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Drought risk and vulnerability in rainfed agriculture: Example of a case study from Australia

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SUMMARY – Many regions in Australia have extremely high levels of rainfall variability leading to periodically high drought risk for many agricultural enterprises. In this analysis, vulnerability and drought risk analysis methods incorporating Plant Available Water Capacity (PAWC) and soil moisture recharge levels are shown to have value in strategic planning for a rainfed crop and a pasture regime. Through input from specialist agronomists maps of PAWC at broad spatial scales for Australia have been produced. These maps show wide variation in drought vulnerability levels across Australia with levels of high vulnerability in some regions. Use of regional shire scale analysis illustrates important regional differences, important for strategic drought risk vulnerability assessments. For tactical-scale drought risk assessments, use of integrated PAWC, soil moisture recharge levels, crop simulation models and a climate forecasting system provides improved value.

Key words: Strategic, tactical, vulnerability, crop simulation, climate forecasting.

RESUME – *Risque de sécheresse et vulnérabilité en agriculture pluviale : Exemple d'un cas d'étude en Australie". Beaucoup de régions en Australie ont de très hauts niveaux de variabilité des chutes de pluie causant périodiquement de hauts risques de sécheresse pour beaucoup d'entreprises agricoles. Dans cette analyse, la vulnérabilité et les méthodes considérant la quantité d'eau disponible pour les plantes (PAWC) et les niveaux de rétention en humidité des sols, démontrent avoir de l'importance dans la planification stratégique pour les cultures alimentées par la pluie et les pâturages. Avec la contribution d'agronomes spécialisés, des cartes de PAWC de grande dimension pour l'Australie ont été produites. Ces cartes montrent de larges variations des niveaux de vulnérabilité à la sécheresse à travers l'Australie avec des niveaux de haute vulnérabilité dans quelques régions. Une analyse à l'échelle locale illustre des différences régionales importantes, ceci étant indispensable pour des évaluations stratégiques de vulnérabilité au risque de sécheresse. Pour les évaluations tactiques des risques de sécheresse, l'utilisation du PAWC intégré, de niveaux de rétention en humidité des sols, de modèles de simulation de cultures et d'un système de prévisions climatiques fournissent des données améliorées.*

Mots-clés : *Stratégique, tactique, vulnérabilité, simulation de cultures, prévisions climatiques.*

Introduction

Hewitt (1997) points out that, globally, drought ranks first among natural disasters in the numbers of persons directly affected. Agricultural drought is the leading cause of crop failure throughout the world (Wilhelmi *et al.*, 2002). However, importantly, the impacts of drought depend largely on soil or land preconditions, farming practices and other aspects of societal vulnerability at the time the drought occurs. Remarkably, losses from drought can significantly increase without there being any quantified evidence of an increased number in or severity of droughts (Wilhite, 2000). Additionally, rainfed agricultural drought is a complex phenomenon in that it links meteorological drought and soil moisture deficits to impacts on crop yields and livestock or grazing production (Wilhite and Glantz, 1987; Wilhelmi *et al.*, 2002). There is continued effort to demonstrate in an objective manner those regions, communities, or farming systems that are more vulnerable to drought risk.

Drought risk can be viewed as a product of both exposure to the climatic hazard and the vulnerability of farming or cropping practices to drought conditions (Wilhite, 2000; Wilhelmi *et al.*, 2002). Vulnerability to drought can also be regarded in a dynamic sense and, in particular, be the result of land use and management as well as government farm policies and other societal factors (Wilhelmi *et al.*, 2002; Nelson *et al.*, 2005).

It remains the case that while many farmers partially mitigate drought impacts through judicious use of crop selection, irrigation, and tillage practice, at many levels of government the emphasis on disaster management has been mostly on the response to and recovery from drought (Stone and Meinke, 2007). In many world regions there is little or no attention to mitigation, preparedness, and prediction of drought. In attempts to move more towards a proactive, risk management approach a more concerted effort towards planning for drought involves vulnerability assessment (Wilhite, 1993, 1997, 2000; Wilhelmi and Wilhite, 2002).

However, in assessing regional or national vulnerability, issues related to the complexity in assessment leads to subjectiveness in measurement, partly because issues related to vulnerability may only be quantified as a relative measure (Downing and Bakker, 2000). Vulnerability factors may include economics, technology, social relations, demographics and health, biophysics, individual perception and decision-making in industry and in government. Furthermore, vulnerability levels may constantly change because of changes in farming and associated technologies so that even from season to season vulnerability can vary enormously (Downing and Bakker, 2000). This makes modelling and mapping drought vulnerability a challenging task. Nevertheless, if assessments appropriate for drought vulnerability could be produced, these systems would greatly aid key decision-makers in government and industry in identifying appropriate mitigation actions, hopefully before the next drought onset. The aim would be to lessen the impacts and, possibly, place more emphasis on self reliance by farmers in drought risk management.

In the example for Australia, especially north-east Australia, rainfall variability is extremely high so that rainfed agricultural production values are also extremely variable (Nicholls *et al.*, 1997; Potgieter *et al.*, 2002). However, in some regions, quantifying aspects associated with drought vulnerability has, until recently, received only scant attention. This is despite the fact that drought continues to seriously impede rural economic development in Australia and government continues to seek alternative solutions to reactive drought policies (or, as some call it "proactive reactivity") (Nelson *et al.*, 2005).

The aim of this manuscript is to review issues associated with drought risk and vulnerability, especially in relation to regions in Australia that suffer enormously from drought impacts. This review will address issues related directly to rainfed agricultural systems in order to provide a measure of improved capability for industry and government in drought risk management systems. A further aim is to provide an assessment of the use of integrating measures of drought vulnerability with developments in seasonal climate forecasting in order to provide an example of processes that may further assist in tactical aspects of drought management.

Methods

Strategic approaches

A key approach in this analysis was to identify those factors that define agricultural drought risk and vulnerability in rainfed cropping and agricultural systems and to review two conceptual methods: (i) use of Plant Available Water Capacity (PAWC) as a proxy for risk assessment and vulnerability (e.g. Wilhelmi *et al.*, 2002; Potgieter *et al.*, 2005; H. Cox, pers. comm.); (ii) use of more complex vulnerability assessments that incorporate human, financial, physical, social and natural dimensions that can also be individually ranked before being aggregated into a measure of drought risk vulnerability (e.g. Nelson *et al.*, 2005).

Maps produced by the Bureau of Rural Sciences provide broad soil water level potential values (in mm) as aggregated from the dominant soil types within each soil landscape across Australia. Some of these values were further refined for simulating starting soil moisture values (using APSIM) (McCown *et al.*, 1996) at shire scales for North-Eastern Australia. In this, (following Wilhelmi *et al.*, 2002), PAWC of soil is estimated as the difference in water content between field capacity and permanent wilting point. The water-holding capacity of soil is largely dependent on soil porosity which depends on soil texture and structure. An effective measure, therefore, is the use of the soil root zone water-holding capacity as a significant agricultural drought vulnerability factor. The agro-climatic component of this type of drought vulnerability analysis needs to be based on those measures that correlate well with drought impacts. In this respect, water availability can be applied as a key factor in this type of drought risk assessment because it is particularly critical in determining plant survival, development, productivity

and ultimately crop yield through the availability of soil moisture during the course of the growing season (Dale and Shaw, 1965; Rosenberg *et al.*, 1983; Wilhelmi *et al.*, 2002; Wilhelmi and Wilhite, 2002). Indeed, Wilhelmi *et al.* (2002) provide compelling argument for this approach in stating that "the best characterisation of the climatology of the state from the agricultural drought vulnerability perspective is the probability of seasonal crop moisture deficiency". Wilhelmi and Wilhite (2002) provide the following useful example of an index-scale of PAWC (in mm) and associated index scale drought risk rating. This type of approach has been applied in this study (Table 1).

Table 1. Example of an effective index-scale of PAWC (in mm) with associated index scale drought risk rating (Wilhelmi and Wilhite, 2002)

	PAWC	Index
Water-holding capacity (mm) 150-200 mm	2	
	100-150 mm	3
	< 100 mm	4
Probability of seasonal crop moisture deficiency (%)	Less than 30% (low)	2
	30-50% (moderate)	3
	50-70% (high)	4
	More than 70% (very high)	5

It is suggested this type of approach can provide useful strategic information for decision-makers involved in drought risk monitoring and social welfare measures.

To initiate an overall assessment, maps of soil types were obtained from the Australian Bureau of Rural Sciences, especially through information provided through the National Agricultural Monitoring System (NAMS) (<http://www.nams.gov.au>). Detailed descriptors of likely PAWC can be obtained from local specialists, agronomists, and rural extension officers working "in the field" to develop initial indications of PAWC. In the NAMS information, "data are sourced and modified by the Australian Bureau of Rural Sciences, from the Australian Soils Resources Information System (ASRIS) (http://www.asris.csiro.au/index_le.html#) which was produced as part of the National Land and Water Resources Audit in 2001". In this approach estimations are derived from spatial analyses of point-based models, polygon-based models or combined point and polygon models depending on the quality of the available data. For more detailed studies, more extensive measurement and appraisal has been carried out in each shire. For this study, case-study shires in which sorghum is a major crop grown in the summer period in Australia, but which is subject to high levels of year to year rainfall variability, is also provided. Agricultural drought is regarded as being relatively common in these production regions and, thus, considered ideal for this study and review.

More complex social and natural systems inputs may also be useful for this type of analysis in that the individual dimensions of drought vulnerability can be weighted in order to provide appropriate information in the context of interest. In particular, in this type of approach the extent of on-farm land degradation and the frequency of extreme growth conditions can be used to construct an indicator of "natural capital", assuming that the vulnerability score increases with the proportion of degraded land and the proportion of extremely low growth days (Ellis, 2000; Nelson *et al.*, 2005). This approach also supports the notion that issues of land use are critical in strategic assessments of drought risk and vulnerability and can be regarded as one of the driving forces behind water demand and critical factors of agricultural drought vulnerability (Wilhelmi and Wilhite, 2002). In particular, this approach of applying a vulnerability index to an important issue such as drought risk may support the concepts of Nelson *et al.*, (2005), in which they state in that a "vulnerability index can assist in ensuring that government policies enhance the self-reliant resilience of farm households in regions at risk".

Tactical approaches

In order to provide more tactically-based systems suitable for decision-makers attempting to manage during or ahead of drought periods, developments in regional-scale models for forecasting likely crop yield (deficits) have been assessed here. These allow quantification of production risk through the integration of crop modelling with seasonal climate forecasting (Hammer *et al.*, 2000). The seasonal climate forecast model used to provide case-study examples in this study (which,

importantly, is capable of integrating climate model outputs with crop simulation model outputs) is based on the system developed by Stone *et al.* (1996). This system uses patterns or "phases" of the Southern Oscillation Index (SOI) developed through the combination of principal components analysis and cluster analysis to analyse patterns incorporated in a time series of the SOI over 100 years. In this way, forecasts of the effects of likely deleterious seasonal conditions on rainfed crop yield can be applied by industry, government and farmers to help manage drought risk and vulnerability issues within respective agricultural industries in likely poor years. Applications of this approach in aiding decisions in the transport and bulk handling of grain, importing, exporting, forward selling or buying, and especially in seeking indemnification against low production in drought years can be helped by incorporation of these technological developments.

Indeed, a preliminary modelling study of the reliability of supply of feed-grains in northern regions of Australia emphasised the value of this type of information in aiding industry in drought-risk management (Hammer *et al.* 2003). Following the success with use of relatively simple agro-climatic modelling for rainfed wheat in Australia (Stephens *et al.*, 2000; Potgieter *et al.*, 2002) the sorghum yield forecasting system was considered potentially useful for this analysis through incorporation of a simple water stress index model developed by Fitzpatrick and Nix (1969), determining input parameters (including dynamic sowing criteria and plant available water holder capacities), by calibrating the model against actual shire yield data, and assessing the accuracy of this model in predicting actual shire yields using cross-validation techniques (Potgieter *et al.*, 2005). In this, model input calibration was performed to determine the optimal PAWC and optimal sowing criteria for each shire. The final values of PAWC, sowing criteria and those critical periods [the period during the growing season when the daily average water stress index (SI) correlates best with the actual shire yield] were chosen based on goodness of fit to actual shire yields and expert knowledge of agronomic practice and soils. Maintaining a soil water balance through to the fallow period prior to the crop was required to determine the amount of available soil water at sowing as this is known to have major effects on crop yield (Muchow *et al.*, 1994). The fallow simulation was started on the 1st of April of each year, assuming 10 per cent of the PAWC was in the soil at that time. This assumption reflected what would be expected in a conventional summer cropping system whereby April available soil water would have been depleted by the previous summer crop which would have matured by this time (Potgieter *et al.*, 2005).

Results

In the first instance, maps that incorporate soil type and knowledge of PAWC were produced in order to gain an initial appraisal of likely more vulnerable regions in Australia (Fig. 1). A surprising outcome from this initial analysis was the realisation that many parts of eastern Australia close to the eastern coast have relatively low levels of PAWC (e.g. 75-100 mm) and thus, potentially, increased vulnerability to drought risk. These regions are in, what are considered to be, more reliable rainfall zones but also subject to periodic high levels of rainfall variability (Nicholls *et al.*, 1997). Conversely, there are regions located further inland in southern Queensland (shaded dark green – 150-175 mm PAWC) that have relatively high levels of PAWC and, presumably less long-term drought-risk vulnerability in a major cropping region of Australia. Additionally, it is apparent that some areas in eastern Queensland possess usefully high levels of PAWC associated with deep clay soils. Many regions of inland Australia, but also extending into far south-western Victoria and a considerable portion of South Australia (above, what is referred to as, the "Goyder Line" that depicts a recognised boundary of the northern limit of sustainable agriculture), are depicted as having potentially low PAWC (50-75 mm PAWC) and thus potential for increased drought-risk vulnerability. Importantly, a major rainfed wheat production region in south-west Western Australia, known for extensive coverage of sandy soils, has, not surprisingly, relatively low PAWC (75-100 mm PAWC) and thus enhanced potential for increased drought-risk vulnerability when definitions applied in this study are used. In key sorghum growing shires, the shires in what is referred to as the Eastern Darling Downs located in southern Queensland have "medium" levels of PAWC while shires a little further west have relatively low PAWC values and, one suspects, higher drought vulnerability likelihood.

When more detailed assessment of PAWC was made incorporating higher spatial scales and, importantly, in relation to specific crop types grown in a key productive region (*viz.*: Wilhelmi *et al.*, 2002), a potentially more useful result was obtained. Figure 2 provides an example of a more detailed assessment when a specific agricultural region and rainfed crop type has been defined before-hand.

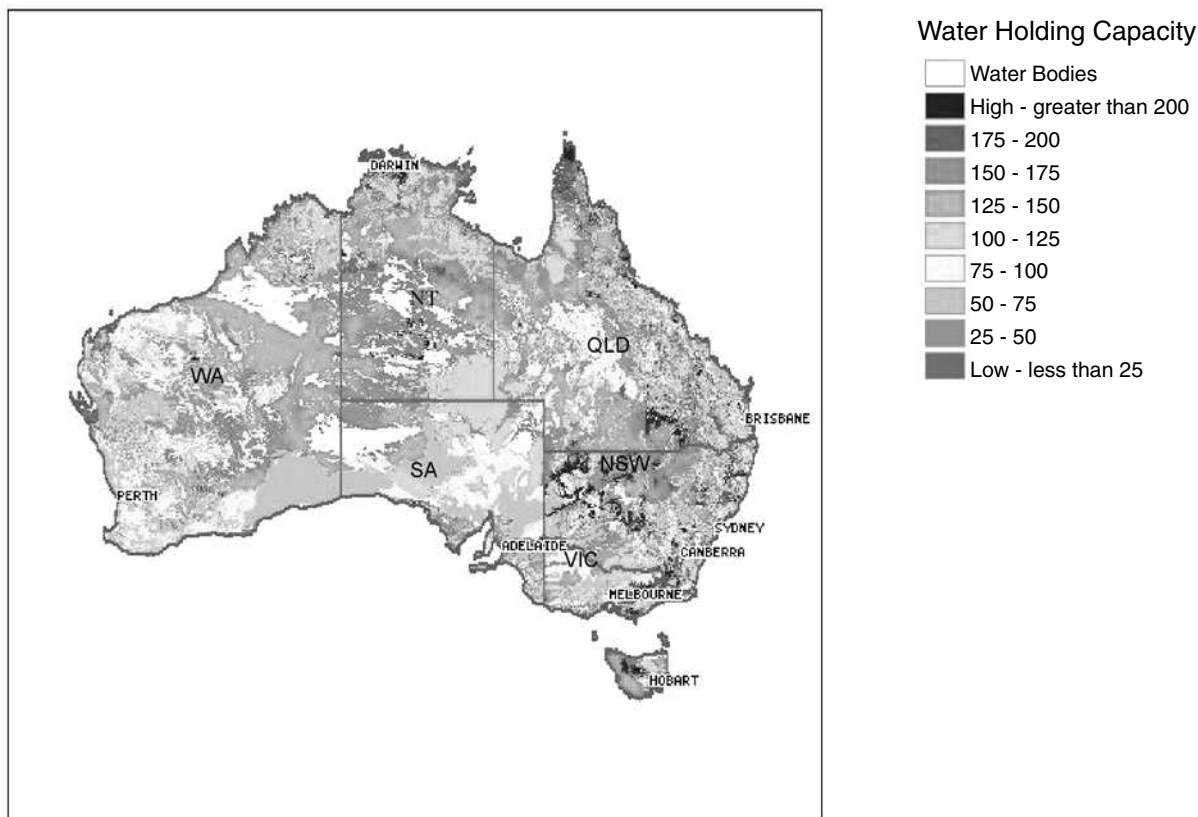


Fig. 1. An approximation of the major water-holding capacities of soils within selected regions, measured in mm (source: Australian National Agricultural Monitoring System – NAMS) (QLD represents the State of Queensland; NSW represents New South Wales; VIC represents Victoria; SA represents South Australia; WA represents Western Australia; NT represents the Northern Territory).

In this example, depicting sorghum-growing regions of North-East Australia, a potentially more realistic and useful outcome is provided compared to the initial assessment depicted in Fig. 1. Figure 2 suggests some shires in eastern regions where sorghum is grown as a major rainfed crop have a relatively high PAWC. However, there tends to be a grading from east to west where lower levels of PAWC are present ("medium" levels of PAWC grading to "low" levels of PAWC). Although PAWC may increase further to the west, when specific crop types and knowledge of soil types (and PAWC) appropriate for that crop are included in the assessment, this leads to a more appropriate level of drought risk and vulnerability.

When additional assessment is applied using the methods of Nelson *et al.* (2005) a more complex but potentially enlightening outcome results. Figure 3 provides details of outcomes of vulnerability assessment for rainfed pasture production. In this, there is a strong relationship between drought risk vulnerability and measures of natural, physical, financial, and social capital. Somewhat surprisingly, when just measures of capital that incorporate natural and physical capital and in which rainfed pasture growth is usually low there is not an obvious associated level of high drought-risk vulnerability. However, when levels of land degradation are spatially analysed, the area of reported land degradation, often due to over-utilisation of the land resource base due to over-grazing by pastoralists, becomes one of the more important contributors to a high value of the vulnerability index, especially in eastern Australia where analysis is made of the rainfed wheat-sheep agricultural production zone. This result recognises that issues of land-use are critical in assessments of drought risk and vulnerability and can be regarded as one of the driving forces behind water demand and critical factors of agricultural drought vulnerability (Wilhelmi and Wilhite, 2002; Wilhite, 2007). These results support an critical finding of Nelson *et al.* (2005) in that agricultural activity and farming in a harsh rainfed-only environment does not necessarily lead to a high score on a vulnerability index. This result also indicates that appropriate farming systems may be able to effectively manage drought risks so long as these systems operate at an adequate scale.

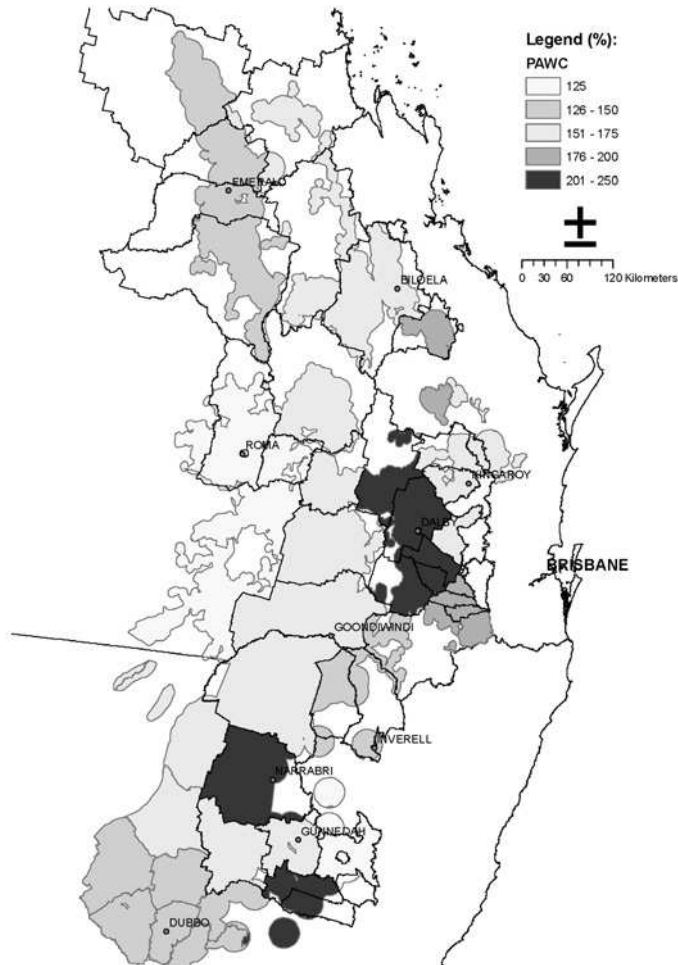


Fig. 2. Plant Available Water Holding Capacity (PAWC) information for North-Eastern Australia using more detailed information, local knowledge, and agronomic advice at a fine spatial scale. Local regions ("shires") with "low" PAWC (less than 150 mm) are depicted in yellow or fawn colouring, with "medium" levels of PAWC (150 mm-200 mm) are depicted in green or light blue colouring, while those shires or part shires with "high" levels of PAWC re depicted in dark blue (see legend).

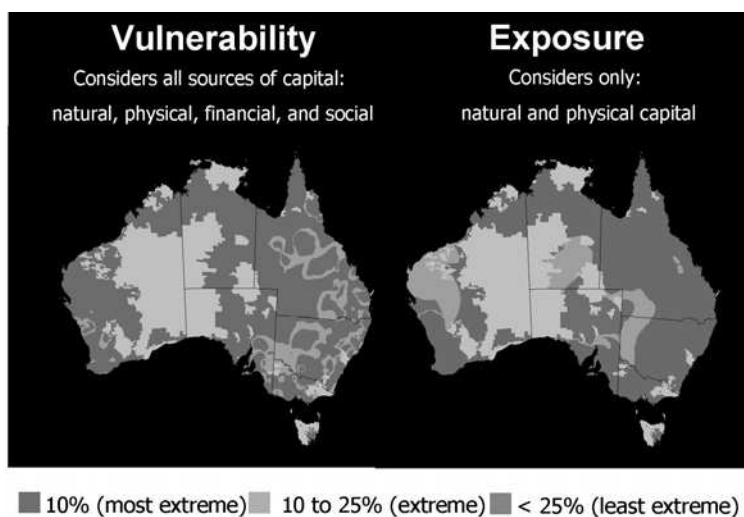


Fig. 3. Vulnerability exposure variation in Australia for rainfed pasture producing regions, depending on whether a suite of measures are included (left-hand image) (and including such aspects as significant land degradation) or only natural and physical capital is included (right-hand image) (Nelson *et al.*, 2005).

Tactical approaches to drought risk and vulnerability through incorporation of an appropriate rainfed crop production model, in this case, use of the regional-scale model for forecasting sorghum across North-East Australia (Potgieter *et al.*, 2005), provided the following results:

(i) Widely differing PAWC values across shires and the cropping region as a whole highlighted the challenge and value of use of such values in calculation of likely crop yield values and potential poor yields in drought years. These PAWCs varied from 125 mm to 250 mm in Central Queensland, to 100 mm to 250 mm in Southern Queensland and 100 mm to 250 mm in Northern New South Wales (NSW). In the three case-study years analysed (2005, 2006 and 2007), widely differing results of soil water recharge values were obtained. In 2005 (Fig. 4), following an assumed fallow from the previous April (and there was no double-cropping of wheat in the same soil) soil water recharge values indicated relatively high values of aggregated soil water recharge status. Values of between 60 and 90% were obtained in far southern and far western shires. Values in excess of 80% were obtained in a few shires in eastern New South Wales. Conversely, relatively low values (20 to 40%) were obtained in some key growing regions on the eastern "Darling Downs" and in some far northern shires. Furthermore, incorporation of a climate forecasting model (Stone *et al.*, 1996), integrated into the crop simulation model, indicated the chances of rainfed crop yields exceeding long-term medium yields were mainly between 30 and 60% with a few shires in southern regions exceeding 80% probability.

(ii) In 2006 (Fig. 5) (an El Niño year), aggregated soil water recharge values were mostly less than 10 per cent through many of the centrally located shires (shaded in red on the accompanying figure) and rose to only 30 to 40% in most of the remaining shires. One shire in the north-west of the study area obtained relatively high soil water recharge values (80 to 90%) but this was an exception. Not surprisingly, forecast crop yields were almost entirely in the 10 to 30% range of exceeding long-term medium yields-range for that year and would have aided assessment of agricultural drought risk that year (Figs 6 and 7).

(iii) For crops sown in 2007, aggregated soil water recharge levels were very low in value in many shires, especially in far western locations (Fig. 8), with values as low as 10 to 20%, as at 1st November 2007, suggesting potential for poor, drought affected, crop yields in this particular season. However, incorporation of a seasonal climate forecasting system, provided to aid potential drought risk assessment in this example (Fig. 9) showed the value of knowledge of likely in-crop growing rainfall in tactical assessments of this kind. Relatively high forecast probability values of high in-crop growing rainfall in many regions incorporated into the crop simulation models and incorporating PAWC and soil water recharge values provided likely yield probability values (probability of exceeding long-term median yields) of 60 to 90% in many shires (shaded dark green in the figure) with the lower values still relatively high at about 50%. All these crop yield values are considerably higher than would have been suggested as potential yield values from the sole use of soil water levels and PAWC.

Discussion

The assessment of drought risk and vulnerability applied in this study, using the example of a key rainfed agricultural crop in Australia, has largely reinforced the concept of Wilhite (2000) and Wilhelmi *et al.* (2002) that drought risk can be viewed as a product of both the exposure to the climatic hazard (e.g. low in-crop growing rainfall due to the influence of large-scale circulation systems such as ENSO) and the underlying vulnerability of farming or cropping practices, primarily due to low plant available water holding capacity (PAWC). In a contrasting environment incorporating rainfed pasture use, vulnerability issues related to land use management in sheep/cattle pastoral zones were shown to be highly important. It is suggested that a broad assessment of potential drought vulnerability incorporating an understanding of PAWC can be useful in providing policy makers and industry with advanced notification of likely drought vulnerability. Indeed, this initial analysis provided indication that many parts of both eastern, southern, and south-western Australia have relatively low levels of PAWC and thus, potentially, increased vulnerability to long-term drought risk, depending on land use. Further, incorporation of analyses at shire scales revealed that, at a regional scale, some important regional scale variations can exist and be of value in assessment of long-term drought risk. These analyses suggest potential value in use of PAWC and such key issues as land use management in strategic drought risk vulnerability assessment.

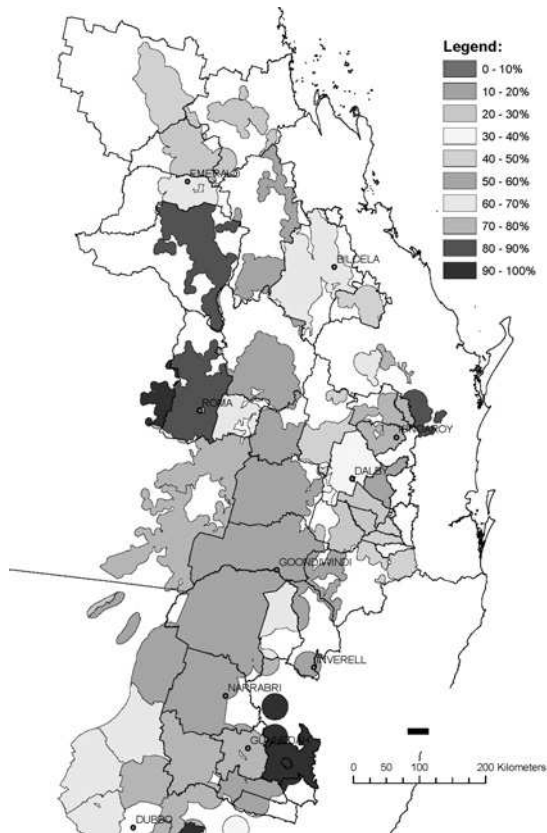


Fig. 4. Aggregated soil water recharge status (%) for NE Australian cropping regions at end of October 2005. Fallow simulated from 1 April in each year with 10% available water at that time (using APSIM crop simulation model).

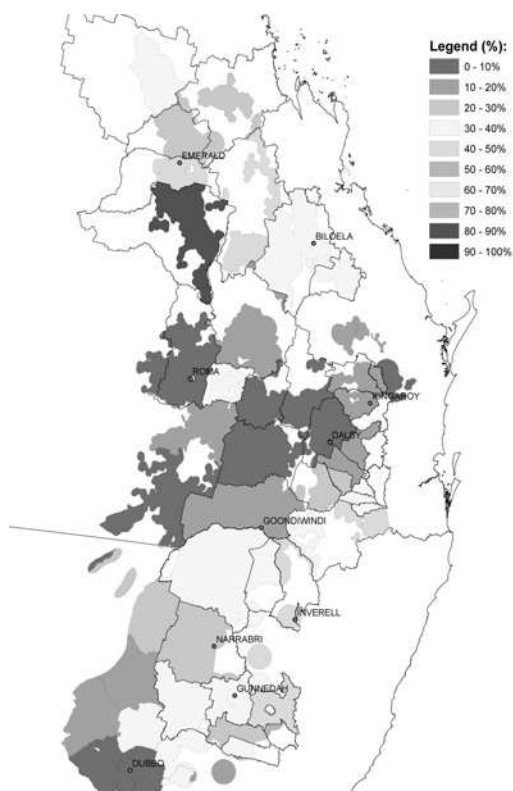


Fig. 5. Aggregated soil water recharge status (%) as at end of October 2006. Fallow simulated from 1 April in each year with 10% available water at that time (using APSIM crop simulation model).

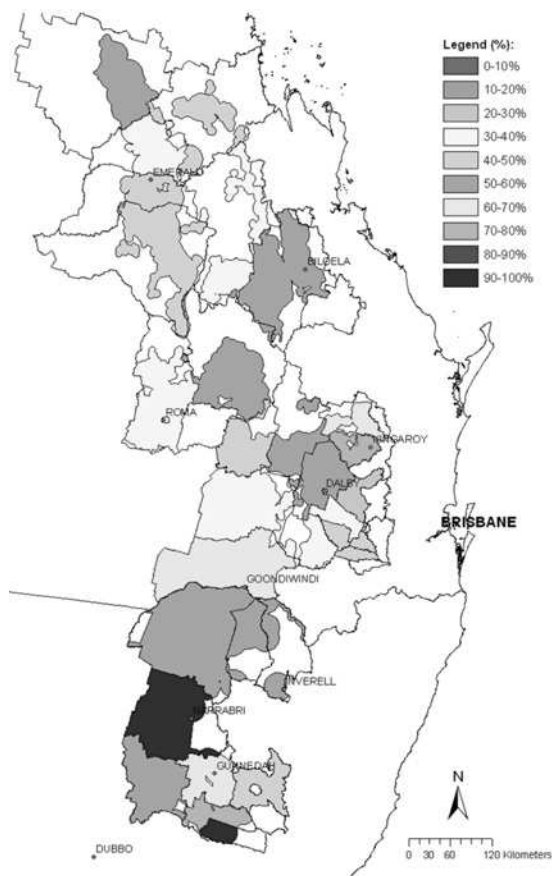


Fig. 6. Forecast rainfed sorghum yields for summer 2005, expressed as the probability of exceeding the long-term median yields (calculated for each shire) and incorporating soil water recharge, soil type, crop simulation model and climate forecasting model.

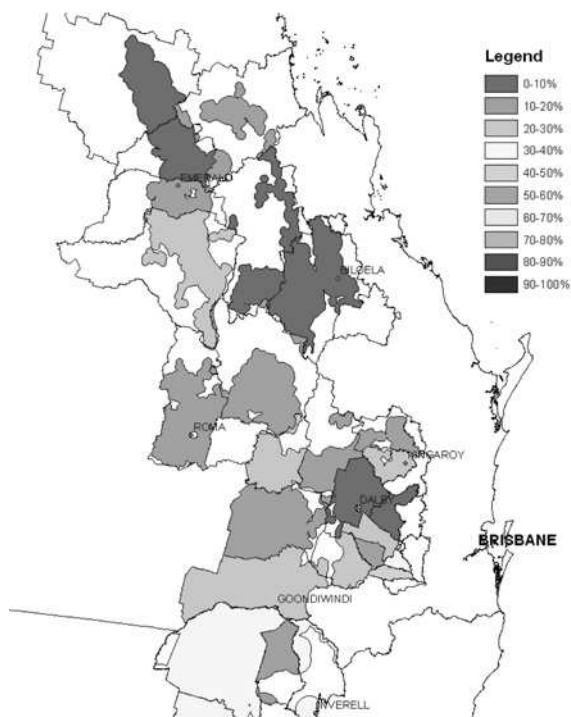


Fig. 7. Forecast rainfed sorghum yields for summer 2006, expressed as the probability of exceeding the long-term median yields (calculated for each shire) and incorporating soil water recharge, soil type, crop simulation model and climate forecasting model.

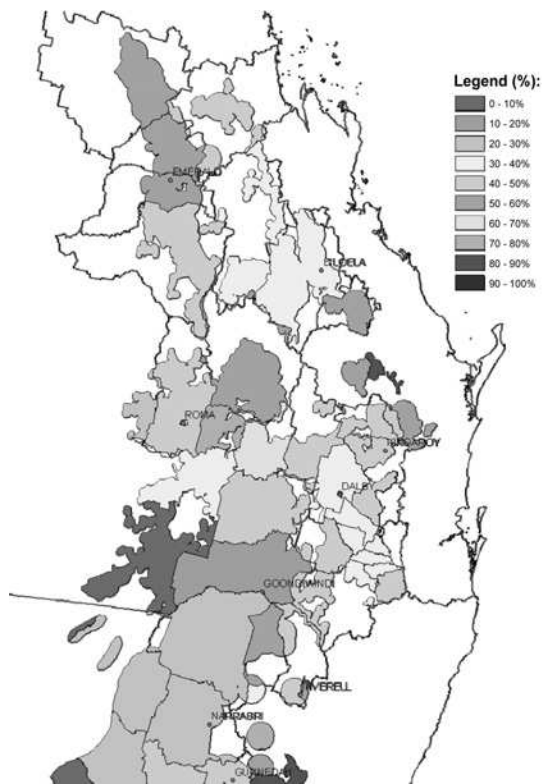


Fig. 8. Soil water recharge levels as at 1st November 2007. Note, the extremely low values (<10 per cent) in some far western shires.

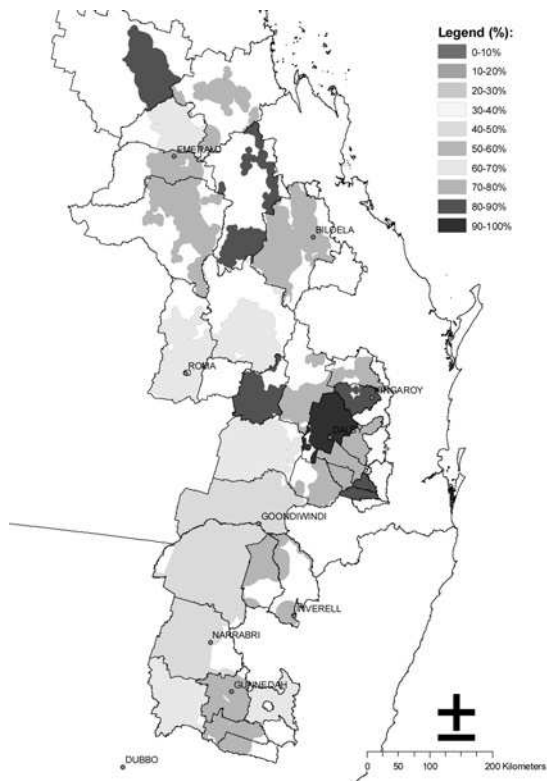


Fig. 9. Forecast of rainfed sorghum yields as at 1st November, 2007 incorporating likely in-crop growing rainfall through the coming summer growing season. Note the differences forecasts of likely in-crop growing rainfall provide in terms of reducing the likelihood of deleterious yields for the summer of 2007/2008.

However, in terms of more tactically-focussed assessments of drought risk and vulnerability, it is suggested that there may be considerable value in a combined use of PAWC and soil water recharge levels with climate forecasting systems that are able to be integrated into agricultural simulation models. In this respect, once a strategic assessment has been compiled using PAWC, in any given year or season, tactical issues related to drought risk assessment can be further assessed through use of appropriate forecasting systems and agricultural simulation models. These systems can provide indication of the likelihood of very low crop yield risk, potentially leading to loss of income and potential land degradation thereby providing useful and timely warning of more precise drought risk issues for industry and government (and farmers). An interesting finding from the case study assessments in this study was that low PAWC and low soil water recharge may not always provide enough information for appropriate *tactical* information for drought-risk for rainfed agriculture if these inputs are not integrated into a (skilful) climate forecasting system that may then provide advanced notice of likely high (or low) in-crop growing rainfall and indication of vulnerability.

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