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The Cropping Systems Model PERFECT as a Quantitative Tool in Land Evaluation: An Example for Wheat Cropping in the Maranoa Area of Queensland

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Abstract

The mechanistic cropping systems model PERFECT was validated for six different soils and used as a tool to evaluate land suitability of wheat cropping in the Maranoa, a marginal cropping area of Queensland. Using 100 years of historic climate data from the area, and crop, soil and management parameters, simulations provided an objective insight into the key interactions of the cropping system. Current methods of land suitability evaluation are qualitative and rely on the experience of the land resource surveyor and local precedent. Consequently, where local precedent is lacking, as in marginal areas, current methods are considered less reliable and quantitative data from simulation studies will be useful. Using this process, the significance of key components of the systems (climate, plant available water capacity, soil nitrate and soil loss hazard) were quantified. These quantitative data were used to establish critical values for diagnostic attributes for land suitability evaluation in the Maranoa. The role for this approach as a tool in quantitative land evaluation is discussed.

Keywords: quantitative, land evaluation, cropping systems models Maranoa, Qld, wheat, PERFECT.

Introduction

Current methods of land evaluation, while systematic (van De Graaff 1988), are qualitative (Land Resources Branch Staff 1990) and rely heavily on the experience of the surveyor to class soils into one of a number of categories; from suitable without limitation, to not suitable for a particular land use (van De Graaff 1988). The most important decision made by the surveyor is in defining the critical limits that separate soils that are suitable for a land use from those that are not suitable (Land Resources Branch Staff 1990). Local precedent, as well as the experience of the surveyor, helps in this process. As the aim of land evaluation is to provide planners and farmers with information that will enable them to make objective land-use decisions (van De Graaff 1988), any quantitative information on the sustainability and profitability of a land-use will be useful.

Current methods rely on local farm and district records of land use to provide quantitative input to the evaluation. However, where such precedent is lacking due to poor or limited records, the reliability of the evaluation decreases. Thus, for new technology or crops, or in new or marginal areas, current methods must

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rely more heavily on the experience of the surveyor and evaluations are considered less reliable (Land Resources Branch Staff 1990).

One reason that the current qualitative approach is not as reliable in Australia as it might be, is the lower reliability of rainfall when compared with other parts of the world. For example, Russell (1984) reported that the 'long-term' coefficient of variation (C.V.) in annual wheat yield is 9% and 10% for the U.S.A. and India respectively. However, for Australia as a whole the C.V. is 19%, and 35% for Queensland in particular. Russell attributed this yield variation to the variation in seasonal rainfall.

The higher yield variability in Queensland is due to the increased dependence of wheat cropping on moisture stored in the soil over a summer fallow rather than in-crop rainfall. Generally this means that poor summer rainfall results in poor winter crops.

Variation in yield has as much to do with the amount of rainfall as with its timing, and land evaluation should take into account such temporal variability (FAO 1976). Determination of the implications of such variable rainfall in land-use systems that include economic as well as biological factors has been a qualitative process.

The recent development of computer-based biophysical simulation models such as CREAMS (Knisel 1980), EPIC (Williams 1983) and PERFECT (Littleboy *et al.* 1989) and the ready access to computers offer an objective and quantitative tool for land evaluation. This process has been termed quantitative land evaluation (QLE), and it strives to provide an insight into the profitability and sustainability, of a particular land use on an area of land, through quantitative prediction (Comerma and de Guenni 1987). Further, we believe that QLE should include quantification of risks associated with land use/land-type combinations. The use of models in QLE requires some process of validation so that a trust is developed in the model (Comerma and de Guenni 1987).

Models do not simulate all aspects of a system relevant to land evaluation, but they do use the historic climate record, soil parameters and the biophysical requirements of the land-use. In this way they focus on one of the most complex aspects of the system (Bouma 1986).

To be a useful tool for QLE, a model needs to consider more than just the yield potential of single crops. Crop rotations including pasture phases and alternative management strategies should be considered. In particular, models need to provide information that enable quantitative estimates of the profitability and sustainability of the system to be made. As such there is no complete model available that simulates all processes in complex and integrated cropping systems. It is also important that such models are not so complex as to require extremely detailed data that are not generally available. A compromise between precise models (that are difficult to use) and broad-scale models (that lack physical reality) needs to be made.

The use of models as tools in land evaluation is not a new idea. In Europe where rainfall is more reliable than Australia, models have been used as tools to determine soil trafficability and work-day opportunities using climate data and soil driven water balance models (Wosten and Bouma 1985), or for regional estimation of production potential using climate data and integrated crop and water balance models (Dumanski *et al.* 1987). The use of models in this way has been conducted in other areas as well. The International Benchmark Sites Network for Agro-technology Transfer (IBSNAT) have been involved in land evaluation in developing countries using the CERES-maize and SOYGRO models (Comerma and de Guenni 1987).

In Australia, Berndt and White (1976) used a simple soil water balance model (WBAL3) to evaluate three cropping systems for three cracking clay soils in the Darling Downs region of Queensland. They relied on empirical equations to relate soil water to yield, while surface runoff alone was used as an indicator of erosion hazard.

In a more recent study, Carberry *et al.* (1991) used the cropping models of CERES (maize and sorghum) and QNUT to evaluate crop potential in North Queensland. Whereas Carberry *et al.* assessed the chance of financial survival and level of economic risk, they did not consider sustainability of the land use, e.g. potential soil loss.

The cropping systems model PERFECT (Littleboy *et al.* 1989) has many of the attributes of a complete cropping systems model. PERFECT is mechanistic and based on physical principles, and it allows for a number of crops in rotation. Yet is has less rigorous data requirements than other models (Littleboy *et al.* 1989) and is considered appropriate for use in Queensland (Carberry and Abrecht 1991).

This paper validates and uses PERFECT to quantify profitability and sustainability of wheat cropping in the Maranoa area of Queensland. In doing this, a role for cropping systems models as tools for land evaluation is discussed. In particular, we use the model to do three things; firstly to establish any overriding effect that rainfall of the Maranoa area may have on cropping; secondly to establish the relative importance of the different limitations of moisture availability (plant available water capacity), nutrients (soil nitrate), and soil erosion hazard (soil loss); and thirdly to establish the relative critical values for these limitations that can be used to separate suitable land from unsuitable land.

Materials and Methods

Study Area

The Maranoa area lies on the western margin of the southern wheat growing area of Queensland and is centred on the town of Roma (26°35′ S., 148° 46′ E.), 500 km west of Brisbane (Fig. 1.). The annual rainfall varies about a mean of 600 mm, from 195 mm (1902) to 1526 mm (1890) with a standard deviation of 178 mm. This variation is larger than for the adjacent areas such as the Darling Downs, and reflects the less reliable rainfall. The low reliability is because the Maranoa lies between major winter and summer rainfall systems, and neither has a consistently strong influence.

The climate is generally considered a limiting factor to land suitability for winter cropping in the Maranoa (B. Slater; pers. comm.). High spring and summer temperatures, and potential evapo-transpiration (ET), as well as a high frost risk, confines the optimal flowering time for wheat to the last two weeks of August. This restricts the planting of many varieties of wheat to the first two weeks of May. The average district wheat yield from grain delivered into silos is $1 \cdot 1$ t ha^{-1} (s.d. $0 \cdot 5$ t ha^{-1}). Due to the cropping history of the area, this grain comes from crops grown mainly on grey clay soils. These soils originally supported open Mitchell grass downs. Summer cropping potential is limited by the high potential ET and unreliable rainfall over the growing season (Berndt and White 1976).

Study Soils

A recent land suitability study in the Maranoa described 48 soil types (B. Slater; QDPI, in prep.). Of these, 17 were considered suitable for cropping (B. Slater; QDPI, pers. com.). This

Table 1. Selected physical and chemical properties for six Maranoa soils

Soil Type[A] [Soil taxonomy]	Northcote Key[B]	Suitability rating[C]	Depth interval (m)	pH[D]	EC[D] (mS cm^{-1})	Org. C (%)	Tot. N (%)	CEC (cmol(+) kg^{-1})	ESP (%)	Clay (%)
Shallow-surfaced solodic soil (A horizon $\leq 0\cdot1$ m)	Dr 2·33 (now a	4	0–0·1	7·8	0·443	0·7	0·04	26·0	13·85	38
[Typic Natrustalf]	Uf 6·31[E])		0·5–0·6	8·7	1·170	N/A	N/A	38·0	22·63	56
Deep-surfaced solodic soil (A horizon $\leq 0\cdot3$ m)	Dy 2·33	3	0–0·1	6·8	0·407	1·1	0·09	11·0	0·82	25
[Typic Natrustalf]			0·5–0·6	9·2	0·359	N/A	N/A	25·0	20·80	48
Red earth	Gn 2·11	3	0–0·1	7·6	0·057	1·00	0·08	13·0	0·38	22
[Adridic Haplustalf]			0·5–0·6	7·4	0·070	N/A	N/A	8·00	0·63	26
Grey clay	Ug 5·22	3	0–0·1	8·2	0·114	0·8	0·07	39·0	3·85	58
[Typic Torrert]			0·5–0·6	8.9	0·354	N/A	N/A	36·0	16·70	60
Brown clay	Ug 5·32	3	0–0·1	7.6	0·100	1·0	0·08	25·0	0·60	52
[Mollic Torrert]			0·5–0·6	8·5	0·169	N/A	N/A	32·0	2·68	57
Red clay	Ug 5·34	2	0–0·1	8·6	0·208	1·0	0·06	40·0	4·50	58
[Mollic Torrert]			0·5–0·6	9·0	0·358	N/A	N/A	41·0	11·20	61

[A] Stace *et al.* (1972).
[B] Northcote *et al.* (1975).
[C] Land suitability ratings for wheat cropping based on virgin soils from B. Slater, pers. comm.: 1, suitable with no limitations; 2, suitable with minor limitations; 3, suitable with major limitations; 4, land currently not suitable; 5, unsuitable land.
[D] 1:5 suspension with H_2O.
[E] Classification changed as a result of cultivation.

study focuses on six soils which represent the range of surface texture, structure, morphology and chemistry commonly found in the region and thought to affect cropping productivity and degradation hazard. A summary of soil properties is presented in Table 1. The wheat cropping suitability ratings presented were derived from the recent survey. All three clays showed shrink–swell properties to varying degrees. The red clay has the most strongly self mulching surface and the grey clay the least.

The shallow-surfaced solodic soil has a higher proportion of clay in the surface than the deeper surfaced solodic. The shallow-surfaced solodic soil also has a sodic clay B horizon and cultivation has mixed this layer with the surface, resulting in an exchangeable sodium percentage (ESP) of 13·8%. ESP values in this range are considered high and have been correlated with the formation of hard dry aggregates (Coughlan and Loch 1984). As such, it would be a likely cause of crusting, hardsetting and subsequent emergence problems. This mixing has altered the Northcote classification as shown in Table 1. The deeper surfaced solodic soil also has a sodic B horizon.

Cropping Systems Model PERFECT

PERFECT (Productivity, Erosion and Runoff Functions to Evaluate Conservation Techniques) is a daily time-step continuous-simulation model of the plant–soil–water–erosion system (Littleboy *et al.* 1989). PERFECT simulates a range of cropping systems and intervening fallow management strategies (Sallaway *et al.* 1989) and was developed for the grain growing areas of Queensland and northern New South Wales. It explicitly considers the interactions between climate, soil, crop and management using mechanistic submodels.

PERFECT is based on the hydrology models of the USDA CREAMS (Knisel 1980) and EPIC (Williams 1983) models. It uses crop growth and yield models for wheat (Woodruff and Tonks 1983) and sunflower (Hammer *et al.* 1982) developed in Queensland, and a sorghum model, SORKAM (Rosenthal *et al.* 1989), developed in the United States.

Surface-management/soil loss relationships are handled by functions developed in Queensland using the universal soil loss equation (USLE) to calculate soil erosion (Freebairn and Wockner 1986). These relationships include the crop residue and cover relationships developed by Sallaway *et al.* (1989). Littleboy *et al.* (1992*a*) validated these functions against field runoff and soil loss data from wheat cropping soils from the Darling Downs, Maranoa, and central Queensland areas.

PERFECT requires daily climate data, parameters that describe the soil profile and parameters that affect crop growth. Many of these parameters can be obtained in the field as described below (see field trials and model validation).

PERFECT produces quantitative outputs such as annual yield and soil loss which can be analysed to produce probability distributions and average annual data for both yield and soil loss on each soil. The time series of annual data can provide an insight into the system but generally provides only a visual appreciation of the dynamic nature of the system. Statistical analyses of the data help to summarize the central tendencies and the scale of the variability. In addition to calculating simple statistics, another useful method for summarizing and comparing these outputs is to graph the probability of equalling or exceeding different outcomes. These graphs allow the different nature of risk for each soil and management combination to be better understood as shown by Littleboy *et al.* (1992*b*).

Field Trials and Model Validation

Before a simulation model should be used for land evaluation, it needs to be validated against field data either from well documented farmer or district records (as described earlier for the grey clay), existing research trial data, or specially constructed trials (Comerma and De Guenni 1987).

Field trials

Field trials were established to provide quantitative yield and crop development data for wheat cropping on the six soils previously described. The soil parameters plant available water capacity (PAWC), hydraulic conductivity, soil nitrate at planting, curve number (CN), soil erodibility (K factor of USLE), and bulk density required for PERFECT were derived for each soil.

Two replicate field plots were established on five of the six soils, and were cropped to wheat for four consecutive years (1987–1991) using a tilled fallow-management system to control weed growth. The sixth site, the red clay, was established in 1990 and cropped for 2 years (1990–1991).

All field sites had been cultivated for less than 15 years, except the red clay which had been cropped for 60 years. The red clay had the largest PAWC but the lowest soil nitrate levels at planting (41 kg ha^{-1} in 1991).

Each year, a range of crop performance data was recorded from five $0 \cdot 5$ m^2 quadrats in each plot. The percent seedling establishment was recorded 2 weeks after planting to allow the plant density to be input into PERFECT. Biomass was recorded at flowering and biomass and grain yield were recorded at harvest. In 1990 the grain yield from a virgin red clay site adjacent to the field trial was recorded.

Each year, at each site, a range of soil parameters were recorded. Soil nitrate in the profile was measured at planting. Gravimetric moisture samples were taken from each plot at planting, flowering and harvest. Fortnightly, a neutron moisture meter, calibrated to each soil, was used to monitor soil moisture by depth. This established soil water use by the crop and the rooting depth of wheat at each site.

The PAWC was calculated for each soil from the differences between the upper soil water storage limit (USL) and lower soil water storage limit (LSL) for each soil layer, and then summed over the rooting depth. The USL is the wettest field moisture profile after significant drainage has ceased. It was measured using ponded rings. The LSL is the driest profile under a mature wilted wheat crop. It was determined from the driest recorded profiles and −15 bar moisture percentage as determined by the pressure plate method. The USL and the LSL were expressed on a volumetric (v v^{-1}) basis. The red clay had the highest PAWC (260 mm) and the shallow-surfaced solodic the lowest (120 mm) (Table 2).

Table 2. Input parameters used in PERFECT for six Maranoa soils

Soil type (Stace *et al.* 1972)	RD[A] (m)	PAWC[B] (mm)	NO_3–N[C] (kg ha^{-1})	Curve[D] number	K-factor[E]	Slope (%)
Shallow-surfaced solodic soil	0·7	120	90	85	0·093	2
Deep-surfaced solodic soil	0·9	140	70	74	0·072	1
Red earth	1·3	190	84	85	0·052	1
Grey clay	0·8	160	82	85	0·046	2
Brown clay	1·0	180	80	85	0·046	2
Red clay	1·3	260	41	85	0·046	2

[A] RD, rooting depth of wheat.
[B] PAWC, plant available water capacity.
[C] NO_3–N, NO_3–N at planting.
[D] Curve number (Glanville *et al.* 1984).
[E] K-factor, USLE K-factor (Loch and Rosewell 1992).

Bulk densities were determined from 100 mm diameter soil cores taken from the soils when near the USL. Bulk densities were used to convert gravimetric soil moisture data to volumetric, to convert soil nitrate data from ppm to kg ha^{-1} and to determine total porosity. Saturated conductivity figures were estimated using data from similar soils (E. A. Gardner, QDPI, pers. comm.).

Curve numbers (CN) characterize the relationship between rainfall and runoff and are used in the water balance component of PERFECT. They were determined by rainfall simulation after the method described by Glanville *et al.* (1984) which uses cumulative rainfall and runoff to derive the curve number.

The K-factors of the USLE are an index of soil erodibility and were determined for the six soils after the method of Loch and Rosewell (1992) that includes sediment density in its derivation. As such, their method is suited to aggregated as well as non-aggregated soils.

Model validation

A series of simulations were carried out, using recorded climate data and measured soil parameters, to validate PERFECT against yield and soil water observed in the field trials. The wheat varieties used in the field trial were input into the model. This ensured that the period between emergence and flowering calculated in the model matched that observed.

As the grey clay site was representative of the land most commonly cropped in the past, the yield records from the district closely reflect long-term cropping on this soil. Hence, a simulation using the properties of this soil and conventional fallow management was run. The mean and standard deviation of these simulated yields under tilled fallow management were compared with those from local district records.

To test the ability of PERFECT to predict outcomes for different nitrate levels on the same soil, a simulation was run using the red clay site. The simulation used the soil properties from a virgin site which had only been cultivated since 1986 (<6 years old with soil nitrate at planting >400 kg ha^{-1}). This run was contrasted with that from an adjacent site where the soil had been cropped for 60 years.

Long-term Simulation Studies

A series of long-term (100 year) simulations were run to derive yield and soil loss data from each soil under tilled fallow-management for the current nitrate levels as given in Table 2, non-limiting nitrate levels, and low nitrate levels (41 kg ha^{-1}). The red clay, with a current nitrate level of 41 kg ha^{-1}, was included as part of this last group. The current levels of nitrate for the other soils lay between 70 and 80 kg ha^{-1}. To allow comparisons between each level of soil nitrate for wheat cropping on all soils, the missing intermediate nitrate level of 70–80 kg ha^{-1} for the red clay was also simulated.

To compare the effect of climate on crop yield, a second series of runs was carried out on each soil. This series used the milder climate of the eastern Darling Downs region of Queensland (average annual rainfall 721 mm, s.d. 172 mm) on the same six soils with non-limiting nitrate levels.

Simulated annual yields and estimated production costs were used to calculate the gross margins for the various soils. The gross margin is the difference between income and production costs and excludes any fixed costs such as rates, interest, or capital costs. A wheat price of \$100 t^{-1} and growing costs of \$75 ha^{-1} without fertilizer,and \$110 with 116 kg ha^{-1} urea (46% N, \$0·30 kg^{-1}) were used. A break-even gross margin of around \$50 ha^{-1} has been estimated for the Maranoa (R. Murphy, Economist QDPI, pers. com.).

Results

Model Validation

To validate PERFECT for wheat cropping in the Maranoa, the predicted yields and available soil water were compared with field data for all six sites (Fig. 1). Correlation coefficients of 0·97 and 0·90 were obtained for wheat yield (Fig. 1*a*) and soil water (Fig. 1*b*) respectively. These statistics are about a line fixed through the origin as shown, rather than through the mean. All data shown in Fig. 1 lie within the 95% confidence limits about the 1:1 line, that is ±0·9 t ha^{-1} and ±76 mm. However, most data (70%) lie within 0·5 t ha^{-1} and 50 mm.

To test the ability of PERFECT to reflect the mean and standard deviation of the local yield records, a 100 year wheat cropping simulation using tilled-fallow on the grey clay was performed. The local mean wheat yield is 1·1 t ha^{-1} with a standard deviation of 0·5 t ha^{-1}. PERFECT simulated a mean yield of 1·4 t ha^{-1} with a standard deviation of 0·6 t ha^{-1}. The greater mean yield of the model is expected because the model harvests all yields, even uneconomic ones, and the model does not consider disease effects.

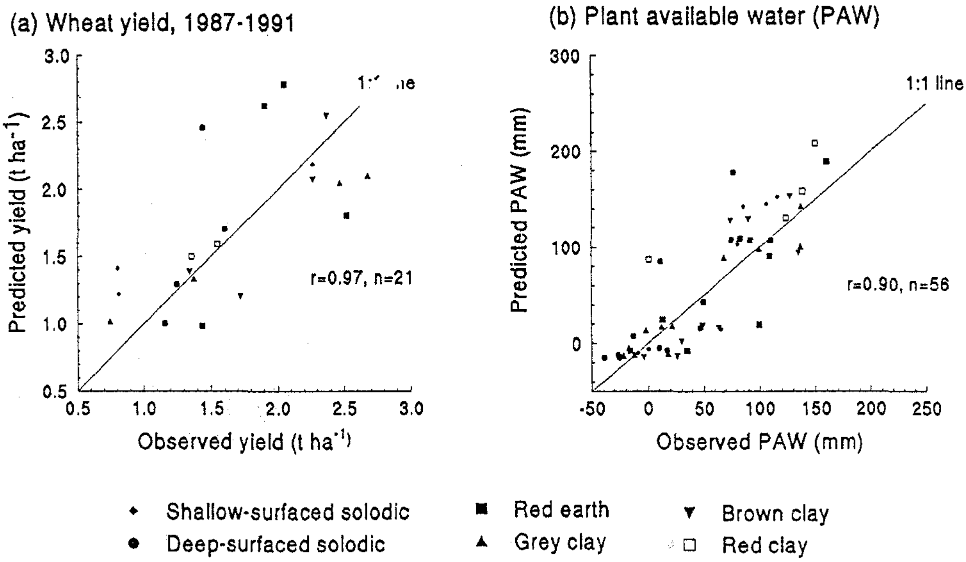

Fig. 1. Predicted *v.* observed yield and plant available water for six Maranoa soils.

To test the ability of PERFECT to simulate yields for the same soil when nitrogen conditions are altered, a simulation was performed using the soil properties of the red clay and the nitrate levels were recorded at the virgin site. The observed yield for the virgin red clay in 1990 was $2 \cdot 9$ t ha^{-1}. PERFECT simulated a wheat yield of $2 \cdot 6$ t ha^{-1}.

Long-term Simulation

Fig. 2 shows a simulation by PERFECT of the temporal variability of wheat yield and soil loss that occurs as a result of the climate each year in a 100 year sequence (1892–1991) for the grey clay. For example, the droughts of 1928–1930 and 1969–1970 are clearly reflected in the low simulated yields for these periods. The effect is less clear for soil loss. However, the episodic nature of soil loss, a well recognized feature of erosion, is also reflected in Fig. 2 where some 80% of all soil loss occurred in only 20% of years.

Comparison of climates

To identify the relative limitation of the Maranoa climate on wheat cropping, a comparison of the climate of the Maranoa to the milder (wetter) climate of the eastern Darling Downs is shown in Fig. 3. For all soils, median yield for the Darling Downs was nearly twice that of the Maranoa. There is also a general trend that median yield increases with the increasing PAWC for both climates. However, the slope of this trend is greater for the Darling Downs.

Wheat yield probabilities

Probability distributions of wheat yield for the three levels of nitrate (41 and 71 kg ha^{-1}, and non-limiting) for each soil are shown in Fig. 4. There is a general similarity between probability distributions for all soils and for each level of nitrate. All soils with at least 70 kg ha^{-1} nitrate (current and non-limiting levels) had median yields greater than 1·2 t ha^{-1}. Yields for non-limiting levels of nitrate were only larger than those for current nitrogen levels in the wetter 10% of years for most soils. The only exception, the red clay, showed improved yields due to extra nitrogen in the 30% of wetter years. In contrast, low levels of nitrate reduced median yields to approximately 0·7 t ha^{-1}, for all soils representing around a 40% decrease.

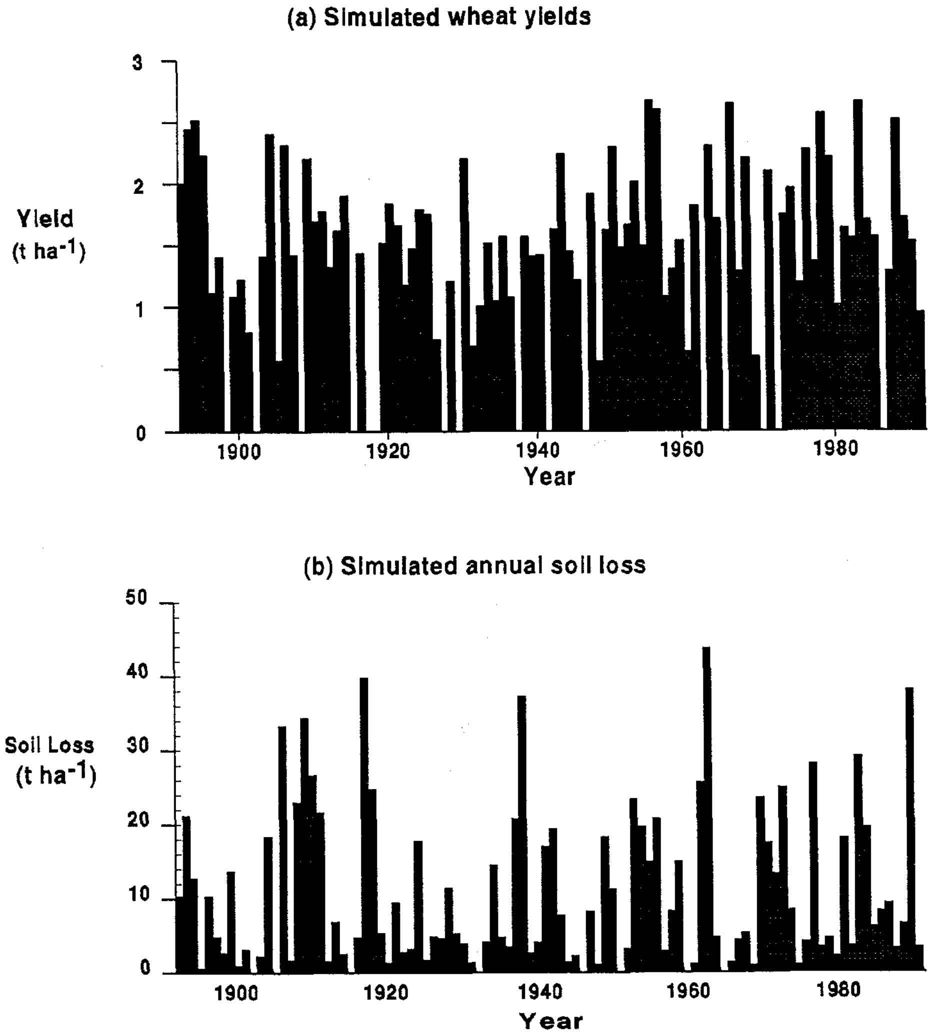

Fig. 2. Time series of predicted wheat yield and soil loss for a grey clay in the Maranoa (1892–1991).

There are also some clear differences between these distributions. The red clay with low nitrate produced yields greater than 1 t ha^{-1}, but only in the wetter 30% of years. The red earth produced yields of around 1 t ha^{-1} for most years (70%).

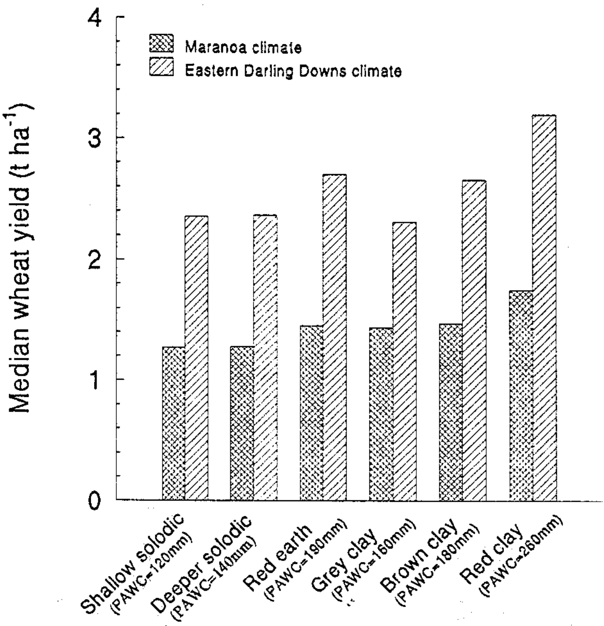

Fig. 3. Comparison of median wheat yield for six Maranoa soils and plant available water capacities (PAWC) under two climates. (The climate of the eastern Darling Downs is wetter and cooler than the Maranoa. The climate of the Maranoa is considered marginal for cropping.)

Soil loss probabilities

Probability distributions of annual soil loss for the three levels of nitrate are shown in Fig. 5. For each soil, soil loss is least under the current and non-limiting nitrate conditions. There is little difference between soil loss under these two levels. The predicted soil loss is much higher under wheat cropping with low soil nitrate than for the other levels. The deep surfaced solodic had the highest soil loss of all soils (34 t ha^{-1}) and the red earth the least (4 t ha^{-1}).

Average annual yield, gross margin and soil loss

Table 3 presents the annual means for the data in Figs 4 and 5, as well as the average annual gross margins. The gross margins reflect the yields but amplify the differences between soils because they account for the similar cost of production for all soils. For the low nitrate levels, wheat cropping, on all soils but the red earth, lost money or barely broke even. For both the current and non-limiting nitrate levels, there was a small positive trend between the soils PAWC and gross margin. However, for PAWCs of less than 180 mm, little difference in gross margin is evident.

The effects of including the cost of fertilizer to provide adequate nitrogen did not affect the trends described and showed that such practice was likely to be profitable on all soils. However, the lower PAWC soils, the shallow and deep surfaced solodic soils and the grey and brown clays are likely to be only marginally profitable when the local break-even gross margin of \$50 ha^{-1} is considered.

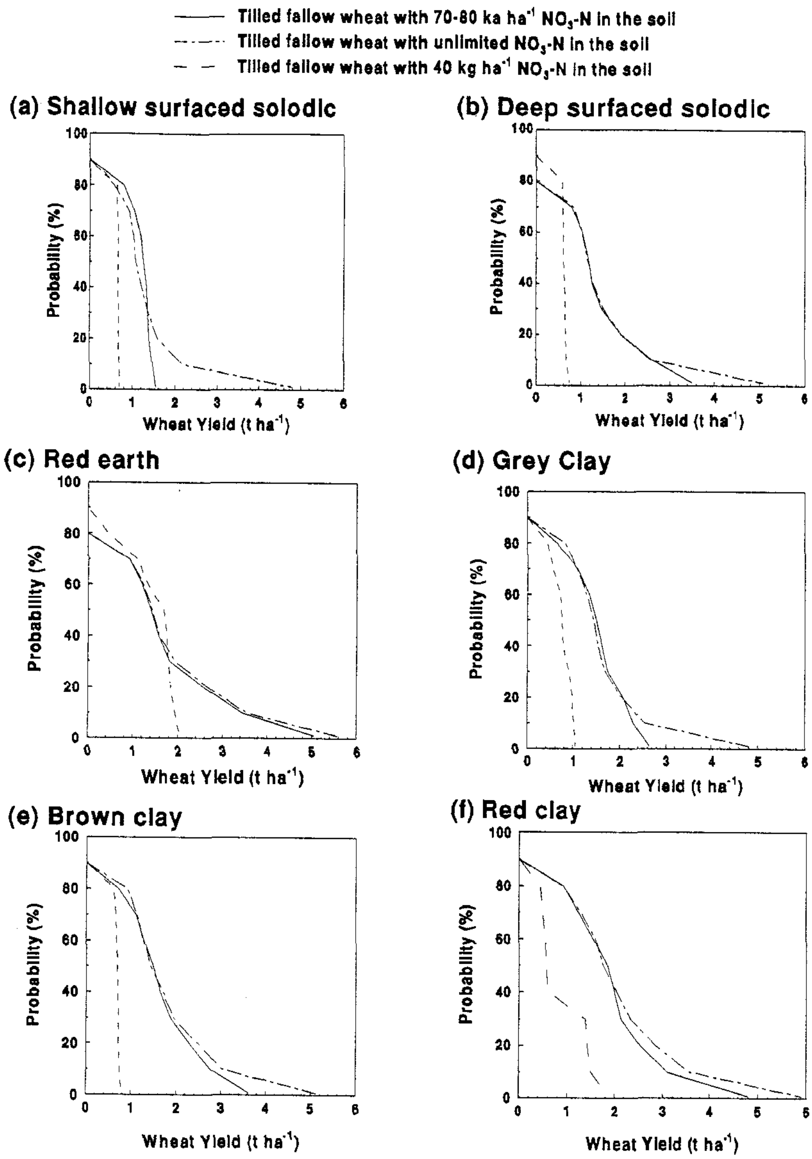

Fig. 4. Probability of exceeding a given wheat yield for six Maranoa soils with different levels of soil nitrate at planting.

Discussion

Model Validation

It is sensible to validate a model against field data before using it for land evaluation. This builds a trust in the model and in its ability to predict outcomes such as yield. For the six soils used in this study, PERFECT was able to make acceptable predictions of the yield and available soil water (Fig. 1). The accuracy of the model in the Maranoa was similar to that reported by Littleboy *et al.* (1992*a*) for other cereal cropping regions of Australia.

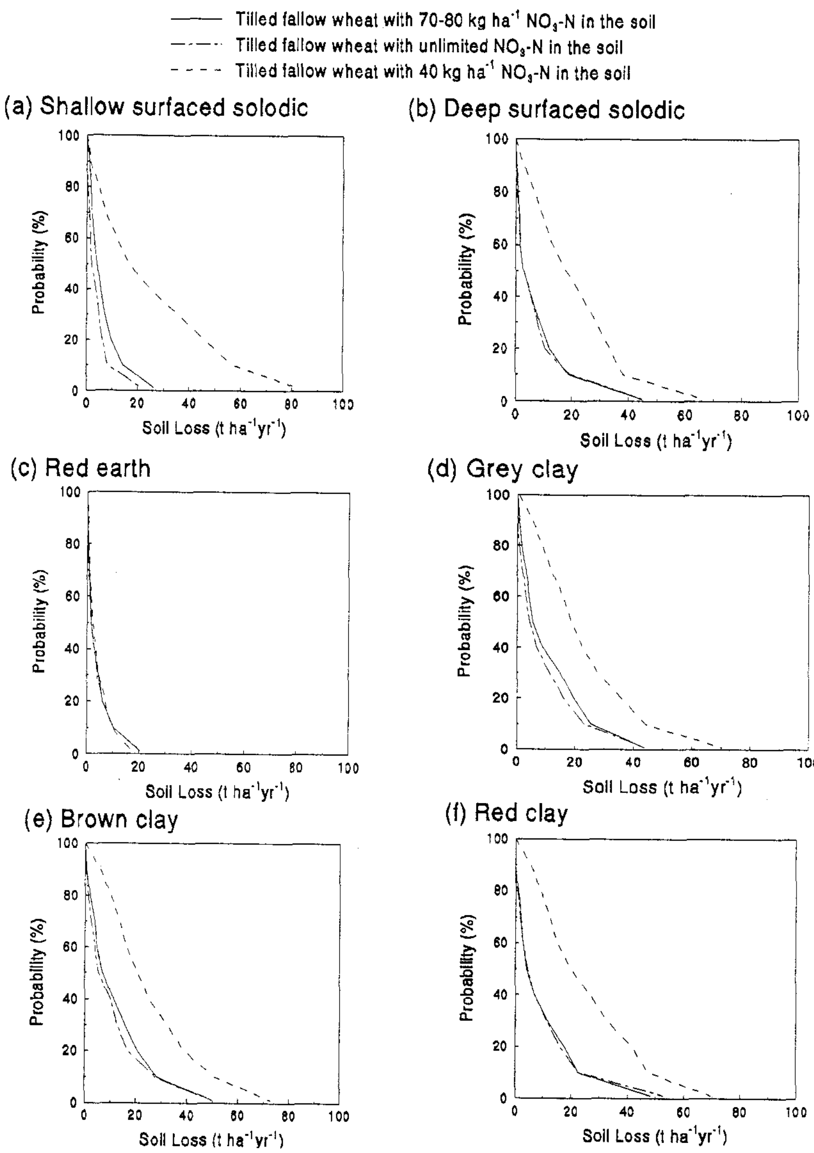

Fig. 5. Probability of exceeding a given soil loss for six Maranoa soils with different levels of soil nitrate at planting.

The potential scale of the error for single year yield simulations (around $0 \cdot 5$ t ha^{-1}) would be considered large to a farmer. However, such errors balance out over the longer term and the model was able to simulate the mean and standard deviation of the historic wheat yield records of the district. The over prediction of average yield by $0 \cdot 3$ t ha^{-1} was expected. This is because the model counts the yield of all crops including those that were not economic to harvest. Also the model does not consider catastrophic effects such as pests, disease or frost losses. However, the standard deviation of the simulated yields $0 \cdot 6$ t ha^{-1} was only $0 \cdot 1$ t ha^{-1} greater than that of the records.

Table 3. Simulated average annual yields and soil loss, and calculated gross margins for six Maranoa soils

Gross margins were calculated with wheat at \$110 t^{-1} growing costs of \$75 ha^{-1}. Values in parentheses represent gross margins using added nitrogen fertilizer and costs of \$110 ha^{-1}

Soil type	Yield[A] ($t\ ha^{-1}$)	Yield[B] ($t\ ha^{-1}$)	Yield[C] ($t\ ha^{-1}$)	Gross margin[A] (\$ ha^{-1})	Gross margin[B] (\$ ha^{-1})	Gross margin[C] (\$ ha^{-1})	Soil loss[A] ($t\ ha^{-1}$)	Soil loss[B] ($t\ ha^{-1}$)	Soil loss[C] ($t\ ha^{-1}$)
Shallow-surfaced solodic soil	0·6	1·0[D]	1·2	−9	35[D]	57 (22)	24	16[D]	10
Deep-surfaced solodic soil	0·5	1·2[D]	1·5	−20	57[D]	90 (55)	34	13[D]	12
Red earth	1·3	1·6[D]	1·6	68	101[D]	101 (66)	4	3[D]	2
Grey clay	0·7	1·3[D]	1·4	2	68[D]	79 (44)	22	10[D]	10
Brown clay	0·6	1·5[D]	1·7	−9	90[D]	112 (77)	25	10[D]	9
Red clay	0·7[D]	1·8	1·9	2[D]	123	134 (99)	21[D]	9	8

[A] With soil NO_3-N at 41 kg ha^{-1}.
[B] With soil NO_3-N at 70–80 kg ha^{-1}.
[C] With soil NO_3 -N non-limiting to plant growth.
[D] Under current soil NO_3-N status.

PERFECT was also able to simulate the effects of different nitrate levels on the same soil in a single year. The predicted yield from the virgin red clay site for 1990 was slightly lower than that observed. However, this underestimate was well within the range established from Fig. 2.

Increased confidence in yield predictions over the longer term provides a sound basis for subsequent gross margin analysis. Similarly, confidence in the available soil water predictions provides confidence in the model's water balance and runoff predictions. This in turn provides confidence in the predictions of soil loss from the previously validated runoff–cover–erosion relationships (Littleboy *et al.* 1992*a*) of the model.

Long-term Simulations to Explore Major System Components

PERFECT is able to predict outcomes for individual years, and also reflect the dynamic behaviour of the cropping system for long sequences of years, as shown in Figs 2 and 3 respectively.

By using PERFECT and subsequent analyses, a clearer understanding of the potential and limitations associated with wheat cropping in the Maranoa was achieved. This 'desk-top' exploration of data provided a rapid way to study the fundamental interactions in the system (climate and rainfall, nitrate, PAWC, and soil loss).

As it is not easy to compare or contrast systems directly from time series data, as depicted in Fig. 2 some further method of analysis is required. Summary statistics, such as the median, provide some insight as in Fig. 3. However, graphing the probability of equalling or exceeding a given outcome, as in Littleboy *et al.* (1992*b*), was found to be more useful. This method allowed more quantitative comparison of the risks between soils and for different managements, making similarities and differences between soil and management combinations, as in Figs 4 and 5. These comparisons, when combined with gross margin analysis, help to objectively establish the relative performance of soil and management scenarios.

Climate and rainfall

Climate and rainfall were perceived to be a limitation for production in the Maranoa (Berndt and White 1976). In the recent land resource survey, this limitation was incorporated by rating all soils as having an available moisture limitation (B. Slater, QDPI, pers. comm.). However, such general conclusions would benefit from quantitative data that identify the scale of any limitation and its likely effects.

Fig. 3 shows that the limitation exists as expected. It also quantifies the extent of this limitation. It demonstrates that wheat yields on the Darling Downs are nearly double those from the Maranoa, independent of soil type. This verifies the approach generally adopted in the Maranoa that all soils be rated as having an available moisture limitation.

This result alone does not verify the assumption that only the virgin red clay should be rated as only having a minor available moisture limitation compared with the other soils which were rated as having a major limitation. However, the increased yields on the red clay in the 30% of wetter years, due to its larger PAWC, compared with increased yields on the remaining soils in only the 10%

of wettest years, does support this conclusion. Thus, simulation may not always disprove a well conducted survey, but it can quantify the decision criteria used on diagnostic attributes.

Nitrate

Current levels of soil nitrate at planting for most wheat cropping soils in the Maranoa are 70–80 kg ha^{-1} for all soils in the study. Extra nitrogen (non-limited) only made marginal increases to yield and only in wetter years. This indicates that, in the Maranoa climate, an optimal level of soil nitrate at planting would be around 80 kg ha^{-1} or greater. In contrast, all soils showed significantly lower yields when under the lower level of nitrate (40 kg ha^{-1}). This level of nitrogen was measured on the red clay after some 60 years of cropping, and may have occurred after as few as 20 years (Dalal and Mayer 1987). These results suggest that nitrogen management, through fertilizer application or some legume rotation, will be necessary on all soils as part of a sustainable cropping system and should be considered in land evaluation.

Wheat yields also increased on the red clay with low levels of nitrate in the wetter 30% of years. This result is due to the effect of increased moisture available to the plant in these wetter years compensating for the lower levels of nitrogen (D. Woodruff, QWRI, pers. comm.). The quality (protein %) of the grain in these years would be expected to be low. A similar result is observed for the red earth where wheat yields under the low nitrate level were greater than for other soils. The PAWC of the red clay is 260 mm and that of the red earth is 190 mm, all other soils had lower PAWCs. This suggests that, in low nitrogen situations, crops on the other soils were moisture-stressed even in the wetter years. Such results are typical of the complex interactions driven by climate and rainfall that determine water and nitrogen use by crops.

PAWC

A large PAWC can provide a buffer to crops, placing less reliance on in-crop rainfall. Hence, PAWC may be expected to be a very significant factor in marginal areas. However, the relatively flat response of median yield to increasing PAWC (Fig. 3) suggests that PAWC may be less important in the Maranoa than first thought due to the nature of the rainfall. This result is also reflected in the similarity between the probability distributions for yield on all soils with non-limiting nitrogen (Fig. 4).

The relationship between PAWC and median yield, although weak, does provide a quantitative insight into the moisture availability limitation. This limitation is determined from land attributes such as climate, PAWC, soil texture and structure, and rooting depth. For example, the shallow-surfaced solodic soil was originally expected to be the least suitable for cropping of all the soils studied. Its PAWC of 120 mm over a rooting depth of only 0·7 m was considered small. The simulations verified this, as profits for wheat cropping on this soil were low for all levels of nitrate.

However, profits on the grey clay were also low and PAWCs in excess of 180 mm were required to make cropping more reliable. Nonetheless, soils with a PAWC of less than 120 mm would be either marginal or unsuitable for cropping, independent of soil type.

Soil loss

Fig. 5 and the soil loss data of Table 3 show that nitrogen management is important in reducing soil loss and improving sustainability of wheat cropping on these soils. The red earth had the lowest rate of soil loss for all levels of nitrate due to its low slope and freely draining nature, allowing greater infiltration of rainfall and consequently less runoff. There was little difference in soil loss rate between the other soils for each level of nitrate. Low nitrate levels resulted in poor crops with low amounts of crop residue over the summer fallow period.

Consequently, soil loss rates were nearly double that when nitrate levels were higher. The similarity between soil loss rates for each soil at each nitrate level is a function of the low slopes (1–2%) used. These slopes limited the effect that the different soil erodibilities had in determining soil loss. These simulations did not consider the effects of nutrient export in sediment or in grain which would increase the rate of nitrogen decline and soil loss.

Use of Models in the Land Evaluation Process

Models, such as PERFECT, do not consider all aspects of a cropping system. However, they can be used to better understand the complex interaction between climate, soil, crop and management. The quantitative insights that PERFECT provides offer a tool for land evaluation. This type of quantitative information can be used to establish the relative importance of specific limitations, and critical values for associated diagnostic land attributes. For example, in an approach similar to that used in this paper, Grundy *et al.* (1992) used PERFECT to improve land evaluation in North Queensland by considering yield and soil loss probabilities. These data were then used to establish decision criteria for the limitation subclasses.

Yield and PAWC

In this paper the results of the simulations were used to identify a critical PAWC of 120 mm below which cropping was uneconomic, i.e. produced gross margins of <\$50 ha^{-1}. For the Maranoa, this PAWC could be translated into a diagnostic attribute such as rooting depth for different soils. For example, a rooting depth of at least 0·6 m would be required on a uniform clay soil, whereas at least 1·0 m would be required on a sandier textured uniform soil.

Yield and nitrate at planting

This process also quantified the effect of nutrient deficiency on yield, showing that cropping in the Maranoa was not economic when soil nitrate levels fall to 40 kg ha^{-1} at planting. This fall could occur after only 20 years of continuous cultivation. Such insight allows better interpretation of laboratory data in terms of sustainable land-use. For example, in the Maranoa, Dalal and Mayer (1987) have shown that soils with low levels of nitrate at planting would have low total nitrogen levels of around 0·05%. Therefore total nitrogen could be used as a surrogate for soil nitrate at planting. Direct measurement would be preferable but requires established cropping lands and timely sampling, and processing. These are not always easily achieved in field surveys.

Soil erosion hazard

Soil erosion hazard and sustainability can be related to the rate of soil loss and to the depth of the soil profile and of any subsoil layer that may cause restriction to root penetration. As the rate of soil loss is similar on all soils with the same level of nitrate, it is a simple task to rank the soils with respect to their soil-loss hazard and sustainability, i.e. the deeper the rooting depth the lower the hazard.

The two solodic soils would be most at risk of any of the soils due to the dispersive properties of the clay subsoil. The shallow-surfaced solodic soil would be most at risk due to the highly sodic B horizon only 1·0 m from the surface. Cultivation has already begun to mix the two layers. This can cause crop emergence problems and poor rainfall infiltration due to surface crusting after heavy rains, as well as narrow workable moisture range. The deep surfaced solodic soil has a similar problem but subsoil exposure is less at risk because of its deeper (0·3 m) A horizon. The remaining soils, in decreasing order of soil erosion hazard, are the grey clay, the brown clay, the red clay and the red earth.

However, the task of defining a critical limit depends on economic considerations, such as the likely reduction in yield. The depth of soil lost over 100 years at a rate of 10 t ha^{-1} $year^{-1}$ (assuming current nitrate levels on most soils studied) is about 0·1 m. As discussed above, a loss of this magnitude would have greatest effect on the shallow surfaced solodic soil by exposing the sodic B horizon resulting in poor infiltration, crop establishment and higher erosion. In addition, the PAWC of the soil would be reduced to below 120 mm, decreasing the potential for profitable cropping. While the grey clay and the deep surfaced solodic soil would also become less profitable through such erosion, they would remain profitable for longer.

Soil nitrate levels were also shown to affect soil loss rates. Low nitrate levels will result in double soil loss rates through poorer crops with lower levels of crop residues. This would again have its greatest effect on the lower PAWC soils, but would also begin to affect the other deeper soils.

Application of modelling in the land evaluation process

A series of simulations run prior to any land resource survey could be used to objectively understand how major components of the system interact, such as those discussed here. For example, the general relationship between PAWC and profitability could be established using a range of soils such as those in this paper. This information could then be used to determine the relative importance of many diagnostic attributes and help determine the level of precision that should be used for each. In addition, such insight could be translated into a preliminary diagnostic attribute to assist in framing and interpreting the field survey. The critical level of each limitation that determines suitable land from unsuitable land is of prime importance. As the survey progresses, more information will become available to refine these first approximations and more simulation studies may be required. As cropping systems models also consider alternative management systems, this information could also be included to support land-use recommendations.

As land use changes, re-interpretation of old land resource survey data is often required. In some cases, entirely new surveys are needed. By requiring a more quantitative database for surveys, and providing a more quantitative basis for evaluations, the use of models will enhance the utility of existing surveys for subsequent re-interpretation. In addition, models could help identify key parameters and attributes necessary for new surveys and the level of precision that is needed. For example, this paper showed that detailed measurement of PAWC in the Maranoa would be less productive than improved measurement of soil nitrate at planting. Such insight will help to make surveys better focused and more efficient.

Conclusions

This paper used PERFECT as a tool to provide the quantitative simulations of a cropping system in a marginal rainfall area. The climate was shown to be a major limiting factor in the Maranoa. Soils with a PAWC of <120 mm were shown to be barely profitable and were most at risk from soil loss, i.e. they are unsuitable as wheat cropping soils.

Current levels of soil nitrate (70–80 kg ha^{-1}) were shown to produce crop yields similar to non-limiting nitrate levels in most years (90%). This level of nitrate may be considered to be near optimal for wheat cropping in the Maranoa. Low levels of nitrate (40 kg ha^{-1}), as observed on the red clay after some 60 years of cropping, resulted in lower yields and increased rates of soil loss. These levels were shown to be at best marginally profitable and were less sustainable for all soils. Overcoming nitrogen deficits with added fertilizer was shown to be only marginally profitable for most soils in the Maranoa. These results indicated that management of nitrogen is essential for profitable and sustainable cropping in the Maranoa. Such management may include rotations with lucerne or medics or chickpeas.

This work ratified many of the climate, rainfall and PAWC interactions already understood in the Maranoa, and was able to express them quantitatively. These quantitative data were translated into critical limits for diagnostic attributes. Such quantitative limitation data can be re-interpreted more efficiently than current survey data and, if required, key parameters, such as nitrate at planting, can be described or measured with increased precision.

PERFECT is a useful tool for land evaluation in southern Queensland, and other models could be equally suited to other areas. However, models should be validated for the area and should include relevant crop growth and erosion components. These models should provide outcomes that can be analysed quantitatively. Then models, such as PERFECT, can be used in quantitative land evaluation.

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