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GROWEST PLUS: A tool for rapid assessment of seasonal growth for environmental planning and assessment

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Abstract

GROWEST PLUS is a software interface, designed to run a new version of the GROWEST plant growth index simulation model, originally developed by Fitzpatrick and Nix in 1970. The GROWEST model was designed to integrate the major climatic determinants of potential plant growth at broad geographic scales, and GROWEST PLUS allows comparisons of current conditions relative to historical variability. Substantive literature demonstrates the robustness, simplicity and application of GROWEST at regional to national scales. This has led the Bureau of Rural Sciences (BRS) to use this tool as one of a suite of analyses and models in the assessment of Exceptional Circumstances drought applications. The advantage of GROWEST is its simplicity. The model synthesises well established biological responses to seasonal trends in climate. It has the advantage of few dimensions, which significantly reduces computational and processing time. GROWEST performs well with the SGS Pasture Model outputs. In fact, GROWEST's performance is encouraging given the level of simplicity in the model. GROWEST, however, trades off some processes that are important at detailed scales in order to be able to run with readily available input variables for regional scale assessments. Unaccounted processes include detailed simulation of soil moisture, soil fertility and differences between phenological responses at the plant species level. GROWEST PLUS was developed by BRS and the Centre for Resource and Environmental Studies at the Australian National University. The most significant feature of GROWEST PLUS is its ability to analyse variability in seasonal growth over time using time-series outputs from the GROWEST model. For this purpose, the GROWEST model was comprehensively upgraded to run on weekly and monthly climate data, in point or grid form, to produce weekly and monthly outputs. This will have benefit in the analyses of specific events such as drought or the characterisation of growing season reliability for natural resource management. This paper demonstrates how users can easily and intuitively run the upgraded GROWEST model through the GROWEST PLUS graphical user interface, utilising 'real time' climate data, in point or grid form, to undertake a range of spatial and temporal analyses.
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1. Introduction

When a severe event, such as drought, impacts on agricultural industries, the Australian Government can provide financial assistance to producers through the Exceptional Circumstances (EC) policy. The EC policy aims to provide assistance to producers impacted by 'rare and severe' (predominantly drought related) events that are considered beyond the scope of normal risk management (ARMCANZ, 1999; Clark et al., 2000). In order for EC to be declared, a region must demonstrate that it has experienced a 'rare event' that results in a 'severe impact' on farm income (ARMCANZ, 1999). Assessments are made in short timeframes on the basis of information that is available during the application process, with

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a community or industry defining the geographic boundaries and severity of the event (Clark et al., 2000). The Bureau of Rural Sciences (BRS) of the Australian Government provides independent scientific advice to the National Rural Advisory Council on whether an EC application demonstrates that an event is 'rare' given long-term historical variability and has resulted in a 'severe and prolonged impact' on production.

An approach was sought to integrate the major climatic factors that determine plant growth potential and incorporate rainfall effectiveness at spatial scales from regional to national and at time scales of greater than 12 months (White et al., 1998; Angus, 1991). To operate within the constraints of the EC decision-making process, the approach also had to be computationally efficient, readily transferable to a range of climatic regions, be able to be integrated with easily available, near real-time point and spatial climatic data and have parameters that could be estimated as part of a desktop study.

Several plant growth models can be used for EC assessments. They range from complex (APSIM, McCown et al., 1996; GRAZPLAN, Moore et al., 1997; and AussieGRASS, Carter et al., 2000, 2003) to relatively simple (GROWEST, Fitzpatrick and Nix, 1970). APSIM is a crop production model that requires detailed descriptions of soil and crop data. The GRAZPLAN suite of models, which include the pasture growth model GrassGro, require multiple parameters related to pasture species phenology, soil characteristics and animal physiology (Moore et al., 1997). AussieGRASS is applied across Australia by averaging inputs for different pasture communities and soils (Carter et al., 2000). It provides the capacity to validate near real-time data and forecasts of a range of features critical to natural resource management in grazing lands and for EC assessments (Howden et al., 2002). GROWEST has been used in the analysis and characterisation of plant growth potential in a wide variety of grassland communities at different spatio-temporal scales and several studies have also demonstrated its robustness and simplicity (Nix et al., 1977; Nix, 1981; Murray and Nix, 1987; Hill et al., 1989; Hutchinson et al., 1992; Blumenthal and Ison, 1993; Grist and Menz, 1995; McDonald, 1998; White et al., 2001). GROWEST has also been used as a parameter in the forecasting of wool and livestock production (Connolly, 1992; Flavel et al., 1987; Shaw and Findlay, 1990). Additional work has also extended the growth index through integration with remotely sensed metrics (Hill et al., 1996).

GROWEST was comprehensively upgraded by the Centre for Resource and Environmental Studies at the Australian National University to enable it to run on long-term weekly and monthly climate data in point or grid form, to produce either weekly or monthly outputs. GROWEST and AussieGRASS are currently used in EC assessments at BRS, with GROWEST used broadly to characterise climatic conditions in relation to potential plant growth.

The upgraded GROWEST model and software interface, GROWEST PLUS, provides a quantitative approach for assessment of rainfall effectiveness at the spatial and temporal scale of analysis encountered in most EC applications. A significant feature of GROWEST PLUS is its ability to analyse variability in seasonal growth over time using time-series outputs of the weekly plant growth index.

GROWEST PLUS also has potential for broader application. For example, it may be used in the assessment of broad scale crop or pasture growth potential over large regions. The analysis of seasonal growth reliability (using conditional probability statistics) through the use of extended time-series climate data may have the potential to assist in risk management decisions for sustainable environmental and agricultural planning (Laughlin et al., 2003). The move away from a reliance on analyses based on long-term averages of historical climate data is one of the most important features of GROWEST PLUS, as it captures the variability of seasonal growth over time. This is particularly useful in regions with highly variable climates.

This paper describes the value of using the GROWEST model, some of its limitations and the development process of GROWEST PLUS. A limited validation of GROWEST with a well-calibrated model is accomplished as a part of this study. Two case studies that demonstrate the uses of GROWEST PLUS are also presented. These include an analysis of a drought event (as might be expected in the analysis of EC applications) and an analysis of climate-related risks associated with annual pasture growth. Both of these analyses are based on monthly gridded outputs from GROWEST, which are analysed using the GROWEST PLUS interface.

2. Modelling plant growth potential: GROWEST's value

The GROWEST plant growth simulation model was originally developed to characterise broad pasture environments in terms of well-established biological responses to seasonal trends in climate. It was constructed to run at a single point using average and actual weekly climate data. Fitzpatrick and Nix (1970) noted "… simulation of pasture response using long-term historical records of weather sequences will permit assessment of growth in probabilistic terms at stated times and at stated locations" (p. 25). The model was expanded and described in detail by Nix (1981). The attractiveness of the GROWEST model's use in environmental assessments including EC is its ability to model extensive systems with apparent simplicity and to quickly analyse potential plant growth over large regions using minimal soil information and climatic data (Nix, 1981; Rimmington and Charles-Edwards, 1987). Such a simple model is ideally suited to estimating regional or national crop and pasture growth potential in terms of climate variability. One of the objectives of developing such a model was to minimise input variables and parameters and to ensure that the model could be applied to a large region without making assumptions about specific pasture species phenology.

The GROWEST model calculates three primary output indices that characterise relative plant growth in response to light, temperature and soil moisture. These indices are combined to generate a fourth index, the growth index (GI), which is the product of the light (LI), moisture (MI) and temperature (TI) indices (Fitzpatrick and Nix, 1970):

$$GI = LI \times MI \times TI$$

The values of all of these indices vary between zero and one. When each of the three primary indices has a value of one, the value of GI will also be one, representing optimum growth rate. If any of the three primary indices has a value of zero, GI will also have a value of zero, indicating that the plant is not growing. The growth index approach employed in GROWEST has been found to work well, especially in the early stages of growth or for assessing the length of growing seasons (McCown et al., 1981; McCaskill, 1991; McCaskill and McIvor, 1993).

2.1. Temperature response index

Temperature plays a major role in controlling plant development, growth and yield in the absence of other restrictions. Temperature response can be summarised in terms of three fundamental temperatures, namely, the lower temperature threshold, optimum temperature and upper temperature threshold, on a daily basis. A number of plant models are based on these three fundamental temperatures. Yan and Hunt (1999) summarised plant models based on temperature into five major groups: linear, bilinear, multi-linear, exponential/polynomial and beta distribution models. They stated that beta distribution models give a smooth curve, which is ideal for characterising plant responses to temperature. This is opposed to a series of lines with abrupt changes between them, which is inevitable with bilinear or multi-linear models. Temperature–response curves in GROWEST are fairly similar to beta distributions because, in general, the difference between the lower temperature threshold and optimum temperature is not equal to the difference between the upper temperature threshold and optimum temperature.

Australian grassland pasture species can be classed into four broad groups according to plant responses to temperature, as described by Nix (1981): C3 microtherm, C3 mesotherm, C3 megatherm and C4 megatherm. In general, C3 plants are temperate and prefer cooler and moister conditions, whereas C4 plants grow better in warmer and drier conditions. A critical point for continent-wide comparative studies is that each of the plant group thermal responses is relevant only to that group.

2.2. Light response index

Nix (1981) states that the functional relationship between dry matter production and total daily solar radiation used in the GROWEST model is based on theoretical considerations by Davidson and Philip (1958) and De Wit (1959, 1965), together with experimental data relating to a range of tropical and temperate species (Hesketh, 1963; Cooper, 1966; Tanaka et al., 1966). This relatively simple approach works well in the GROWEST model, as Hutchinson et al. (1992) have demonstrated that sufficient solar radiation is found for crop growth over much of the Earth's surface, therefore broadly justifying the estimation of a common light index for all species.

2.3. Moisture response index

Soil moisture fluxes are difficult to measure and simulate. In 1953, Van Bavel (1953) suggested that a straight-line relationship between evapotranspiration and soil water content would enable simple calculations of soil water balance. Subsequent studies have shown that this relationship is more likely to be curvilinear (Denmead and Shaw, 1962; Eagleman, 1971; Nix, 1981) or exponential (Baier, 1969). Soil water storage is calculated in GROWEST by maintaining a 'single bucket' weekly water balance (Hutchinson et al., 2002) based on a curvilinear relationship between relative evapotranspiration and soil water content.

2.4. GROWEST's limits

It should be understood that GROWEST produces growth indices and not absolute estimates of plant production. To meet the requirements for computational efficiency and transferability, GROWEST trades off some processes associated with plant growth at detailed scales. Processes other than temperature, light and moisture that directly or indirectly influence plant growth are unaccounted for in GROWEST. These include detailed simulation of soil moisture, crop or pasture condition, differences between phenological responses at the plant species level, soil properties such as pH and fertility, wind speed, day length, frost and pests. Although these factors play a role when translating growth indices into plant production, the exclusion of these in GROWEST is not necessarily a limitation of the model for rank ordering seasons, for example, where those unaccounted factors in the model are likely to be unchanged over a long period of time. There are however limitations to the application of this model that may inhibit its usefulness when characterising growth in particular seasons, regions or at some scales of analysis. Some of these limiting factors are discussed below in the context of where GROWEST can be applied.

The growth condition or growth stage of plants is not incorporated in the GROWEST model, which assumes that plants are perennial, healthy and ready to grow at all times. For example, characterisation of growth following a severe climatic event such as drought or frost using GROWEST will not incorporate the reduced capacity for the plants to respond at a normal rate.

Soil depth and its relationship to soil moisture and potential plant growth is not explicitly incorporated into GROWEST. Soil depth is defined as the depth of soil penetrable by roots and is usually between 50 and 100 cm for agricultural soils. Since GROWEST defines available water storage irrespective of the crop or pasture, it may have some limitations when applied to areas where shallow or deep soils are found.

As stated above, the moisture index in GROWEST is based on a simple relationship between a filling soil moisture bucket and evaporation. This approach does not accurately account for runoff, floods or soil water logging and is limited by an inability to discriminate between high and low rainfall intensity during weekly intervals.

In contrast to GROWEST, many plant growth models include soil fertility, soil salinity and soil pH. Assessment of soil fertility is a good indicator of variability in potential plant growth. Both nitrogen and phosphorus are typically low, especially in arid and semi-arid Australia (Bennett and Adams, 2001) and the spatial heterogeneity of nitrogen is high (Bennett and Adams, 1999). Soil pH is a standard measure of soil acidity and alkalinity and is known to affect the influence of toxins and nutrient deficiencies on plant growth. Therefore, the value of soil pH is a good measure of extreme soil conditions and may indicate where plants are unlikely to grow (Hackett, 1991). Soil salinity, pH and fertility can play a major role in plant growth and certainly need to be taken into account when modelling growth at more detailed scales.

Wind speed can influence plant growth, particularly when high wind speeds cause plant damage. Therefore, the application of GROWEST for a particular growing season where unseasonably high winds have occurred could have limitations. In cases where actual pan evaporation data is used, windspeed, to a certain extent, is implicit in the data. This will account for some of the variability caused by unseasonable wind.

Events such as unseasonable frosts can greatly impact on plant growth. Whaley et al. (2004) state that frost at certain times during the growth of wheat can kill spikelets, restrict internode extension and reduce yields. Therefore it can be important to distinguish between frost-tolerant and frost-sensitive plants.

Day length influences the initiation of plant organs, especially when flowering. Since day length often interacts with day temperature, it is reasonable to suggest that GROWEST captures the influence of day length within the thermal regime incorporated in the model.

The dynamics of pest and pathogen populations have a direct impact on plant growth. Spatial application of GROWEST to a large region could lower such an influence because most pest and pathogen damages are localised.

With the exclusion of these detailed scale factors, GROWEST PLUS may not be an appropriate model for undertaking specific simulations of farm scale productivity and comparison of farm management strategies.

3. The revised GROWEST plant growth index model

GROWEST has undergone two major developments since its inception as a simple point based model. It initially relied on input of actual and average weekly climate data to produce five output indices; temperature, moisture, light, runoff and growth (Nix et al., 1977). Average weekly climate inputs were initially derived from monthly mean climate values using Fourier transform (Fitzpatrick and Nix, 1970) and later using a cubic Bessel interpolation procedure (Hutchinson, 1979). The weekly values produced by the latter procedure preserved the input monthly totals exactly, making due allowance for the relationship between weeks and months of the year.

The GROWEST program was then incorporated into the GROCLIM module of ANUCLIM (Houlder et al., 2000). This application also used cubic Bessel interpolation to supply weekly inputs to the underlying GROWEST model from monthly mean climate values. In this case, the monthly mean climate values were obtained from continental climate surface coefficient files produced using the methodology described by Hutchinson (1991, 2001). The GROCLIM application enabled the model to be run effectively on interpolated long term monthly average climate data at any point location in Australia for which the longitude, latitude and elevation were known.

For the application described here, the GROWEST program has been completely rewritten (Hutchinson et al., 2002) to significantly expand its spatial and temporal capabilities. The revised GROWEST program now processes actual weekly, actual monthly and average monthly input climate data, all supplied in either point or grid form. Basic soil moisture properties can also be supplied in point or grid form. As before, the underlying GROWEST model remains at the weekly time step, so monthly climate inputs are interpolated to weekly values using the cubic Bessel interpolation procedure as stated earlier. Moreover, the weekly output indices can be averaged to monthly output indices, also in point or grid form depending on the form of the climate inputs. The revised GROWEST program is implemented in FORTRAN 90 to take advantage of the extensive vector processing capabilities of this language. This was particularly advantageous in enabling the model to run on gridded input data.

All input weekly interpolations and output monthly aggregations are performed making due allowance for the temporal coverage of each month by whole and partial weeks. This means that the annual averages of GROWEST output weekly indices and output monthly indices are identical when the model is run on the same input data. The aggregation of weekly to monthly values is appropriate when broader time scale responses, such as those arising in drought assessment, are required. It can also be appropriate when the input climate data are supplied as monthly values.

The growth index is a relative measure of increase in plant size (Salisbury and Ross, 1992) that can only be quantified in terms of biomass production through further calibration with production data (Stephens, 1995). However, it is the added spatial and temporal functionality of the latest version of GROWEST that allows it to be effectively used as part of a toolset for analysing individual events and characterising seasonal growth variability with minimal calibration.

4. Simulations to compare SGS model with GROWEST

The simple structure of GROWEST makes it ideal for the large-scale simulations across temperate Australia. It is beyond the scope of the present paper to provide a detailed validation of GROWEST. However, we see value in providing some model assessment and so have performed a limited comparison with the SGS Pasture Model (Johnson et al., 2003), which is a detailed biophysical, deterministic, mechanistic pasture simulation model, that has been widely applied across southern Australia. The SGS model has been tested for several sites during and after Sustainable Grazing Systems project of Australia (Johnson and Lodge, 2006). Among several experimental sites for SGS, Hamilton in Victoria and Wagga in New South Wales were chosen randomly. Core simulations for Hamilton and Wagga were carried out for 50 years with meteorological data from the SILO database. Soil water characteristics for the SGS model were derived from observed data and the equivalent water holding capacity was then used in the GROWEST. The SGS simulations have a combination of pasture species (phalaris, sub-clover, forbs and either with or without native C4), since it is unusual to have monoculture pastures. In GROWEST, a broad plant category; C3 mesotherm has used. Growth rate in the SGS model was calculated from simulated monthly cutting trails and GROWEST's potential growth rate is then scaled to same order of magnitude for comparison. For both models, long-term simulations have been run and median growth rates calculated (Fig. 1).

Hamilton is characterized by a winter dominant rainfall with little summer growth. It can be seen that there is very good agreement between GROWEST and the SGS in relation to pasture growth apart from summer and early autumn (Fig. 1A). The SGS simulation without C4 natives suggests that there is no pasture growth in summer (Fig. 1B). This highlights GROWEST's limitation in summer growth condition, particularly for C3 pastures.

With more rainfall in summer, Wagga is more likely to have C4 grasses present than Hamilton. Fig. 1C and D show SGS growth simulations with and without C4 natives for Wagga, respectively. These results are almost identical to Hamilton. The SGS simulation has slightly more growth in C4 natives than in Hamilton.

Overall, GROWEST works well in relation to estimating potential pasture growth. However, it is identified that GROWEST appears to have to more C3 growth during summer. This limitation is most likely to due to daily minimum and maximum temperatures employed by GROWEST do not encapsulate the impact of temperature extremes.

5. GROWEST PLUS

The aim of developing GROWEST PLUS was to provide a tool that easily enables users to run the latest version of GROWEST. GROWEST PLUS was designed to: simplify the task of accessing and organising numerous input and output files, offer a means to use GROWEST outputs as the basis for spatial/temporal analyses and provide a tool for visualising outputs (this functionality is detailed below).

The GROWEST PLUS application has been written using the JAVA scripting language, providing a flexible, highly functional and user-friendly graphical user interface. Most of the GROWEST PLUS functions are accessed via a simple menu bar. Wizards are used to guide the user through each step of a new project (model run) or analysis. Fig. 2 provides an example of the GROWEST PLUS graphical user interface.

GROWEST PLUS generates a command file using JAVA, that is sent to the GROWEST model specifying what the model run will encompass, where data is located, what output files will be generated and where to save them. Once a simulation is completed, GROWEST PLUS displays analyses (grid outputs) from the model (Fig. 2).

Outputs from GROWEST PLUS can be viewed in the interface in a number of formats, depending on the analysis

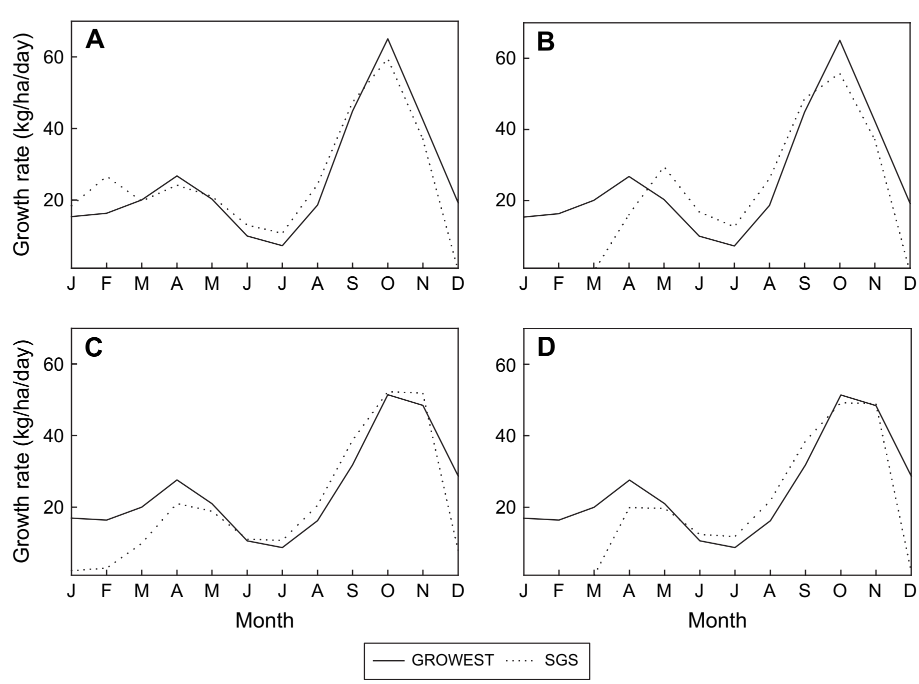

Fig. 1. Comparison of the SGS Pasture Model and GROWEST for Wagga (A and B) and Hamilton (C and D). C4 natives are included for the SGS simulation in (A) and (C). GROWEST's potential pasture growth rate is scaled with SGS outputs to same order of magnitude. For both models, long-term simulations have been run and median growth rates calculated.

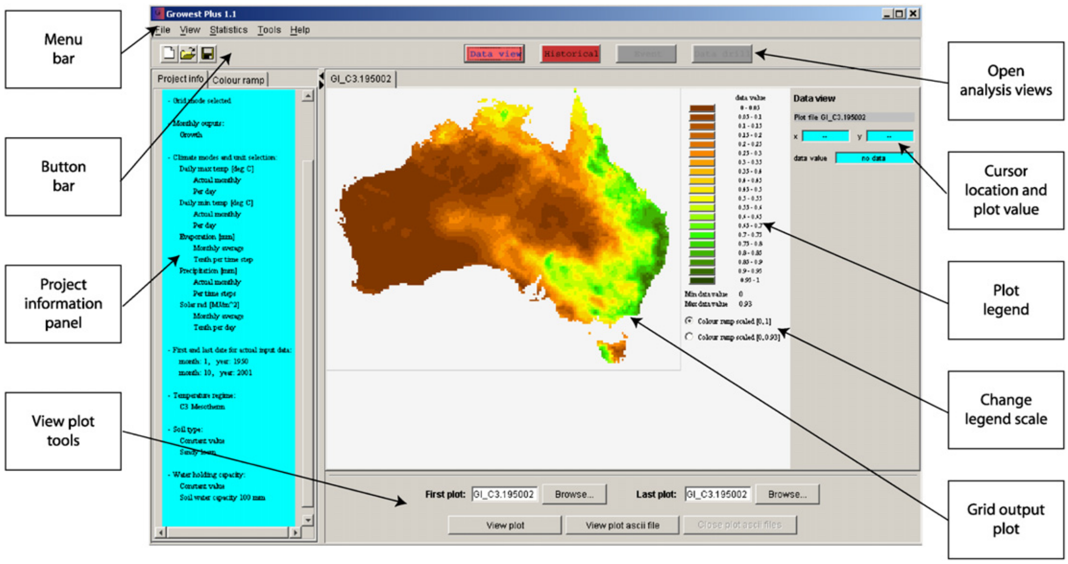

Fig. 2. An example of the graphical user interface (GUI) of GROWEST PLUS.

undertaken. Fig. 2, for example, shows raw (or gridded) output from GROWEST in the form of a map. Legends and colour schemes can be changed depending on user requirements.

While GROWEST PLUS was designed to provide simple tools for viewing output data, users requiring further contextual information or analyses based on this data can export these grids as an ASCII file (ESRI format[1]) and import them into a geographic information system such as ArcView or ArcGIS.

5.1. Input/output data

GROWEST PLUS has the capacity to use a variety of input data types, including real weekly, real monthly and average monthly climate data in point or grid format. Climate data include maximum and minimum temperatures, rainfall, solar radiation and pan evaporation. Grid based analyses provide the user with the ability to generate spatial outputs for each of the indices, enabling quick characterisation of the extent of an event or growing season potential.

5.2. Analyses

GROWEST PLUS analysis tools are only available when outputs from GROWEST form a time-series of grids. There are four types of analyses available to the user: data drill, statistical analysis, historical analysis and event analysis.

The data drill function provides users with a means of extracting and visualising a time-series of values for a single grid cell (a point) or group of grid cells (a region). Selecting a region or point can be done directly from the map or with the coordinates and region size. The data drill may be used to support an event analysis, providing an indication of how an event compares to the historical record. Although the output from the data drill is a series of weekly or monthly values for the entire historical record, it is relatively simple to import this data-series into a spreadsheet application and summarise the values into annual seasonal information. The time-series can also be viewed through the use of a simple graph tool in GROWEST PLUS.

The output from each of the statistical analyses is a single grid. Statistical calculations made at each grid cell are independent of relationships between cells in individual months or weeks. Table 1 contains notations for the calculations shown in Table 2 and Table 3.

Historical analysis incorporates the entire time-series of available grids for an index and provides users with the ability to characterise a given season. Once a user has defined the season (any string of months [or weeks] within a 12 month

Table 1
Notation for calculations

I	Year index within the chosen historical data period. This chosen data period is set at project creation time via the new project wizard procedure or when an existing project is opened. The index i goes from *start_y* to *end_y*
S	Season interval for an arbitrary year (specified either by first and last week or month)
S_i	Season interval for some year i
$m_i = \text{mean}\ (S_i)$	Mean index over the season S_i
N	Fixed number of consecutive years
E_n	Event interval for an arbitrary year. Obtained by taking the list of season intervals over n consecutive years. The event can be a season, i.e. $n = 1$
E_{ni}	Event interval for some year i, namely $E_{ni} = S_i + \cdots + S_{i+n-1}$
$m_{ni} = \text{mean}\ (E_{ni})$	Mean index for the event E_{ni}
N	Total number of historical data slices that lie within a season within the chosen historical data period

[1] http://www.terraseer.com/bsr/help/Importing/Import_formats_for_raster_data.

Table 2
Statistical analyses available as part of 'historical analysis'

Function	Description	Calculation
Seasonal mean	Calculates the average index for the season	Sums all N historical data within S and divides the result by N
Average seasonal sum	Calculates the average sum (area under the curve) of an index for the season	Sums all N historical data within S and divides the result by the number of seasons which is equal to $end\_y - start\_y + 1$
Seasonal reliability based on the mean	Calculates the probability of receiving greater than or equal to a certain percentage of the mean in a season (or multiple seasons)	Given a number n of consecutive years, percent x of exceedance, and season S computes: the mean m of all N historical data within S; the means m_{ni} for $i = start\_y$ to end_y; and returns the frequency of $(x/100) \times m$ exceeding the means m_n
Seasonal reliability based on percentiles	Calculates the frequency of a certain percentile (say, x) has been received in a season a certain number of times in a row (say y, with a maximum value of 5)	Given a number n of consecutive years, percentile value x, and season S computes: the means m_i for $i = start\_y$ to end_y; the percentiles p_i associated with the whole set of scores m_i for $i = start\_y$ to end_y; and returns the number of existing sets $A_i = \{p_i,\ldots,p_{i+n-1}\}$ for $i = i_1,\ldots,i_2 - n + 1$ such that all elements in the set A_i are $\geq x$
Percentile analysis	Calculates what a particular seasonal percentile would look like for an index	Given a percentile value x, retrieves the x percentile index value for the scores $m_{start\_y},\ldots,m_{end\_y}$ over each pixel

period) there are five statistical analyses (functions) available. These are outlined in Table 2.

Event analysis provides users with a tool for analysing how a particular past 'event' eventuated and how it compares to all other similar events in the historical record. An event is a season (any string of months [or weeks] within a 12 month period) or string of multiple seasons (each being the same length) up to 5 years in duration. This method of analysing seasonal quality is applicable to EC assessments. An example of multiple seasons may be a winter growing season (May–October) for 3 years in a row (winter 1992, winter 1993 and winter 1994). There are three event analyses (functions) available. These are outlined in Table 3.

6. Case studies

The following section provides two case study analyses produced using GROWEST PLUS. The aim of these case studies is to demonstrate GROWEST PLUS' features, and how long term growth data may be used to characterise and analyse seasonal growth conditions for typical cool-temperate pasture species such as perennial rye (*Lolium perenne*), cocksfoot (*Dacrylis glomerata*) or phalaris (*Phalaris tuberosa*). These case studies cover the analysis of climate events such as drought, based on percentile ranking of growth indices over the time-series. This is useful for ranking growing seasons in terms of plant growth potential.

The two case studies, conducted in New South Wales (Fig. 3), are based on running the GROWEST PLUS in grid mode using the following parameters:

- grids of Australia at 0.25 degrees of latitude/longitude cell size
- 52 years of actual monthly climate data (rainfall and minimum and maximum temperature) and 52 years of monthly average data for solar radiation and evaporation. Since most available climatic data have been interpolated before 1950, this analysis utilises actual data for the 52 years since 1950.
- constant soil information, with texture set as 'clay loam' and water holding capacity set at 125 mm
- broad plant category, C3 mesotherm

6.1. Case study 1: drought analysis for1967

Fig. 4 illustrates annual average growth values and their respective percentile ranking for the case study region. The percentile ranking of the time-series data from the data drill provides a quick depiction of how each 12 month season in the last 52 years has ranked (percentiles are shown on a scale of 0–1). From the data drill (Fig. 4) it can be seen that conditions in 1967 appeared to be relatively poor for this region, compared to other years. That is, it could be a relatively rare event. However, without analysing many individual data drills

Table 3
Statistical analyses available as part of 'event analysis'

Function	Description	Calculation
Mean for an index during the event	An average of the index is calculated over all months or weeks during the event	Computes the mean of the historical data values over the event E_{nI}
Sum for an index during the event	A sum (area under the curve) of the index is calculated for all months or weeks during the event	Computes the sum of the historical data values over the event E_{nI}
Percentile ranking of the event	The event is ranked in the historical record to find its percentile ranking in all other similar events	Computes the sum S_{nI} of the historical data values over the event E_{nI} Computes the sums S_{ni} of the historical data values for all events E_{ni}, $i = i_1,\ldots,i_2 - n + 1$ For each pixel, returns the percentile of S_{nI} with regards to the scores S_{ni}

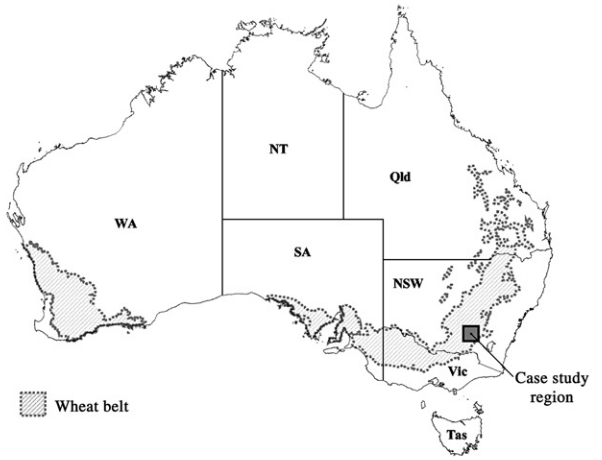

Fig. 3. Location of the case study region in Australia (New South Wales).

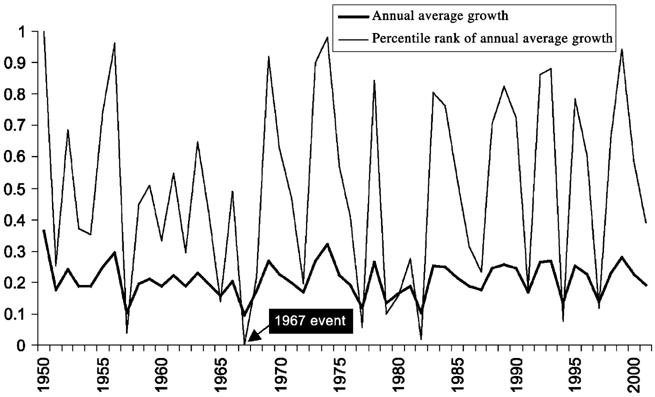

Fig. 4. Summarised annual growth and associated percentile ranking for the region shown in Fig. 3.

it is difficult to visualise the extent of the poor conditions. The 'event analysis' function of 'percentile rank' can therefore be used to show the spatial extent of the event. Fig. 5 illustrates the percentile ranking of the 1967 growing season within the 52 years of historical record.

It should be noted that the specified C3 mesotherm temperature regime is appropriate for cool temperate pasture species, but less suited to tropical species. Separate runs of the model using C3 megatherm (tropical legume) and C4 megatherm (tropical grass) temperature regimes would be more appropriate for tropical Australia. Even though the study area in this example is temperate, the inset box in Fig. 5 shows the same analysis for C4 megatherm species.

Fig. 5 provides a clear indication of the extent of the 1967 event, indicating that dry conditions affected most of south eastern Australia. It is this type of analysis that is particularly beneficial for the assessment of drought events in Australia, providing an indication of the extent and severity of an event based on a chosen growing season.

6.2. Case study 2: characterising a growing season

The historical analysis function can be used to create a picture of how well or how reliably a species may be expected to grow across a region. In this example, Fig. 6 demonstrates typical summarised outputs from the data drill for a single plant group (C3 Mesotherm) representing each of the four main indices (moisture, temperature, light and growth). The relationship between growth and its subsidiary indices is clearly shown. During summer months (December to February) growth in the case study region is limited by moisture and in the winter months (June to August) growth is limited by temperature. As a result of this analysis it is possible to determine the temporal pattern an average growing season for the region would have.

Once the temporal pattern for the growing season is determined, it is useful to develop a spatial representation of an average growing season. Fig. 7 illustrates mean annual growth across Australia for C3 Mesotherm plants. Mean seasonal growth is a useful analysis, showing relative spatial variability of growth across a region for an average season. However,

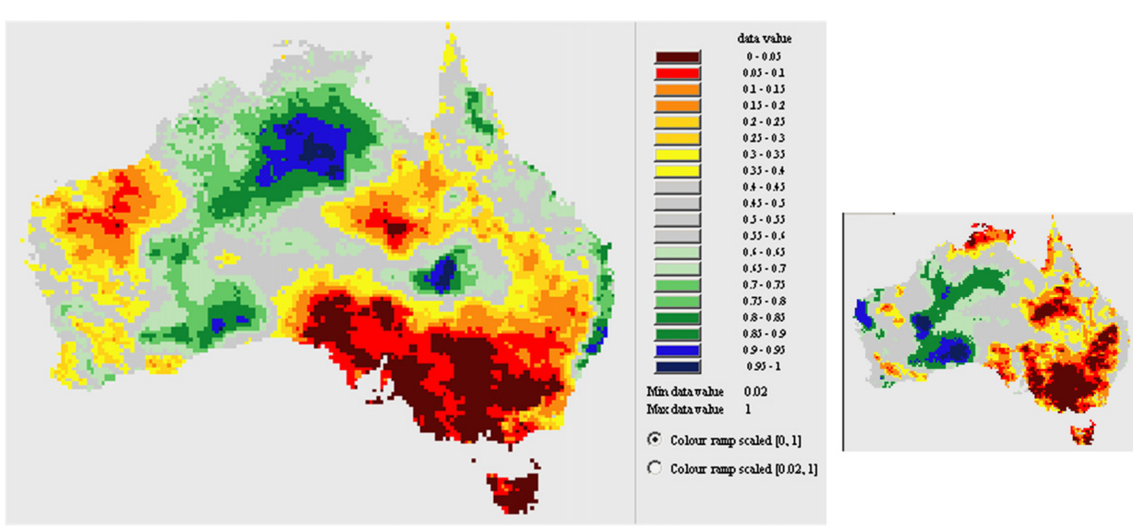

Fig. 5. Percentile ranking of the 1967 season in the historical record (inset C4 megatherm).

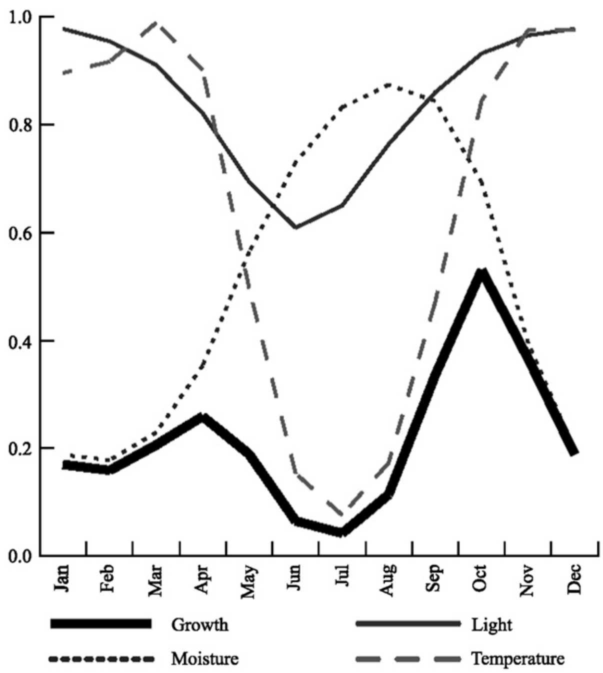

Fig. 6. Monthly average indices for the NSW case study region.

when planning agricultural enterprises or analysing environmental systems it is important to know more than just ‘average’ information, due to the smoothing effect many years of data has (that is, outlier years may not be clearly reflected).

An estimate of reliability may be calculated by GROWEST PLUS using ‘conditional statistics’ (see the ‘analyses’ section above). Reliability provides an estimate of how often one can expect to receive a proportion of the seasonal mean (for an index). For example, in regions that show relatively high annual growth (Fig. 7) and high reliability (Fig. 8) (southern Victoria), a ‘good’ season can be expected in most years. On the other hand, regions that show relatively low annual growth and high reliability (western Victoria and parts of southwest Western Australia) may be less productive but reliable. It is the understanding of seasonal reliability that provides land managers with a tool to assist in making informed decisions on risk management.

As demonstrated in Fig. 6, the case study region has a biannual growing season (autumn and spring). Therefore in order to complete the characterisation of pasture growth in the region, an analysis of seasonal reliability was undertaken for autumn and spring. Fig. 9 shows the result of the growing season reliability analyses. It can be clearly seen that there is a degree of variability in the reliability experienced during the year. In south eastern and south western Australia growth reliability is higher and more widespread in spring than autumn.

7. Discussion

The significance of developing GROWEST PLUS and its linkage with the latest version of GROWEST lies in the provision of a simple and intuitive interface that may be used to analyse and visualise potential plant growth over regions using a time-series of real historical data. It is the quick set-up and fast analyses that make this application an invaluable tool in the suite of methods used by BRS in the analysis of event impacts and extent throughout Australia.

Although GROWEST is a simple model, it provides a reasonable estimate of the relative variability of potential growth for a region (Fitzpatrick and Nix, 1970; Hutchinson et al., 1992; Rimmington and Charles-Edwards, 1987). It is envisaged that this application could have significantly wider

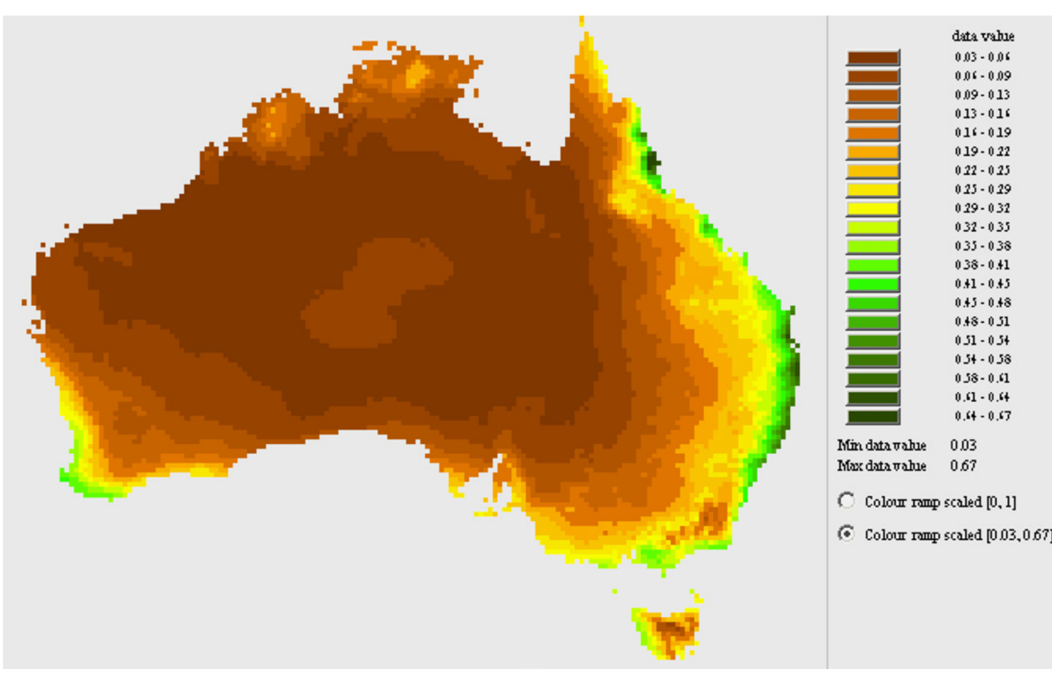

Fig. 7. Mean annual growth for the C3 mesotherm plant group.

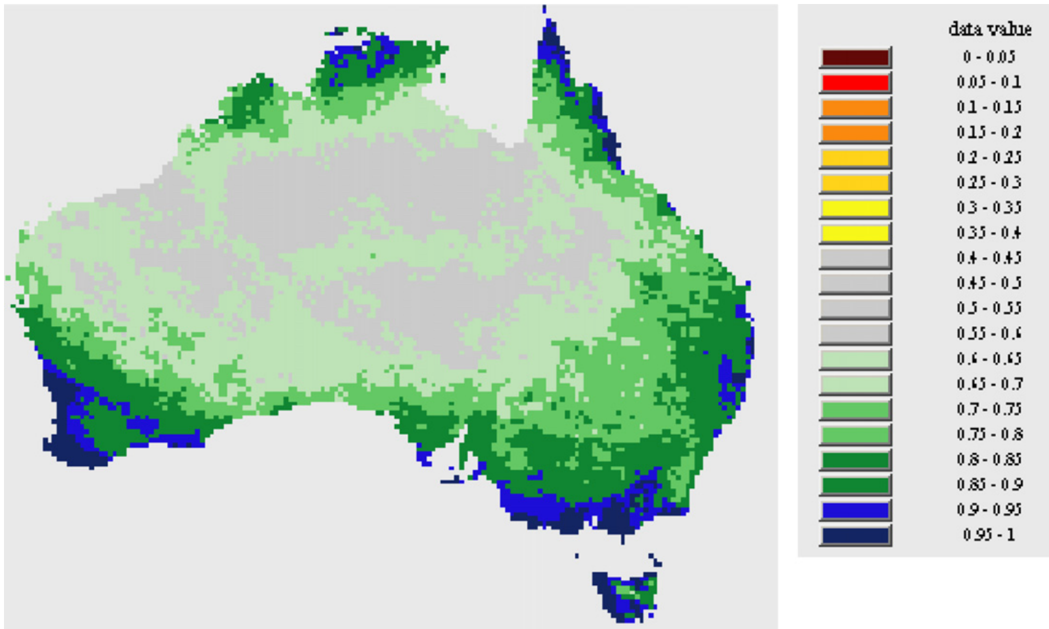

Fig. 8. Growing season reliability, that is, the chance of receiving 75% of mean annual growth in each year, for the C3 Mesotherm plant group.

application in natural resource management. For example, GROWEST was used in conjunction with rainfall analysis and a plantation model to develop land use plans for perennial pastures and timber plantations for the Lachlan Catchment of New South Wales (Laughlin, 2001).

GROWEST performs well in a limited comparison with the SGS Pasture Model outputs. In fact, its performance is encouraging given the level of simplicity in the model. However, there is a general trend of growing C3 species too well in summer which appears to be due to treatment of temperature in the model.

The key feature of this software, with regard to environmental applications, is its ability to run the GROWEST model using real time gridded historical data and undertake analyses based on a time-series of output grids. The use of conditional statistics to analyse seasonal reliability enhances the capacity to describe potential agricultural production beyond standard statistical measures that are often normalised to the mean. As shown in Figs. 8 and 9, analysing growing season reliability can provide an indication of where and when seasonal growth is likely to be dependable. It should be noted however, that specifying the thresholds for this type of analysis often requires a good understanding of what percentage of relative seasonal growth translates to a viable crop or pasture.

Event analysis provides a means of analysing how a season or string of seasons ranks in the historical record. The analysis of the 1967 event (Fig. 5) demonstrated not only the severity and extent of the ‘drought’ event but also the frequency of occurrence of such a drought in the last 52 years. It is perhaps this function that is most beneficial to the EC assessment process.

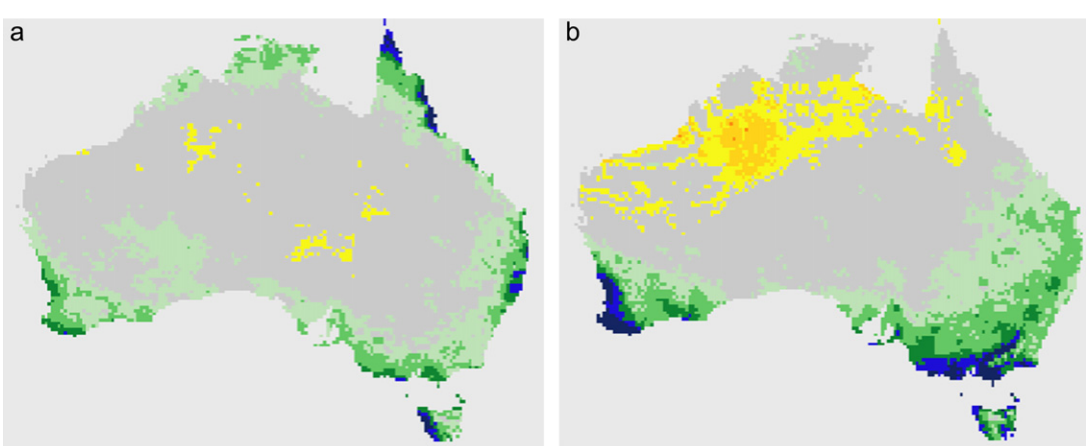

Fig. 9. Growing season growth reliability for the C3 Mesotherm plant group. (a) chance of receiving 75% of mean seasonal growth for autumn (March–May). (b) Chance of receiving 75% of mean seasonal growth for spring (September–November). NB: The same colour scale as Fig. 7 is used here.

8. Future directions

In order to apply GROWEST in a wider range of environments and for a particular season, it is understood that the model is required to incorporate various factors other than light, moisture and temperature into the model appropriately. Adopting a beta distribution may be more accurate than the existing temperature response curve. Incorporating more soil textural curves would be appropriate to represent a greater number of Australian soils.

At this stage there are a few factors that are limiting in GROWEST PLUS and it is envisaged that many of these will be addressed in future versions. At present, input grid data must have the same extent and cell size. The user must also take care to ensure that data is correctly structured and named, as GROWEST PLUS does not have any provision for data checking. Further enhancements to GROWEST PLUS could include; (a) the ability to edit a project (so that if the user makes a mistake or wants to change a single parameter in a model run, they would not need to start from the beginning); (b) the overlaying of contextual data (state boundaries, coastal mask and major cities) on any map shown in the graphical user interface; (c) improvement of run-time and reduction of memory requirements; and (d) the ability to plot and statistically analyse point analysis outputs. It is also envisaged that the JAVA component of GROWEST PLUS could be adapted to suit other models that use similar input and output data to GROWEST.

9. Hardware/software requirements

To use the GROWEST PLUS application on a Windows PC the following are required:

- An Intel Pentium processor or compatible
- Windows operating environment (98, 2000, NT and XP)
- GROWEST Version 2.0 executable
- Java runtime environment V1.3.1 (or later). This is available free from http://www.sun.com/download/api.javatech.html.

Disk space and RAM requirements will greatly depend on the number of years of monthly or weekly data to be analysed. For example, if the model runs and analyses involve greater than 20 years of monthly data (or 10 years of weekly data) then at least 128 Mb of free RAM and a minimum of 500 Mb of free hard drive space is required.

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