silt and sand (Table 2). The cumulative amounts of K released from soil for 11 extractions weighted according to the percent sand, silt, and clay in the whole soil are given Table 2. The contribution of each size separate to total K released ranged from 50 to 87%, 2 to 7%, and 10 to 44% for the clay, silt, and sand fractions, respectively. Note that this calculation assumes that there would be no K exchange interactions between the K released from the 3 size classes present in the whole soil. While these results show the importance of the clay fraction in releasing K, they also indicate the significant contribution of the sand fraction to K release for these soils. This result is presumably a consequence of the sandy texture and dominantly kaolinitic clay of these soils, so that feldspar in the sand fraction comprises a significant source of K.

Note that values of K released from the Ca-saturated soils are much less than for the original soil as most of the exchangeable K from the soil had been replaced by Ca. The exchangeable K was presumably mainly located on clay minerals and organic matter. The

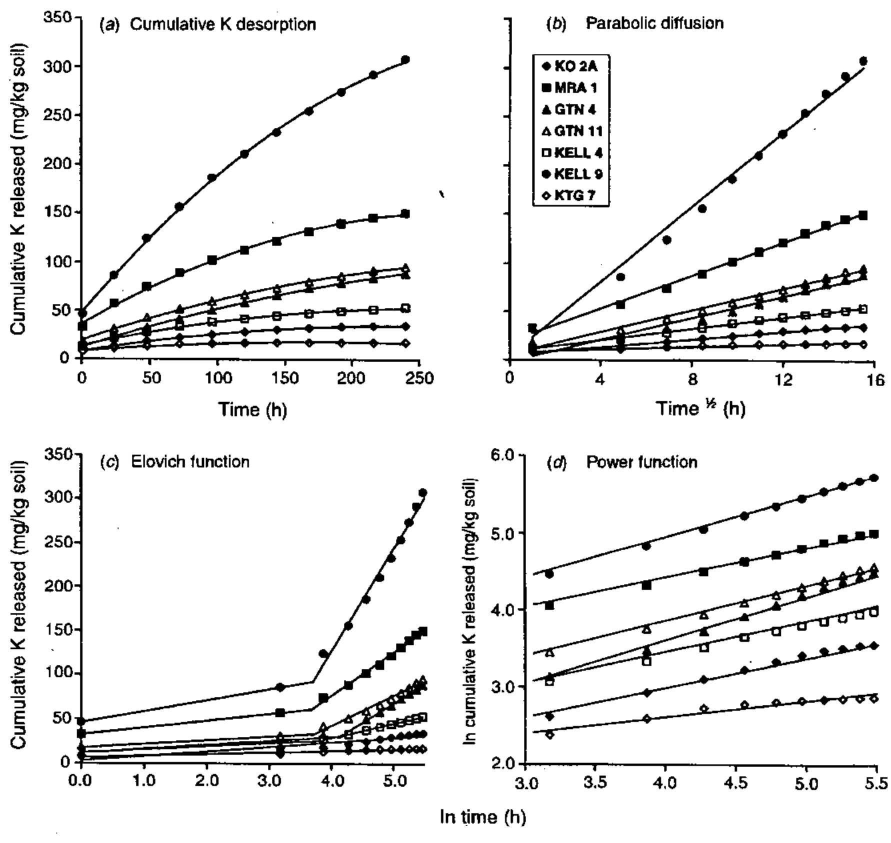


Fig. 2. Data fitted to various models describing the K release to 1 mM $CaCl_2$ from soils saturated with Ca.

amounts of K released by soils and the size fractions had significant positive relationships with the corresponding exchangeable K content. The sand and clay fractions systematically released more K to 11 $CaCl_2$ extractions than had been determined as their exchangeable K contents, using silver thiourea $(AgTU)^+$ as the extracting reagent; therefore, these fractions have released some nominally nonexchangeable K during the prolonged extraction. These results are consistent with those of Mashayekhi and Malakouti (1997). The silt fraction released similar amounts of K to $CaCl_2$ extractions as to $(AgTU)^+$.

Four mathematical equations, the power, first-order, Elovich, and parabolic diffusion equations, were used to describe the kinetics of K release for soils and their size fractions. These functions were selected on the basis of their common use in the literature to describe soil release reactions (Sparks *et. al.* 1980; Jardine and Sparks 1984; Havlin and Westfall 1985). The first-order equation did not describe adequately the K release kinetics and is not discussed further. The linear plots of K release *v.* time$^{1/2}$, for soils (Fig. 2*b*), and the sand and silt fractions (not shown), indicate that this parabolic diffusion equation provides a moderately accurate description of the K release process. Thus release of K from the soil constituents may be a diffusion-controlled process (Jardine and Sparks 1984; Havlin and Westfall 1985). Pure micaceous minerals such as phlogopite, biotite, and muscovite also release K as a linear function of the square root of time (Feigenbaum *et al.* 1981).

The parabolic diffusion plots for the clays had deviations in linearity for the initial period of K release for all the samples due to large amounts of K being released rapidly. This could be due to mass action exchange at adsorption sites on external surfaces (i.e. CEC sites); the extent of this process depends on the specific surface of the mineral components. Therefore, the diffusion-controlled exchange reaction would not be followed during the initial period of K desorption (Chute and Quirk 1967; Choudhary and Prasad 1997). The Elovich equation plots had discontinuities in their slope for the Ca-saturated whole soil KELL 9, KELL 4, MRA 1, GTN 11, and GTN 4 after a period of about 24 h shaking (Fig. 2*c*). Similar discontinuities occurred in the Elovich plots for the clay, silt, and sand fractions of soil KELL 9.

Low (1960), in describing chemisorption of gases on solid surfaces, suggested that breaks in slope in sorption *v.* ln t plots indicate that different mechanisms control the rate processes for different parts of the curve and K release curves can be analysed in the same way. The first part of the curve might represent rapid exchange from the external surface (e.g. in this instance exchangeable K) and the second part might represent slow diffusion controlled K release from internal surfaces (non-exchangeable K) of minerals. Thus, K release rates vary with the proportion of different K exchange sites involved and the Elovich plots do not provide an adequate description of data for soils that have diverse exchange sites and exchange rates. Thus, Havlin and Westfall (1985) consider that the Elovich equation should not be used to describe data when the reaction time is <1000 h. The non-linear Elovich plot supports the hypothesis of the multireactive nature of K exchange sites in these soils (Choudhary and Prasad 1997).

Parabolic diffusion and power function equations (Fig. 2*c, d*) appear to best describe the kinetics of K release process for these samples (Rausell-Colom *et al.* 1964; Chute and Quirk 1967; Sparks *et al.* 1980; Jardine and Sparks 1984; Havlin and Westfall 1985). In some instances the data points for rapidly exchanged K do not fall on fitted lines and perhaps data should be adjusted to remove the contribution of this component. Table 3 shows the correlation coefficient, intercept, and slope values for parabolic diffusion and power functions that best describe the kinetics of K release for Ca-saturated soils. The magnitude of the apparent rate constants (k) for the sand, silt, and clay fractions ranged

Table 3. Correlation coefficient, intercept and slope values for the two kinetic models which best describe K release from whole soils

Kinetic equation	KO 2A	MRA 1	GTN 4	GTN 11	KELL 4	KELL 9	KTG 7
			$y = a + bt^{1/2}$ *(parabolic diffusion)*				
r	0.996	0.997	0.986	0.994	0.998	0.992	0.958
a	5.03	18.71	-2.04	5.94	8.34	3.66	8.03
b	2.02	8.57	5.66	5.70	2.98	19.23	0.70
			$\ln y = \ln a + b \ln t$ *(power function)*				
r	0.979	0.972	0.954	0.965	0.974	0.964	0.983
a	1.89	3.34	2.28	2.68	2.39	3.62	1.98
b	0.30	0.29	0.37	0.32	0.28	0.36	0.17

from 0.60×10^{-3} to 2.60×10^{-1}.h. Munn *et al.* (1976) reported k values of 2.28×10^{-3} to 5.62×10^{-3}.h for the sand, silt, and clay separates of some soils from Ohio state. The values of k for the sand fraction were smaller than those for the silt and clay.

The comparison of rate coefficients of diffusion equations (Table 3) with plant K uptake may provide evidence for the utility of an equation to describe the kinetic of K release to plants from soils (Havlin and Westfall 1985). The diffusion rate coefficient for the parabolic equation proved to be the best predictor of K supply to plants. The parabolic diffusion coefficient has a highly significant positive relationship ($r = 0.99$) with K uptake by ryegrass over a period of 260 days in a glasshouse experiment (Fig. 3). Therefore, 1 mM $CaCl_2$-extractable K appears be an effective soil test procedure for these soils. On the other hand the diffusion rate coefficient for the power function equation had a nonsignificant positive relationship ($r = 0.58$) with K uptake by ryegrass.

Conclusions

Potassium release from these soils is dependent on their mineralogy. The results indicate that an equilibrium exists between non-exchangeable K and exchangeable K. The amounts

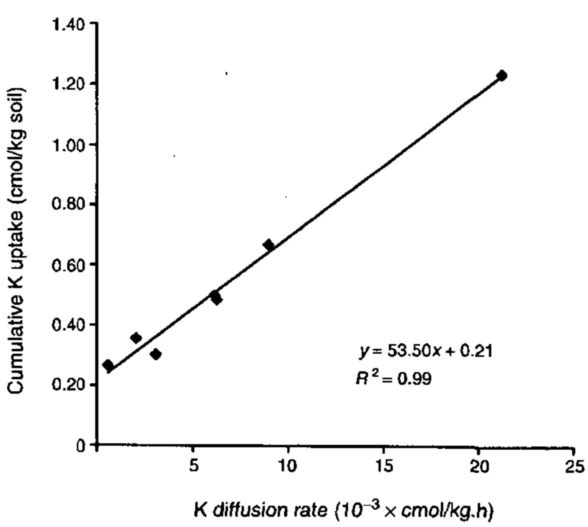


Fig. 3. Relationship between parabolic diffusion rate coefficient and cumulative K uptake by ryegrass during 260 days growth.

and proportions of K released from illite/mica containing soils are much higher than from soil containing only kaolinite and inhibited vermiculite clay minerals. Potassium release from the mineral matrix is adequately described by the parabolic diffusion and power function equations. The strong positive relationship between the parabolic K diffusion rate constant and cumulative K uptake by plants indicates that the K release process in 1 mM $CaCl_2$ might be similar to the process of K uptake by plant roots. At later plant growth stages, the slow K release from the mineral matrix did not match plant demand and plants died of K deficiency.

References

Brown G, Brindley GW (1980) X-ray diffraction procedures for clay mineral identification. In 'Crystal structures of clay minerals and their x-ray identification'. (Eds GW Brindley, G Brown) pp. 305–359. (Mineralogical Society: London)

Choudhary K, Prasad B (1997) Kinetics of potassium desorption from Inceptisols and Entisols. *Journal of the Indian Society of Soil Science* **45**, 460–464.

Chute JH, Quirk JP (1967) Diffusion of potassium from mica-like clay minerals. *Nature* **213**, 1156–1157.

Feigenbaum S, Shainberg I (1975) Dissolution of illite a possible mechanism of potassium release. *Soil Science Society of America Proceedings* **39**, 985–990.

Feigenbaum S, Edelstein R, Shainberg I (1981) Release rate of potassium and structural cations from micas to ion exchangers in dilute solutions. *Soil Science Society of America Journal* **45**, 501–506.

Glassford DK (1980) Late cainozoic desert eolian sedimentation in Western Australia. PhD thesis, The University of Western Australia, Australia.

Havlin JL, Westfall DG (1985) Potassium release kinetics and plant response in calcareous soils. *Soil Science Society of America Journal* **49**, 366–370.

Havlin JL, Westfall DG, Olsen SR (1985) Mathematical models for potassium release kinetics in calcareous soils. *Soil Science Society of America Journal* **49**, 371–376.

Huang PM, Crossan LS, Rennie DA (1968) Chemical dynamics of K-release from potassium minerals common in soils. In '9th International Congress Soil Science Transactions'. pp. 705–712. (International Society of Soil Science and Angus and Robertson: Adelaide, Australia)

Jardine PM, Sparks DL (1984) Potassium-calcium exchange in a multireactive soil system: I. Kinetics. *Soil Science Society of America Journal* **48**, 39–45.

Low MJD (1960) Kinetics of chemisorption of gases on solids. *Chemistry Review* **60**, 267–312.

Martin HW, Sparks DL (1983) Kinetics of nonexchangeable potassium release from two coastal plain soils. *Soil Science Society of America Journal* **47**, 883–887.

Mashayekhi HH, Malakouti MJ (1997) Kinetics of potassium desorption in some calcareous soils. *Soil and Water Journal* **10**, 55–62.

McArthur WM (1991) 'Reference soils of south-western Australia.' (Australian Society of Soil Science, WA Branch/WA Department of Agriculture: Perth)

Mengel K, Uhlenbecker K (1993) Determination of available interlayer potassium and its uptake by ryegrass. *Soil Science Society of America Journal* **57**, 761–766.

Mulcahy MJ (1960) Laterites and lateritic soils in south-western Australia. *Journal of Soil Science* **11**, 206–225.

Munn DA, Wilding LP, McLean EO (1976) Potassium release from sand, silt, and clay soil separates. *Soil Science Society of America Journal* **40**, 364–366.

Norrish K, Pickering JG (1983) Clay minerals. In 'Soils: an Australian viewpoint'. (Ed. Division of Soils, CSIRO Australia) pp. 281–308. (CSIRO: Melbourne/Academic Press: London)

Ogwada RA, Sparks DL (1986) A critical evaluation on the use of kinetics for determining thermodynamics of ion exchange in soils. *Soil Science Society of America Journal* **50**, 300–305.

Pal Y, Gilkes RJ, Wong MTF (2001) Soil factors affecting the availability of K to plants for Western Australian soils: a glasshouse study. *Australian Journal of Soil Research* **39**, 611–625.

Rausell-Colom JA, Sweatman TR, Wells CB, Norrish K (1964) Studies in the artificial weathering of mica. In 'Experimental pedology'. (Eds EG Hallsworth, DV Crawford) pp. 40–72. (Butterworth: London)

Rayment GE, Higginson FR (1992) 'Australian laboratory handbook of soil and water chemical methods.' (Inkata Press: Melbourne)

Sharpley AN (1990) The kinetics of soil potassium desorption. *Soil Science Society of America Journal* **51**, 912–917.

Singh B (1992) Mineralogical and chemical characteristics of soils from south-western Australia. PhD thesis, The University of Western Australia, Australia.

Singh B, Gilkes RJ (1992) XPAS: An interactive computer program for analysis of X-ray powder diffraction patterns. *Powder Diffraction* **7**, 4–10.

Soil Survey Staff (1987) Keys to soil taxonomy. 3rd edn. SMSS Technical Monograph No. 6, Ithaca, New York.

Sparks DL (1987) Potassium dynamics in soils. *Advances in Soil Science* **6**, 1–63.

Sparks DL, Jardine PM (1981) Thermodynamics of potassium exchange in soil using a kinetics approach. *Soil Science Society of America Journal* **45**, 1094–1099.

Sparks DL, Zelazny LW, Martens DC (1980) Kinetics of potassium desorption in soil using miscible displacement. *Soil Science Society of America Journal* **44**, 1205–1208.

Manuscript received 2 June 2000, accepted 6 November 2000