Assessing the potential distribution of buffel grass (*Cenchrus ciliaris* L.) in Australia using a climate-soil model

B.E. Lawson[A,C], **M.J. Bryant**[A] and **A.J. Franks**[B]
[A] Pest Management Strategy, Land Protection, Department of Natural Resources, Mines and Energy, GPO Box 2454, Brisbane, Queensland 4001, Australia.
[B] School of Environmental Science, Murdoch University, Murdoch, Western Australia 6150, Australia.
[C] Present address: School of Natural and Rural Systems Management, St Lucia Campus, The University of Queensland, Brisbane, Queensland 4072, Australia, email: b.lawson@uq.edu.au

Summary

The purpose of this study is to test a simple, rapid method of assessing the potential distribution of environmental weeds. As a case study, we model the potential distribution of buffel grass, an invasive exotic perennial pasture grass species, for the Australian continent based on an analysis of the global distributional records, climatic requirements and edaphic preferences of the species. The CLIMEX climate-only model predicts that approximately 31% of mainland Australia is potentially highly suitable and 32% suitable for buffel grass growth. In contrast, the climate-soil model predicts a potential Australian distribution of 25% highly suitable and 43% suitable for buffel grass growth. The results of both models are consistent with available specimen data regarding the present national distribution and the biology of this species. We conclude that our climate-soil model shows some improvement over the climate-only model although further refinements are necessary to extend this work.

Keywords: CLIMEX, exotic species, GIS, invasive species, native vegetation management, pasture grass, predictive modelling, soils.

Introduction

It is imperative that agencies charged with managing the weed threat to Australia have access to methods that enable the rapid analysis of potential weed distributions, often with a minimum of information about species biology and distribution (Craig Walton, Department of Natural Resources, Mines and Energy, personal communication). The identification and management of weed species requires a diverse range of measures (NWS 1999), of which a central component is the modelling of species potential distributions based upon climate and other considerations (e.g. QDNRM 2001). Kriticos and Randall (2001) comment that the purpose of such modelling is to enhance decision-making rather than to exactly recreate reality. As such, it is important to remember that distributional modelling provides only a subset of the information necessary to assess and manage a species, rather than representing an end point in the process.

The objective of this research is to outline a simple and efficient method for the modelling, assessment and mapping of the potential distribution of weed species rather than a comprehensive model of the species. In achieving this, we hope to further Weed Risk Assessment (WRA) methodologies by testing a method to quickly appraise the weed potential and management of environmental weed species by examining species response to both climate and soil-type. The intent of WRA is to examine the likelihood of weedy plant species expanding their range into new areas, establishing and becoming problematic (Kriticos and Randall 2001).

This study seeks to model the potential distribution of buffel grass (*Cenchrus ciliaris* L.) in Australia based on its climatic and edaphic preferences. Our approach is based on the use of CLIMEX software and geographic information systems (GIS) modelling techniques to combine climate and soils models. There are several reasons why buffel grass was selected for this case study – it is a species which presents substantial ecological threat to Australia (Fensham 1996, Franks 2002); both soils and climate have been identified as key factors influencing the distribution of this species (Duke 1983); and adequate data exists to model the species potential distribution and to validate this model.

Since its accidental introduction into north-western Australia sometime in the 1870s (Humphreys 1967, Low 1999), buffel grass, including its many cultivars, has been actively promoted for pasture improvement, soil stabilization and mined land rehabilitation. This promotion has facilitated its spread across much of northern semi-arid Australia (Griffin 1993). It is one of the most drought tolerant of the introduced pasture grasses making it a vital component of pastoral development throughout much of the semi-arid region. Consequently, many 'low producing' shrublands have been converted to highly productive grazing lands primarily through this species' ability to establish and spread under highly variable climatic conditions (Paull and Lee 1978).

The ease of establishment, rapid growth rate, fast maturation, prolonged flowering/fruiting periods, prolific seed production, and high seed dispersal ability all contribute to the success of buffel grass as a pasture improvement species (Fenton and Campbell 1981, Franks *et al.* 2000). It is easily naturalized on most soil types and climates and quickly forms self-sustaining populations under a range of disturbance regimes. The life-history traits that make buffel grass such a successful pasture species are the same traits that have led to its invasion and establishment in other parts of the landscape, including significant areas of remnant native vegetation occurring outside the established conservation network (Franks 2002).

By the year 2000 it was estimated that buffel grass had naturalized approximately 30 million hectares of inland Queensland (Hannah and Thurgate 2001) and covered large areas of Western Australia, Northern Territory, South Australia and New South Wales (Pigott 1995, Low 1999). Once established within native vegetation, buffel grass alters the character and disrupts the natural ecological functioning of these systems (D'Antonio and Vitousek 1992, Lonsdale 1994, Franks 2002). This disruption of the natural ecology has contributed to this species being listed as one of Queensland's sixteen and Australia's eighteen worst environmental weeds (EPA 1999, Humphries *et al.* 1991).

Materials and methods

This study combines the predictive output from the climate-modelling software (CLIMEX) of the species with a system of soils rating. Whereas most weed species modelling to date has focussed on modelling the climatic factors (e.g. Panetta and Mitchell 1991, Kriticos *et al.* 2003), the information on the biology of buffel grass highlighted the important influence of soil type on the distribution of this species (e.g. Humphreys 1967, Fenton and Campbell 1981, Duke 1983, Skerman and Riveros 1990). Therefore, to provide a more robust assessment of the potential distribution of buffel grass, a climate-soil model was developed with the underlying assumption that climate and soil are the primary determinants of its broad distribution. Firstly, the climate model was developed, followed by an assessment of the documented soil preferences of this species. This information was then combined in a GIS using assigned weightings to produce a map of the potential distribution across the Australian continent.

Data collation

Data on which the climatic component of these models was based were obtained from several sources. Internet searches provided much of the distribution and species biology information (including soil preferences). Further information on species distribution and biology was obtained from scientific literature, e-mail discussion groups, personal contacts and herbarium specimen records. Approximately 300 records from 62 countries were used to develop the CLIMEX model. The countries where buffel grass specimen records have been located are illustrated in Figure 1. Due to the large amount of information it is impractical to append all records, however a complete list of data on which the model was based is available from the corresponding author.

It has been reported that over 80 varieties of buffel grass have been introduced into Australia by CSIRO since 1926 (Bryant 1961), each of which has particular ecological tolerances. For example, where the cultivated varieties Biloela and Tarewinnabar prefer heavier soils, Gayndah and Western Australia varieties have a preference for lighter soils. The majority of species records used to construct this model did not differentiate between the varieties. The model presented here includes all of the different varieties and cultivars of buffel grass under a unified *Cenchrus ciliaris* complex.

Climate modelling

CLIMEX for Windows, Version 1.1a was used to develop a predictive model of the potential distribution of buffel grass in Australia. CLIMEX is a widely recognized predictive software package that provides a measure of potential distribution based upon the climatic requirements of a species. The program has been used to predict the potential distribution of many species (e.g. Panetta and Mitchell 1991, Pheloung *et al.* 1996, Kriticos 1997, Yonow and Sutherst 1998, Kriticos and Randall 2001). For the purposes of pest management, CLIMEX provides a useful tool to assess the invasion threat posed by a species to a particular country or region.

The semi-arid template within CLIMEX was used as a base from which the model was developed. Two species files were used, one an 'experimental' file and the other a 'control' file. Initially both files contained the same parameter values. Using the 'Compare Locations' function, where two models can be simultaneously compared on maps and tables, each parameter value was systematically altered and the modelled results examined. Changing a value in the experimental file, mapping results, and then comparing the results with those of the control file achieved this. When the changed value was judged to provide an improvement in the coincidence between predicted distribution and actual records, the value in the control file parameter was updated. This method was used to systematically work through each parameter of the model.

The general procedure for fitting CLIMEX growth and stress indices is well documented in Kriticos *et al*. (2003). Their methods were followed with two exceptions: 1) their contention that the lower moisture threshold should be 0.1 (10% soil moisture) due to the incapacity of plants to extract moisture from the soil below this level, and; 2) their fitting of stress thresholds outside of temperature and moisture limits for the species. In regard to the apparent moisture limit, we argue that such limits prevent the growth of species in many arid areas from where they are recorded. For several reasons (e.g. fine-scale climatic and edaphic variations across landscapes, plant drought tolerance mechanisms, etc) we consider such an imposed limit impractical for modelling drought tolerant species such as buffel grass. In terms of fitting stresses, we consider that where stress indices (excluding interaction stresses which represent a special case) are not fitted to the upper/lower temperature or moisture thresholds, they should begin to accumulate somewhere between optimum and threshold conditions. In contrast to this Kriticos *et al.* (2003) locate their cold stress and wet stress indices outside of this range leaving a void where the species is not responding to the prevailing climate in any form. However, despite this disagreement, we argue that achieving the best fit for the model should outweigh theoretical limits in cases where theoretical and practical considerations conflict.

The model was originally fitted to buffel grass distribution in Africa and Asia, the continents to which the species is recorded as native. The model was subsequently fitted to all other countries (excluding Australia) where this species has been recorded as introduced. Records for Croix Rivail in Martinique (Artus and

Figure 1. The worldwide distribution of buffel grass showing those countries where records of the species were located. Shaded areas and rectangles identify countries where the species has been recorded rather than the actual distribution of the species.

Champanhet 1989) and Erap Livestock Station near Lae in Papua New Guinea (Queensland Herbarium record) were excluded from the model as achieving species growth at their nearest CLIMEX locations would have required very substantially reducing wet stress. It was concluded that the records were likely to have been from drier microclimates or very free-draining soils. In support of this, the Encyclopaedia Britannica (2002) states that there is a ten-fold variation in rainfall across the island of Martinique.

Once completed, the model was then used to predict the potential distribution of buffel grass for Australia (Figure 2). The model was validated using specimen records from within Australia to ensure that the model was not grossly underestimating or overestimating the potential distribution of buffel grass. Following preliminary validation of the climate model, the temperature threshold cold stress (TTCS) and temperature threshold accumulation cold stress (THCS) parameters of the CLIMEX model had to be reduced to extend the distribution of buffel grass to include the Hunter Valley, New South Wales (Bryant 1961) and Uluru Kata-Tjuta National Park, Northern Territory (Australia's Virtual Herbarium 2003, Chris Howard, Parks and Wildlife Commission of the Northern Territory, personal communication). While this alteration of the model based on information from the country of prediction is undesirable and impinges on the predictive capacity of the model for Australia, it is necessary given that these records significantly affect the model. In these circumstances, altering the model is considered valid (Kriticos *et al*. 2003).

The parameters used in the CLIMEX model are summarized in Table 1. The role of each parameter is described in Sutherst *et al.* (1999).

Assumptions of the CLIMEX model

The CLIMEX model assumes that climate is the main factor determining the distribution of a species (Sutherst *et al.* 1999). The model does not account for other biophysical factors such as soil, land use (Sutherst *et al*. 1999), vegetation cover, disturbance or the ability of the species to disperse to an area. As such, CLIMEX provides a prediction of the broad climatic suitability of a region for a species. Further details of the CLIMEX model can be found in Sutherst and Maywald (1985) and Sutherst *et al.* (1999).

Soils modelling

This analysis used the Northcote Factual Key of soil classification as a generalized layer of soil information across Australia. This was supplemented by the categories that denote ironstone gravel complexes (K- / KS) and a category denoting 'No data' where soils data (NS) did not exist (e.g. salt pans, large waterbodies, and small islands). Sites without soils data were excluded from the final analysis. This 'No data' classification affects all maps and statistics from the climate-soils model. These 13 soil categories represent broad soil type classifications and were used as the basis for this classification. The authors assigned each soil categories an index for buffel grass growth potential (1 to 8) based upon information related to buffel grass' relationship to soils located during literature and Internet searches (Table 2). The index of buffel grass growth potential on soil types is reflected the species' preference for sandy and sandy loam soils, grading to low levels of growth on heavy clay soil types.

Mapping

ESRI's ArcGIS^{TM} Version 8.3 was the GIS software used to produce the climate-soils model and map its output, which provided the necessary spatial tools for both vector and raster data processing. Firstly, soils and climate-matched outputs were converted to a common spatial format. Each layer was transformed to a cell-based raster layer with a resolution of 0.5 degree. This size was chosen to correspond to the CLIMEX output of regular grid points across the continent (D.J. Kriticos, CSIRO Entomology, unpublished data ESOCLIM-50), providing complete coverage without compromising the integrity of the data. Once each layer was spatially coincident, they were reclassified using the Nearest Neighbour method to matching scales of 1 to 8, which represented the buffel grass growth potential.

These data were then merged using a simple linear algorithm that included an equal weighting for each ecoclimate index (EI) and soil type (i.e. 50% climate influence, 50% soils influence), to produce a

Table 1. Buffel grass parameter values used in the CLIMEX model.

Index	Parameter	Value
Temperature	DV0	2.5°C
	DV1	28°C
	DV2	38°C
	DV3	43°C
	PDD	1000
Moisture	SM0	0.01
	SM1	0.04
	SM2	0.75
	SM3	1.7
Cold Stress	TTCS	17°C
	THCS	0.0001
	DTCS	17
	DHCS	0.0007
Hot Stress	TTHS	38.01°C
	THHS	0.0005
Dry Stress	SMDS	0.04
	HDS	0.001
Wet Stress	SMWS	0.85
	HWS	0.001
Cold/Wet Stress	DTCW	25°C
	MTCW	0.75
	PCW	0.025

Table 2. Soil preference ratings for buffel grass, based upon the Northcote Factual Key.

Northcote Code	Description	***C. ciliaris* soil preference rating**
Db	Duplex soil with brown subsoil - sand over clay	4
Dd	Duplex soil with dark subsoil - sand over clay	4
Dg	Duplex soil with gleyed or grey subsoil - sand over clay usually seasonally wet	2
Dr	Duplex soil with red subsoil - sand over clay	4
Dy	Duplex soil with yellow subsoil - sand over clay	4
Gc	Gradational calcareous soil - rare, loam grading to clay	7
Gn	Gradational soil - common, sandy loam grading to clay	6
K- / Ks	ironstone gravel	1
Uc	Deep or shallow sands	8
Uf	Non-cracking clay soils	2
Ug	Cracking clay soils	3
Um	Deep or shallow loams	8
NS	No soil data	–

single spatial layer. This equal weighting was assigned in the absence of evidence that one factor was more or less important than the other. Areas predicted as climatically unsuitable by the CLIMEX climate model were excluded from the climate-soil model to ensure that suitable soil type did not override otherwise climatically unsuitable areas. For greater simplicity the output categories where economized to four growth categories using a natural breaks classification and denoting these categories as Highly Suitable, Suitable, Marginal and Unsuitable. To compare the success of adding the soils component to the climate model, the potential distribution maps for Australia from both the climate-only and climate-soils models are included and discussed.

Simple geostatistical procedures were then used to tally the numbers of 0.5 degree cells in each of the four growth categories for the two models. This enabled a crude estimate of the predicted potential distribution for Australia, with values rounded to reinforce the generalized nature of such statistics.

Model validation

The final map outputs of both the climate and climate-soils models were validated against herbarium and miscellaneous specimen record data within Australia using ArcGIS geostatistical tools to calculate statistics on the intersection of specimen data points with each of the four growth classes. Miscellaneous data includes non-herbarium specimen records such as published books and reports, journal articles and information from environmental weed listservers.

Results

Predicted potential distribution

The predicted potential distribution of buffel grass in Australia based on the climate-only (Figure 2) and climate-soils suitability (Figure 3) is presented. The results suggest that a large proportion of the Australian continent is suitable to highly suitable for the establishment and growth of this exotic pasture species. The arid to semi-arid areas of the continent are predicted to be most favourable for the species.

Figures 2 and 3 illustrate the substantial change in predicted potential distribution between the climate-only (Figure 2) and climate-soils models (Figure 3). This change includes a broad westward shift in the highly suitable and suitable classes between respective models. It also indicates, as expected, a shift from broad-scale suitability patterns to finer-scale mosaics of suitability classes, particularly in those areas classified as suitable and highly suitable with the addition of the soils model. Furthermore, the addition of soils has the effect of extending the area of the continent classed as suitable much further south and thereby covers a significantly larger area (Table 3).

In broad terms, the climate-only model (Figure 2) derived from CLIMEX predicts that favourable areas (i.e. suitable and highly suitable) for buffel grass growth occur in a broad band covering most of Queensland, with the exception of the south-east Queensland corner, Carnarvon Gorge, the Wet Tropics and some coastal parts of Cape York. These favourable climates extend across the Northern Territory except for areas around Darwin

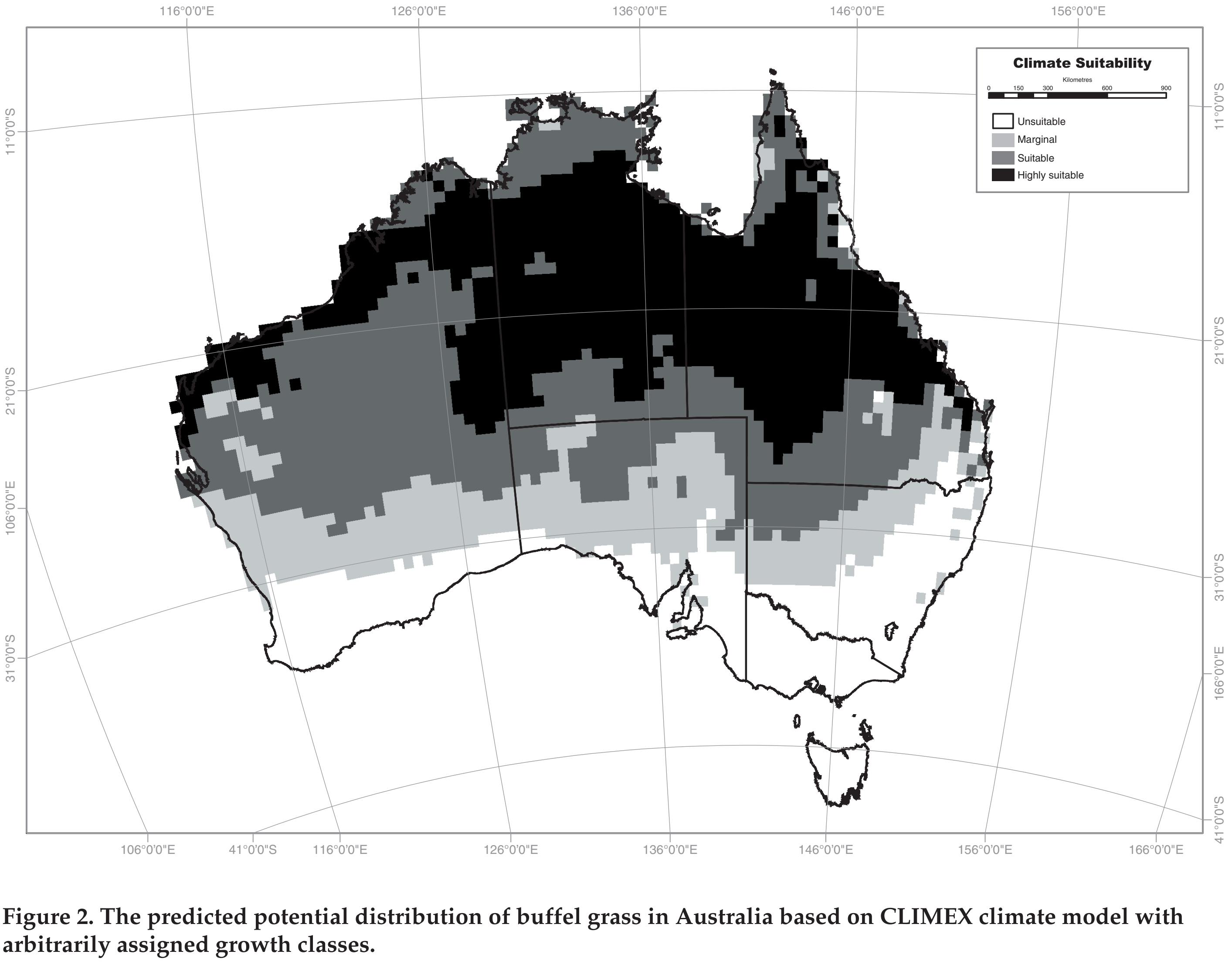

Figure 2. The predicted potential distribution of buffel grass in Australia based on CLIMEX climate model with arbitrarily assigned growth classes.

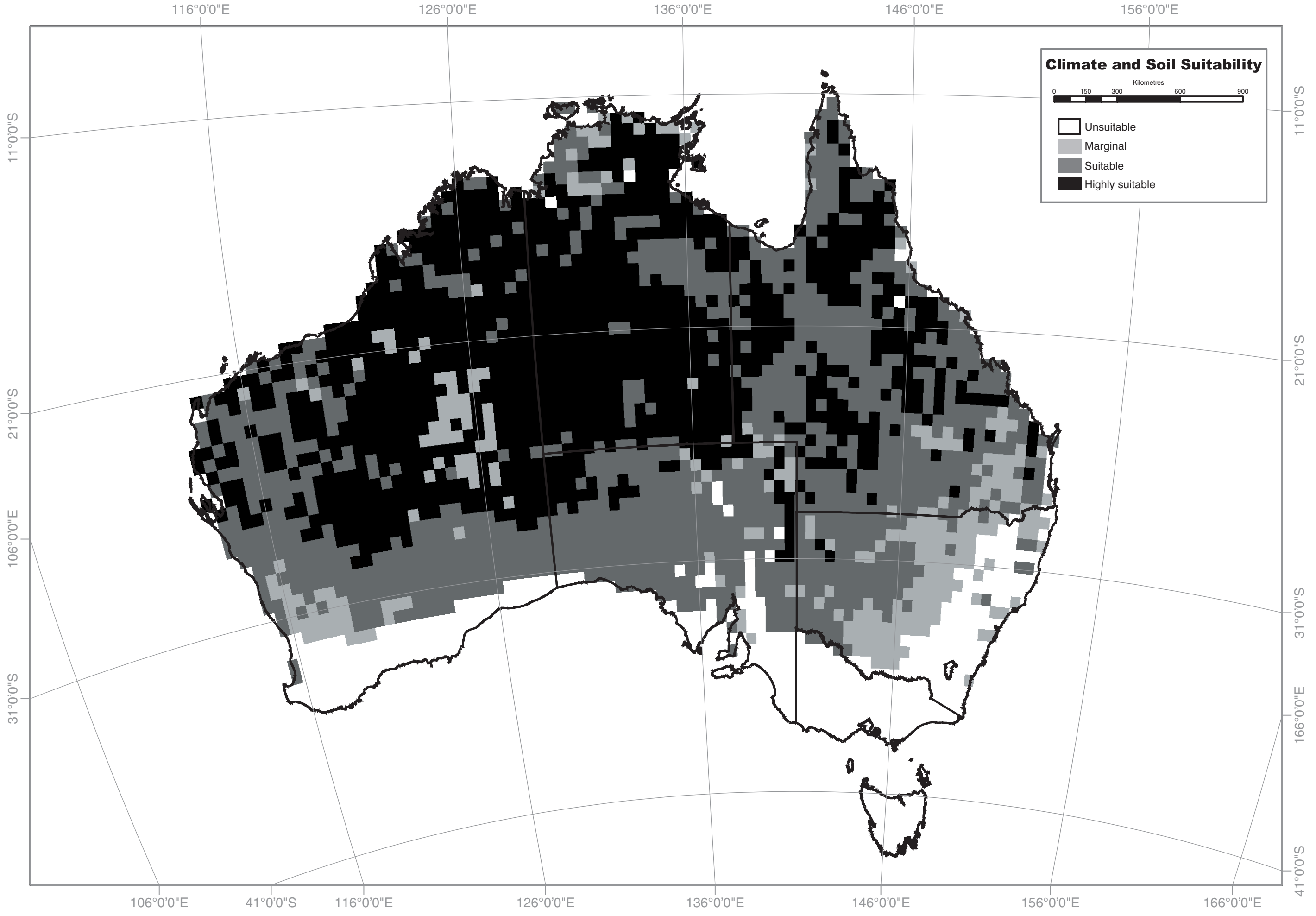

Figure 3. The predicted potential distribution of buffel grass in Australia based on climate and soils model with arbitrarily assigned growth classes.

Table 3. Predicted areas of potential growth of buffel grass suitability in Australia.

	Estimated Area (km² and %)	
Suitability rating	Climate model	Climate + Soil Model
Highly suitable	2 339 180 (31%)	1 913 630 (25%)
Suitable	2 478 350 (32%)	3 340 160 (43%)
Marginal	1 397 090 (18%)	1 132 120 (15%)
Unsuitable	1 477 380 (19%)	979 570 (13%)
No data	0 (0%)	326 520 (4%)
TOTAL	7 692 000 (100%)	7 692 000 (100%)

and Gove, and across much of Western Australia roughly north of a line between Shark Bay and northern Nullarbor Plain. Some areas of northern South Australia and the north-west of New South Wales are also predicted to have suitable climates.

Of the regions predicted to be climatically unsuited for buffel grass growth, most occur in south-eastern Australia, comprising Tasmania, the majority of Victoria, and the southern to northern tableland floristic regions of New South Wales (Figure 2). The CLIMEX model reveals that this unsuitability is mostly due to cold stress, wet stress and insufficient days above the minimum threshold temperature necessary for the species to complete a generation. Outside of south-eastern Australia, very few areas are predicted to be unsuitable for buffel grass. In the south-west of the country, it is cold or wet stress within the model that prevents species growth in areas such as the Warren, Jarrah Forest, Mallee and southern Nullarbor bioregions of Western Australia and parts of the Eyre and Yorke Blocks bioregion and the Murray Basin area of South Australia. Due to the structure of this model, which excludes climatically unsuitable areas from the climate-soil model, climatic factors are largely responsible for the unsuitability of these areas in both models. Although most of northern and eastern coastal areas are predicted to be suitable, growth of the species in these areas is limited by high levels of moisture in the coastal zones of the eastern and northern seaboards of Australia.

In contrast, the climate-soil model (Figure 3) predicts a larger extent of favourable areas across the continent. In Queensland, the combined area classed as suitable or highly suitable for buffel grass growth changes very little between the climate and climate-soil models, however there is a substantial fragmentation and reduction in the area predicted to be highly suitable. The Channel Country, Mt. Isa Inlier/Northern Uplands, Einasleigh Uplands and Brigalow Belt North are those Queensland bioregions predicted to have the highest suitability for species growth. Unlike Queensland, there is a substantial increase in those areas predicted to be highly suitable in the Northern Territory with growth conditions improving between the models in the south of the territory and in large parts of Arnhem Land. Western Australia also experiences an increase in favourable conditions between the models with large parts of the state predicted as highly suitable, with suitable conditions extending further south than the potential distribution predicted by the climate-only model. The climate-soil model also has the effect of making the Gibson Desert region marginal for species growth due to unfavourable soils in that area.

The climate-soil model also significantly increases the potential distribution of buffel grass in the southern states of Australia as compared to the potential distribution predicted by the climate model alone. This is most evident in South Australia with highly suitable conditions predicted in parts of the north-west and north-east of the state. Suitable conditions also extend much further south in South Australia with the only unsuitable areas predicted to be the Eyre Peninsula, Flinders Ranges and south-east of Adelaide. In New South Wales, the addition of the soils model extends the predicted potential distribution of suitable conditions into much of the north-western and western areas of the state, and the extreme north-west of Victoria around Mildura.

In terms of the areal extent of the Australian continent predicted as suitable for buffel grass establishment and growth, there are substantial differences between models. Under the climate model, we find that approximately 2.3 million km^2 (31%) of the land area has a high suitability and nearly 2.5 million km^2 (32%) is suitable for buffel grass growth (Table 4). In contrast, the climate-soil model predicts that potentially 1.9 million km^2 (25%) of Australia is highly suitable and suitable areas a total of 3.3 million km^2 (43%). Only 19% (approximately 1.5 million km^2) of the continent was predicted to having a climate totally unsuitable for buffel grass growth, which decreased to 13% (approximately one million km^2) with the climate-soils model (Table 3). The potential distribution figures for the climate-soil model are slightly affected by approximately 300 000 hectares (4%) of the continent having no soil data which precludes modelling for those areas.

Validation of the model based upon the numbers of specimen records that intersect with any of the four growth categories in the climate-soil model is illustrated in Figure 4. Statistics for both the climate-only and climate-soil models are provided in Table 4 and show that the overwhelming majority of data points intersect with suitable and highly suitable areas of both the climate-only (85%) and climate-soils model (91%), when those points intersecting with areas of 'No data' are excluded.

Discussion

The potential distribution of buffel grass

The results of this study are useful at a broad scale to provide an indication of the potential distribution of buffel grass across Australia. In doing so it is the intention that the model highlights the potential distributional extent of the species, identifies important regions and land uses that might be affected by its spread and enables strategies to be put in place to

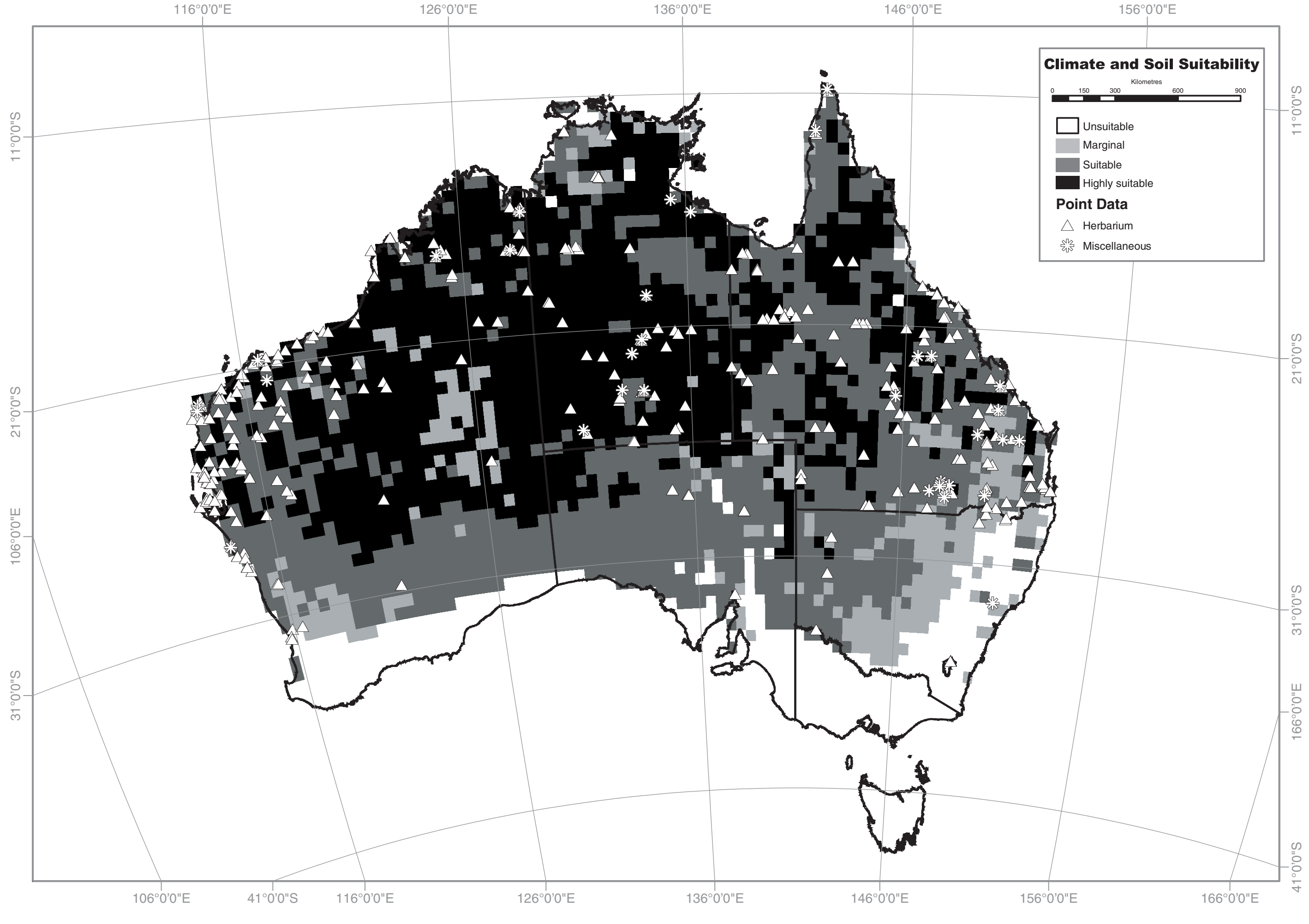

Figure 4. The predicted potential distribution of buffel grass in Australia based on climate and soils model showing herbarium and miscellaneous specimen records for Australia.

Table 4. Validation statistics of intersection of herbarium and miscellaneous specimen point records across Australia with the climate-soils potential distribution.

Model	Records	No Data	Unsuitable	Marginal	Suitable	Highly suitable
Climate	Herbarium	0	12	59	189	217
	Miscellaneous	0	0	4	14	17
	TOTAL	**0**	**12**	**63**	**203**	**234**
Climate + Soils	Herbarium	49	0	36	219	173
	Miscellaneous	3	0	3	15	14
	TOTAL	**52**	**0**	**39**	**234**	**187**

manage the species. Figures 2 and 3 suggest that large proportions of the continent are either climatically, or climatically and edaphically, suited to the establishment and spread of this invasive exotic pasture species. The main areas predicted to be completely unsuitable are the cooler areas in the south-west and the south-east of the continent. The fact that an area is predicted as suitable for this species only indicates that the macroclimate and soils of the area are appropriate; however there may be parts of the landscape (e.g. valleys which pool cold air, wetlands, etc) where buffel grass will not establish or grow. The converse of this may also occur. In terms of weed potential, those areas predicted as being suitable or highly suitable for buffel grass growth are most likely to be significantly affected. Unfortunately there is no current statistics of the extent of buffel grass distribution across Australia with which to compare our models. Although we have over 500 data points across Australia that we have used to validate this model, there is no reliable method by which to derive area statistics from these points and thereby enable a comparison of current versus potential distribution.

Although there is some change in potential distributions predicted under climate-only and climate-soils models, a core distribution in arid and semi-arid Australia remains constant under both models. These predictions of potential distribution are strongly supported by herbarium and miscellaneous specimen records of buffel grass from most arid and semi-arid botanical regions of Australia (Humphries *et al.* 1991, Australia's Virtual Herbarium 2003). While this species is widely accepted to be ideally suited to arid and semi-arid regions, the predictions presented here suggest that the higher rainfall coastal zones in the north of the continent have marginal climatic suitability for growth of this species. In these areas, land use or competition from other species may prevent buffel grass from assuming a greater dominance in the landscape. The growth of this species in coastal areas is greatest in those areas subject to more seasonal rainfall events.

The potential Australian distribution is supported by buffel grass' ability to establish and grow in a wide range of environments. Duke (1983) reports that occurrence of this species extends from deserts to moist forests, from tropical to warm temperate environments. The species is well recognized for its drought tolerance (Graham and Pegler 1999), and appears most suitable in areas receiving between 300 and 1000 mm annual rainfall (Paull and Lee 1978, Skerman and Riveros 1990, NSW Agriculture 1995).

There is some conjecture in the literature about the capacity for buffel grass to survive conditions of high moisture. Certain sources (e.g. Skerman and Riveros 1990) suggest that some cultivars have a poor ability to survive in high rainfall environments. However, our models and many distributional records suggest that certain cultivars are able to establish and persist in mesic areas (e.g. Duke 1983). Anderson (1970) showed that buffel grass has at the very least limited tolerance to short periods of flooding, being submerged for five days without mortality. Much of the lowland areas indicated as suitable in our predictions may be subject to periodic flooding, in both coastal and inland areas (e.g. the Channel Country of south-western Queensland).

Humphries *et al.* (1991) comments that buffel grass has a preference for mesic or moist habitats such as riverbanks and alluvial pans, but will also spread to adjacent habitats. The ability of this species to tolerate high levels of moisture and short periods of flooding (Anderson 1970) extends the predicted distribution of the species into high rainfall zones of coastal Australia. The lack of specimen records from humid maritime areas may be due to buffel grass having a lower competitive ability in these areas versus the drier inland areas as indicated in a study by McIvor (2003).

The model presented in this paper incorporates both climatic and edaphic variables. While both variables were included, the potential impact of interactions between soil and climate were not factored in. For example, better-drained soils may allow the species distribution to extend into higher rainfall areas and vice versa. We are aware that a more complex model could have been developed and may better approximate the potential distribution of buffel grass. However, as our aim was to explore the effectiveness of a simple climate-soil model with a minimum of resources, such complex models were not examined.

Buffel grass is known to have a strong preference for deep soils of lighter texture, particularly those with high levels of phosphorus (Bryant 1961, Paull and Lee 1978, Cavaye 1991, Walker and Weston 1990). Low phosphorus will reduce the drought tolerance and water use efficiency of the species (Fenton and Campbell 1981). The soils layer developed in this model provides a finer scale prediction than that offered by climate alone as a consequence of the different scales over which these variables operate, as demonstrated by the different patterns between Figures 2 and 3. Given the coarse 0.5 degree grid used in this study, the mapping process has generalized the results with finer scale edaphic variations are averaged across the cell.

It is interesting to note that many sources suggest that this species experiences high levels of growth on many of the sandy and lighter clay soils where Brigalow (*Acacia harpophylla*) grows (Humphreys 1967, Knights and Christodolou 1999). Despite this, neither of our models predicts the southern Brigalow Belt as being highly suited to buffel grass due to unsuitable climate. This is supported by a lack of specimen records for this region.

The validity of the modelling process

The high level of correspondence between the predicted potential distribution for Australia and specimen records for the continent (Table 4 and Figure 4) suggests that both the climate and climate-soil models provide a good representation of the Australian data. The results suggest that although there is a decrease in the proportion of specimen records that intersect with the highly suitable classification for the climate-soil model as compared to the climate-only model, overall there is a slight increase in the proportion of records that intersect with favourable growth classes (i.e. suitable and highly suitable). This leads us to conclude that the addition of the soils model to the CLIMEX climate model is useful, although refinements to the modelling process are likely to further consolidate these benefits.

Subjective judgements, based on the best available information, are necessary when endeavouring to model the potential distribution of any species. By combining the variables of climate and soils we have amplified the risk of error in our output. We believe that the coarse nature by which suitability rankings were assigned to soil types (Table 2) and the display of soils information in 0.5 degree grid squares (approximately 50 × 50 km) across the continent (Figures 2 and 3) limits their reliability below these coarse continental scales. However, such a linking of soils and climate (and possibly several other variables) may prove more useful and informative if conducted at state or regional scales. Nevertheless, we believe this study offers a useful starting point from which to refine multi-faceted models for the monitoring and management of both existing and potential weed species. We hope that this study will promote research on incorporating predictive models with other information (such as soils) into GIS environments to provide these important predictions of potential species distribution. GIS also offers the capacity to combine such models at a variety of scales with other important information, such as those conservation reserves threatened by a particular species, the affect of land-uses on likely weed distribution, climate change impacts, and the threat posed to rare and threatened taxa or ecological communities.

The modelling process used in this study was not meant to be an exhaustive examination of the potential distribution of buffel grass. Instead, our intention was to extend the existing weed risk assessment methods by examining the impact of incorporating a soil component into this analysis. Buffel grass offered a good opportunity to trial this technique, as it is an important species in the Australian context and a species where soils and climate have a strong influence on species distribution (Duke 1983). It is the opinion of the authors that this objective has been achieved, and that this study makes an important contribution to rapid and effective WRA methodologies.

Some implications for vegetation management

These models suggest that buffel grass presents a widespread weed threat to a large proportion of the Australian landmass, with the climate-only model suggesting over 4.8 million km^2 (63% of the Australian continent) is potentially suitable to the invasion of the species. The climate-soil model predicts approximately 5.3 million km^2 (68%) to be suited to buffel grass establishment and growth. It must be remembered that these are very broad, crude area estimates and fine-scale patterns are likely to substantially reduce these area estimates. It does however reinforce the widespread threat by this species to much of the northern part of the continent.

For buffel grass to establish in any of the areas indicated as being environmentally suitable within this model there must be the opportunity for propagules to disperse to an area. Cavaye (1991) claims that buffel grass has a preference for cleared country, however, Franks (2002) has demonstrated its ability to establish in native vegetation with minimal disturbance. Domestic stock passing through a patch of remnant vegetation adjacent to pastures may provide sufficient soil disturbance for buffel grass establishment. Several cultivars of buffel grass are known to have colonized road and rail reserves, and spread across fertile loam soils throughout Queensland (Walker and Weston 1990). In addition, buffel grass has been recorded as preventing the regeneration of many indigenous plants (Daehler and Carino 1998, Fairfax and Fensham 2000, Franks 2002). Buffel grass is well known for its ability to displace native grass and herbaceous species in many of the countries where it has established (Paull and Lee 1978, Gonzalez and Latigo 1981, Daehler and Carino 1998, Franks 2002).

The ability to alter the characteristics of invaded ecosystems and the results of our models suggests that buffel grass has the potential to eventually spread through much of the semi-arid and arid zone of Australia. Fensham (1996) raised serious concerns about the particular risk posed to dry rainforest remnants by this species. Buffel grass produces around two to three times the flammable material of displaced native grasses resulting in hotter and more intense fires later in the dry season (Humphries 1993). Buffel grass establishment along the edge and into fire-sensitive plant communities facilitates more intense fires to progressively penetrate and ultimately destroy the canopy (Butler and Fairfax 2003). Humphreys (1967) comments on the capacity of buffel grass to lock up nitrogen in areas that it grows, adversely affecting soil nitrogen concentrations and availability for native plants.

Finally, an explicit warning on the threat posed by buffel grass can be found in Paull and Lee (1978), who state that it will 'compete with and usually eliminate weeds and other native pasture species'. Although aimed at promoting the benefits of buffel grass to the grazing industry, this statement provides a dire warning of the invasive capability of this species. Active and ongoing management of buffel grass will be essential if its detrimental impacts on native species, vegetation and wildlife are to be limited. Importantly, this research demonstrates the benefits that combining predictive models of potential distribution (e.g. CLIMEX) within a GIS environments presents great opportunities to assess and better manage such threats in a timely manner.

Acknowledgments

Craig Walton (Pest Management Strategy, Queensland Department of Natural Resources, Mines and Energy) and Peter Mackey (Alan Fletcher Research Station, Queensland Department of Natural Resources, Mines and Energy) are thanked for their advice, and for making the CLIMEX program available for this project. We are also grateful to the many people on the Enviroweeds and Aliens-L list-servers who replied to our requests for information on buffel grass distribution. The Australian National Botanic Gardens and Australian Virtual Herbarium are thanked for providing distributional information from their databases. John Neldner, Craig Walton and Don Butler provided valuable comments on an early draft of the manuscript. Mike Grundy (Land and Environment Assessment, Department of Natural Resources, Mines and Energy) is gratefully acknowledged for assistance in categorizing soil types. We would like to thank Darren Kriticos of CSIRO Entomology for supplying us with the ESOCLIM-50 grid of Australia.

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