Site index prediction of *Eucalyptus dunnii* Maiden plantations with soil and site parameters in sub-tropical eastern Australia

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Summary

The *Eucalyptus dunnii* Maiden plantation estate in north-eastern NSW and south-eastern Queensland is significantly expanding on ex-grazing land. Thirty-one growth plots (average age 5.2 y) covering a latitudinal range of about 3.2° (370 km) and at altitudes from 8 m to 740 m asl in NSW were used to evaluate the correlation of site, soil and climatic variables with growth of *E. dunnii*. Using height at an age of 10 y as a standard, site indices for *E. dunnii* across the 31 sites averaged about 16 m, ranging from around 5 m to 26 m. The factors available-water storage capacity of the soil, rainfall and altitude accounted for 62% of the variation in site index. Inclusion of measures of fertility did not improve the predictive capacity of the model, possibly because of the limited size of the data set with soil chemical analyses. The predictive model, based on simple, easily assessable site factors, has the capacity to improve the quantitative evaluation of the productivity of sites for *E. dunnii* plantations. The need for a simple field assessment procedure for selection of suitable sites was highlighted by the wide range of productivity exhibited across the plots.

Keywords: plantations; productivity; site indexes; models; *Eucalyptus dunnii*; New South Wales

Introduction

Empirical models derived from the correlation between site variables and growth rates may provide accurate predictions of wood production. In a geographic area of rapidly expanding plantations, with relatively untested species, there is a significant need for such a predictive tool.

In 2007 in north-eastern NSW and south-eastern Queensland there were around 115 000 ha of hardwood plantations, roughly evenly divided between private and government ownership (Gavran and Parsons 2008; Nichols *et al.* 2010). About 13% of that estate was established before 1990, 42% between 1994 and 2004 and 45% since 2004. *Eucalyptus dunnii* Maiden made up about 39 000 ha or 30% of the estate in 2007. The planting rate reached around 5000 ha y^{-1} but is now declining (Smith and Henson 2007). A high rate of hardwood plantation establishment had been predicted to continue for some years (Ferguson *et al.* 2002), but even before the appointment in May 2009 of Administrators and Receivers to Great Southern Limited, which has established a significant portion of the private managed investment scheme (MIS) plantations, the company had ceased planting in the area.

Eucalyptus dunnii has grown rapidly in plantation trials on higher-altitude (> 500 m) fertile sites in north-eastern NSW, whilst having poor growth and survival on lower-elevation sites (< 500 m) (Johnson and Stanton 1993). High growth rates have been reported for *E. dunnii* in plantations—early height growth of over 6 m y^{-1} has been recorded in NSW (R.G.B. Smith, Forests NSW, unpublished data) and 4 m y^{-1} in South Africa (Nixon and Hagedorn 1984). Wang *et al.* (1999) recorded a height of 14.2 m at 4 y of age in China on a red lateritic clay loam with depth of > 2 m and a mean annual rainfall of around 1500 mm. A height of 11.3 m at 3 y was recorded by Johnson and Arnold (2000), and at the same trial 5 y later the mean height was 26 m (Henson and Vanclay 2004). These, however, are high-quality sites not necessarily typical of the sites where most of the *E. dunnii* has been planted.

Eucalyptus dunnii has good pulping properties and is useful for solid timber products (Bootle 1971; Harwood *et al.* 2005; Boland *et al.* 2006; Thomas *et al.* 2007); wood from plantations is suitable for light structural applications (Dickson *et al.* 2003). It has been grown in 10-y rotations for fibre and in longer rotations combining solid timber products with fibre. A common regime consists of a 13-y rotation with a thinning at age 8–10 y.

Site selection criteria for plantations in north-eastern NSW up to 2002 included a minimum annual rainfall of 900 mm, a soil depth of 1 m and slopes less than 18° (Bruskin 1999). This was replaced by a scheme described in an unpublished report to Forests NSW (Holz 2002) and which has been compared with the model developed in this project. The Holz model derived an estimated rooting depth (ERD) by summing soil horizon depths after modifying each depth by a factor determined by rooting limitations due to texture, structure, drainage, salinity and or the presence of texture-contrasting horizons (i.e. duplex soils). Those multiplicative modifiers ranged from one (for horizons that did not limit rooting) to zero (for horizons impenetrable to roots). The ERD was used in a matrix with mean annual rainfall to place the site within one of five productivity classes ranging from < 12 m^3 ha^{-1} y^{-1} to > 30 m^3 ha^{-1} y^{-1} (at 20 y).

There are currently no publicly available site-selection criteria or productivity models for *E. dunnii* in the region, but estimates of hardwood plantation growth in this area (including for this species) as provided in plantation investment product disclosure statements have averaged around 25–28 m^3 ha^{-1} y^{-1} (over a 10–13 y rotation). Prior to the appointment of receivers, Great Southern acknowledged predicted yields would be below initial expectations, leading the company to cease planting in the region.

The rapid expansion of the *E. dunnii* estate has been in new plantations (land not previously used for plantation forestry) on ex-pasture sites. Rising land prices are pushing the most recent plantations into more marginal, lower-rainfall areas. The early stages of any new plantation estate may have a significant degree of trial and error in the selection of appropriate sites; this becomes increasingly important at the margins. In order to understand the environmental and financial risks of a site for a plantation and to develop appropriate silviculture, an accurate quantitative site-productivity predictive model is desirable (Louw and Scholes 2006).

The variables chosen to describe a site are integral to achieving a useful correlation of site with plantation growth. A very wide range of site variables have been used in the description of site and in the assessment of site quality; they include measures of climate, geology, topography and soil physical and chemical characteristics (Louw and Scholes 2002; Ryan *et al.* 2002; Schoenholtz *et al.* 2000). The most useful model that predicts site quality on the basis of site variables is generally the one most easily applied operationally.

This project analysed the capacity of a range of site variables to predict growth of *E. dunnii* in plantations. It defined a quantitative model based on correlation of a subset of those site variables (site and soil characteristics) and productivity of growth plots in north-eastern NSW. Previously only unpublished site models have been used in the selection of land for new *E. dunnii* plantation development.

Methods

Growth information

Forests NSW has established permanent growth plots across its plantation estate. The plots within *E. dunnii* plantations on the north coast of NSW extend from inland of Port Macquarie in the south to near Urbenville in the north, a latitudinal range of around 370 km. Altitude varies from 8 m to 740 m asl (Table 1). The plots were located randomly within the estate, stratified by property and year of planting. Forests NSW established 35 *E. dunnii* plots and these were measured on an annual basis. Thirty-one of these were examined for this project, the remainder being excluded due to their young age (<2 y).

The 31 growth plots each covered around 0.1 ha with stocking that varied from 510 to 1120 trees per hectare (mean 860, s.d. ± 144). At each plot the diameter of all trees and the height of the 100 largest-diameter trees per hectare were measured annually. Age at latest measure on these plots averaged 5.8 y (range 2.3–11.3 y, s.d. ± 2.5). Top height (TH—average height of the 10 largest-diameter trees in each plot) was used to derive a growth curve, rather than using one based on volume, due to the variation in stocking between plots and the relative independence of dominant height from effects of stocking (Grey 1989; West 2004; Leech 2007).

Variation in the age of the plots made it necessary to extrapolate height through to a common age. Predominant mean height at age 10 y was chosen as the measure of site productivity and denoted SI_{10} (Site Index at age 10 y). It was estimated at each growth plot by fitting a function of the form:

$$HT = a[1 - \exp(bA)]^c ,$$

where HT is height at age A and where a, b and c are parameters determined by the annual TH results for each growth plot).

This Chapman–Richards site index function has been found to describe growth well in a range of forest types (West 2004). The 'a' in the function is the asymptotic maximum height. Growth curves were fitted using CurveExpert (Hyams 2003) and used to predict forward to age 10 y, with the results shown in Table 1. Examples of this model fitting and extrapolation are given in Figures 1 and 2.

Site and soil information

The site and soil at each growth plot was described following McDonald *et al.* (1990) and Abraham and Abraham (1992). Soils were revealed by a pit located within the growth plot at a point selected to be representative of the plot and the soil was described down to bedrock or 1.5 m, whichever occurred first. The lower part of the deeper soils was described from an auger boring. A subset (21) of the sites were also sampled for chemical analysis; financial and technical constraints prevented chemical analysis of the soils at all sites. At those sites chosen for analysis, soil samples were collected by auger from within the plot (seven samples for topsoils and five samples for subsoils). The samples were bulked and sub-sampled for analysis. Sampling was carried out by horizon rather than at set depths, except that both the A1 and the 0–10 cm portions were sampled such as to maintain the integrity of both. Sampling at each site was generally of the A1/top 10 cm and the B2 and, in cases where a distinctive (e.g. strongly eluviated) A2 was present, the A2 was sampled.

Of the 31 sites, five were on soils derived from alluvium, four on basalt-derived soils, eleven on mudstone-derived soils, ten on sandstone-derived soils and one on a granite-derived soil. Soil drainage was classed as poor at three sites, imperfect at twelve sites, moderate at eight sites and well drained at eight sites. The sites examined included four Chromosols, ten Dermosols, three Ferrosols, one Hydrosol, three Kandosols, five Kurosols, four Sodosols and one Vertosol (Isbell 2002).

Soil analysis was carried out at the Environmental Analysis Laboratory (Southern Cross University). These results are presented in Appendix 1 and summarised in Table 2. They show that the soils were acidic (surface pH 4.7–5.9) with average levels of total nitrogen in the topsoils moderate and average levels of cations low. Phosphorus levels varied depending on the analysis method used; there is no accepted 'best' measure

Table 1. Growth plot site and soil information

Soil type	PPF[A]	Altitude (m)	Mean annual rainfall (mm)	Drainage	Soil parent material	Slope (%)	Aspect	Age (y)	PMH (m)	Stock	SI_{10}[B]
Red Ferrosol	Gn3.11	70	1208	Well drained	Mudstone	10	55	8.3	14	730	15.6
Brown Chromosol	Db3.11	460	1055	Moderate	Mudstone	8	35	7.3	15.9	690	14.0
Redoxic Hydrosol	Uf4.4	30	1077	Poor	Alluvium	0		10.2	16.6	820	15.7
Black Ferrosol	Uf6.12	100	1336	Imperfect	Basalt	30	30	8.3	17.5	660	17.7
Red Ferrosol	Gn3.11	610	1252	Well drained	Mudstone/Ba	15	150	9.1	26.1	830	26.0
Red Kurosol	Db2.21	600	956	Imperfect	Sandstone	14	335	6.9	13.1	550	14.0
Red Dermosol	Gn3.11	270	967	Imperfect	Mudstone	23	60	10.3	23.2	480	23.4
Grey Dermosol	Gn3.91	205	1256	Moderate	Mudstone	4	105	11.3	26.7	570	24.6
Grey Vertosol	Ug5.28	105	931	Poor	Alluvium	0		6.7	4.9	410	5.1
Brown Chromosol	Dy3.21	125	956	Moderate	Alluvium	2	280	6.2	14.6	670	17.4
Brown Dermosol	Gn3.24	440	956	Moderate	Alluvium	7	250	6.0	14.8	870	17.2
Brown Dermosol	Ug6.3	450	1073	Imperfect	Mudstone	21	360	5.4	11.1	890	13.8
Brown Dermosol	Gn3.21	615	1121	Well drained	Mudstone	11	70	4.2	12.8	960	20.8
Brown Dermosol	Gn3.21	610	1121	Well drained	Mudstone	9	140	4.2	12.4	970	14.6
Grey Sodosol	Dy5.21	175	876	Imperfect	Sandstone	11	335	4.6	12.1	860	15.1
Brown Kurosol	Db2.11	8	964	Imperfect	Alluvium	0		4.5	12.8	880	18.0
Brown Dermosol	Uf6.31	140	883	Well drained	Basalt	17	155	4.5	10.1	850	14.3
Brown Dermosol	Gn3.71	135	1048	Well drained	Mudstone	32	220	4.2	12.3	950	16.6
Grey Dermosol	Uf6.33	530	1584	Imperfect	Basalt	8	10	4.3	9.3	970	17.9
Brown Kurosol	Dy3.21	155	832	Imperfect	Sandstone	0		4.5	8.2	840	10.3
Brown Kandosol	Gn3.21	45	913	Moderate	Mudstone	5	340	4.4	10.5	980	18.7
Brown Chromosol	Dy5.21	370	876	Moderate	Sandstone	9	20	3.6	8.4	1020	14.3
Brown Sodosol	Dy5.11	30	861	Imperfect	Mudstone	10	330	3.3	11.3	840	1.1
Red Kandosol	Dr4.21	170	1205	Well drained	Sandstone	18	70	3.4	8.7	350	5.1
Brown Kurosol	Dy5.21	175	1205	Moderate	Sandstone	6	85	3.4	10.2	820	11.3
Red Kurosol	Dr3.21	200	967	Imperfect	Sandstone	11	105	2.3	8.4	950	15.2
Grey Sodosol	Dy3.21	10	949	Poor	Sandstone	2	175	2.3	5.1	1060	9.0
Grey Sodosol	Dy5.31	50	971	Moderate	Sandstone	5	255	6.7	10.9	510	15.5
Red Chromosol	Dr4.41	140	891	Imperfect	Sandstone	6	210	5.2	10.7	810	19.8
Brown Kandosol	Gn4.31	140	1705	Well drained	Basalt	21	150	9.2	28	630	29.8
Brown Dermosol	Gn3.74	680	1292	Moderate	Granite	2	100	9.1	28.1	730	4.6

[A] PPF = principal profile form

[B] Site index at age 10 derived from fitted height growth curve

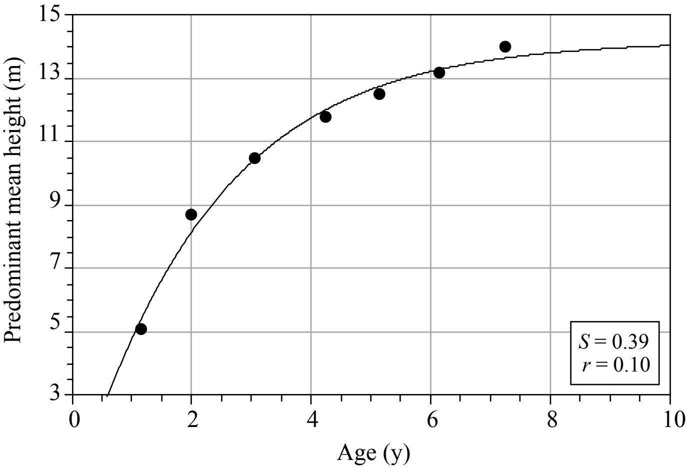

Figure 1. Example of a curve fitted to predominant mean heights. Site 2, on a Brown Chromosol soil, had a fitted growth curve: PMH = 14.6(1 – exp(–0.31 × Age))$^{0.99}$, $r = 0.99$

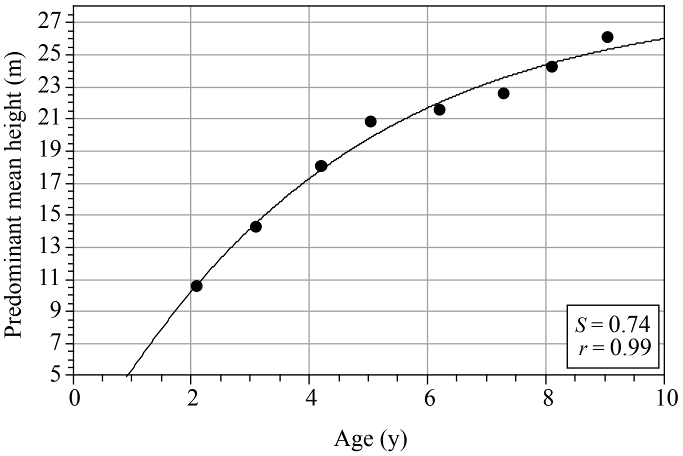

Figure 2. Example of a fitted curve to predominant mean height. Site 5, on a Red Ferrosol soil, had a fitted growth curve: PMH = 28.5(1 – exp(–0.26 × Age))$^{1.11}$, $r = 0.99$

Table 2. Means and ranges of selected soil nutrients

Horizon	Attribute	pH (1:5 water)		Organic C		Total N		Bray 1 P		ECEC		EC ($dS\ m^{-1}$)	Base status	
		Level	Rating	(%)	Rating	(%)	Rating	(ppm)	Rating	($cmol^+ kg^{-1}$)	Rating		($cmol^+ kg^{-1}$ clay)	Rating
Topsoil	Mean	5.3	Strongly acid	2.38	High	0.20	Mod	3.59	Very low	8.8	Low	0.09	34.0	Eutrophic
Topsoil	Minimum	4.7	Very strongly acid	0.84	Low	0.07	Low	0.26	Very low	1.8	Very low	0.03	9.2	Mesotropic
Topsoil	Maximum	5.9	Moderately acid	4.71	Very high	0.50	High	17.02	Moderate	25.0	High	0.22	96.8	Eutrophic
Subsoil	Mean	5.5	Strongly acid	0.95	Low	0.09	Low	1.05	Very low	8.8	Low	0.85	26.7	Eutrophic
Subsoil	Minimum	4.2	Extremely acid	0.22	Very low	0.01	V low	0.20	Very low	1.8	Very low	0.04	2.1	Dystrophic
Subsoil	Maximum	6.6	Neutral	3.62	Very high	0.30	High	3.71	Very low	25.0	High	2.89	122.7	Eutrophic

of phosphorus availability for this species. Ratings are based on Abbott (1985).

A measure of moisture availability was derived using climatic data and an estimate of available-water storage capacity (AWSC). AWSC is equal to FC (field capacity) minus permanent wilting point (PWP), with FC generally considered to be around 0.1–0.3 bars and PWP to be 15 bars (McKenzie *et al.* 2000; Coughlan and McKenzie 2002). AWSC is ideally measured on undisturbed samples, preferably in the field, a process that is intensive and time-consuming. In the absence of those data, estimates of AWSC for this study were made using data collected on soil texture, stone content, horizon depth and previously established relationships between these factors (Craze and Hamilton 1991; Geeves *et al.* 2000; Minasny and McBratney 2003). In particular the NeuroTheta program developed by Minasny and McBratney (2003) was used to provide an initial estimate of AWSC from field texture in conjunction with horizon thickness and total soil depth. For soil horizons with a stone content > 50%, AWSC was reduced by the stone content. The 50% level was chosen as a convenient cut-off level as has been used previously by Laffan (2000) to define severe rooting limitation and by Emery (1985) to define restrictive rock content. AWSC was a variable used to compare directly with growth and it was also used in conjunction with daily measures of rainfall and pan evaporation (see climatic data section) to produce a simple model of daily measures of plant-available water.

Climatic data

Climatic data for each of the growth plot sites was derived from Queensland Department of Natural Resources Mines and Energy (NRME) spatially interpolated surfaces of daily climatic variables (Jeffrey *et al.* 2001). These provided an extensive range of daily measures including rainfall, maximum and minimum temperature, pan evaporation, solar radiation and humidity that were derived by extrapolation from information for the weather station closest to each of the growth plots. The set of sites examined varied in average annual rainfall from about 900 mm to 1800 mm. Mean daily maximum temperature of the hottest month of the year ranged from 24.4°C to 34.0°C and mean daily minimum of the coldest month ranged from 1.8°C to 7.6°C (these figures relate to means of the interpolated daily information over the life of each of the growth plots and are not necessarily representative of long-term climatic means at these growth plots). Mummery and Battaglia (2004) discussed the importance of using climatic data that is both temporally and geographically relevant to the plantation growth data being analysed (in contrast to using average figures). Aspect was transformed to a figure that varied from 2 at the most favourable aspect (south-east) to 0 on the harshest aspect (north-west). The formula used was:

$$A' = \cos(\mathrm{Amax} - A) + 1,$$

where A is the conventionally recorded aspect, Amax is the preferred aspect and A' is an adjusted figure (Beers *et al.* 1966). Flat sites were given a value of 1.

Model fitting

The mathematical description of the correlation between the defining growth variables and growth at a set of existing sites allows the prediction of growth at new sites. Empirical models produced in this manner are tied to the range of variation encompassed within the original set. They can often be accurate within that range but may not extrapolate accurately to conditions outside that range (Austin *et al.* 1997; Louw and Scholes 2002). The selection of a suitable set of variables that accurately model the growth of *E. dunnii* across the area under consideration was critical. The criteria for selection of these variables included that they should reflect known environmental influences on growth and also be reasonably easily measurable.

Initial analysis of SI_{10} (SI at age 10 y) as the dependent variable found a lack of normality in the data and a Box–Cox test indicated that a square-root transformation was needed to stabilize the variance. Correlation (Pearsons correlation coefficient—initial graphical exploration of the data discounted the presence of non-linear relationships) and principal components analysis were used to determine a set of variables that were strongly correlated with $(SI_{10})^{0.5}$ and that could be relatively easily measured in the field. Using these as a guide for a model, backward stepwise multiple linear regressions were used to determine the strongest model. Variable removal was based on maximum adjusted R^2 in conjunction with Mallows Cp (Mallows 1973) and the practicality of the particular variable for use in the field. For instance it was considered that AWSC, which can be derived from simple field assessment of texture and horizon depth, was a more useful variable to retain in a final model than measures of transpirational stress that were obtained from a model incorporating historical daily rainfall and pan evaporation measures along with AWSC. Measures of average daily temperature variation over the year, while useful for regional analysis, would be unlikely to be used for local property assessment, but altitude was a useful surrogate.

Results

Site index (predicted height at age 10 y)

Site index at age 10 y was predicted from fitted growth curves at each of the growth plots, with the results given in Table 1. Contrasting height growth curves are illustrated in Figures 1 and 2.

Soil texture profile and SI

A simple comparison of means using ANOVA of SI against soil type (Principal Profile Form—Northcote 1979) showed a significant difference ($P = 0.002$) between the average SI_{10} on duplex (texture contrast) soils and gradational soils (13.8 m and 20.8 m respectively), reflecting an aversion of *E. dunnii* to duplex soils consistent with other reports (Herbert 2000). However, as the texture profile, chemistry and depth of soils are strongly influenced by climate (Jenny 1941; Laffan *et al.* 1998), this analysis is also likely to be reflecting those other variables. Uniform soils showed an intermediate SI_{10} as they range from soils with good root accessibility (well-drained sands) to those that impede rooting (poorly-drained, poorly-structured clays).

Height growth model

Preliminary analysis suggested AWSC and MAR were the strongest predictors of growth over a range of other moisture estimate parameters including estimates of average daily evapotranspirational deficits (derived using daily water models) and the Prescott Index (Prescott 1948). This analysis also indicated a flattening of the height response to AWSC (as would be expected) so further analysis used the natural log of the AWSC. It also highlighted some outliers. Two plots had problematic growth curves where insufficient data meant that the standard growth curve could not be fitted. Another was a poorly-drained Grey Vertosol (cracking clay), a soil that is colonised by few eucalypt species in the subtropics (Specht 1996). Vertosols pose major physical challenges to root growth and survival due to a combination of poor drainage, water storage that is determined more by limitations on water entry than on the rainfall regime and the depth and moisture characteristics of the soil itself, and soil movement (shrinking and swelling). Poorly-drained soils in general appear to be problematic for *E. dunnii* (Herbert 2000). The relationship between available-water-holding capacity and growth is illustrated in Figure 3, where the outliers that were removed from the analysis are indicated.

Principal components analysis (PCA) using a subset of relatively easily determined variables in the remaining 28 plots with varimax rotation of the eigenvectors found four components with eigenvalues greater than one (see Table 3). These four components explained 80% of the variation, with the first two components explaining 65% of the variation. PCA, using all the variables (including chemical data from 19 plots) with varimax rotation of components, found that a combination of seven components with eigenvalues greater than one explained 90% of the variation (the first four explaining 76%).

A regression model using LnAWSC and MAR (mean annual rainfall—calculated from daily rainfall figures over the life of the trees at each plot) correlated reasonably well ($R^2 = 0.562$, $P < 0.005$) with the square-root of predominant mean height at

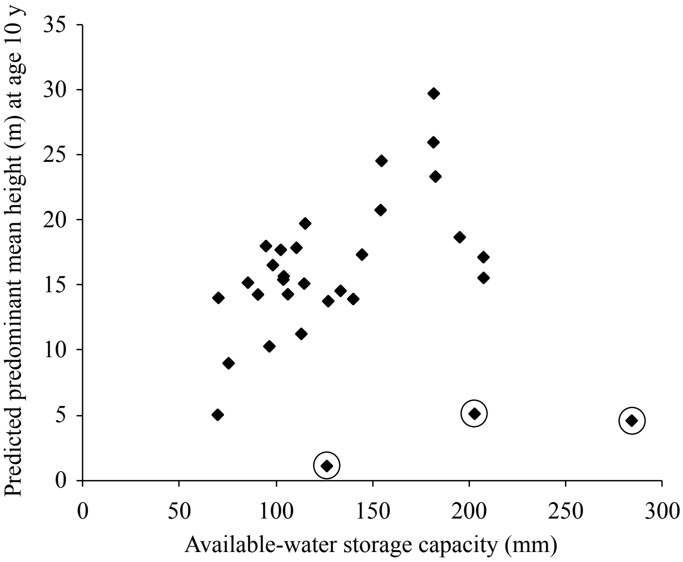

Figure 3. Estimated available-water storage capacity of the soils at each of the growth plot sites plotted against estimated height of plantation at 10 y of age. Three outliers (circled) were removed before proceeding with the analysis as described in the text.

Table 3. Principal components analysis of the non-chemical variables. Varimax rotation was applied to the original eigenvectors.

Variable	Component			
	1	2	3	4
Average Prescott moisture	0.837	–0.046	0.248	0.258
Average daily transpirational supply	0.785	–0.304	0.342	0.358
Percent of days with severe transpirational stress	–0.739	0.351	–0.399	–0.384
Percent of days with no transpirational stress	0.743	–0.366	0.337	0.394
Mean annual rainfall (MAR)	0.953	–0.070	0.030	–0.183
Ln MAR	0.953	–0.102	0.016	–0.126
Available-water storage capacity (AWSC)	0.206	–0.184	0.947	0.080
Ln AWSC	0.210	–0.184	0.946	0.073
Soil drainage	0.185	–0.335	0.280	0.010
Site slope	0.315	–0.117	–0.063	0.235
Northcote class	0.399	–0.172	0.624	0.240
Elevation	0.243	–0.838	0.218	0.021
Aspect	0.185	0.177	–0.071	0.025
Mean daily radiation	–0.350	0.370	–0.105	–0.216
Average daily maximum of hottest three months	–0.482	0.683	–0.118	–0.247
Rainfall in hottest 3 months	0.050	–0.133	0.143	0.948
Average daily maximum of coldest three months (determined on daily maximums)	–0.423	0.828	–0.226	–0.211
Average daily minimum of coldest three months (determined on daily maximums)	0.129	0.949	0.006	–0.015
Average daily maximum of coldest three months (determined on daily minimums)	–0.413	0.812	–0.204	–0.264
Average daily minimum of coldest three months (determined on daily minimums)	0.243	0.768	–0.158	0.059

age 10 (SI_{10}), with both variables highly significant:

$$(SI_{10})^{0.5} = -73 + 1.16 \times \mathrm{Ln}(AWSC) + 0.001 \times MAR$$
(standard error of estimate of ±0.44).

Incorporation of altitude increased the fit of the model ($R^2 = 0.619$, $P < 0.005$) with all variables again highly significant:

$$(SI_{10})^{0.5} = -3.63 + 1.35 \times \mathrm{Ln}(AWSC) + 0.001 \times MAR - 0.001 \times \mathrm{Altitude}$$
(standard error of estimate = ±0.42).

Both models relate strongly to the components derived during PCA (Table 3). MAR was strongly correlated with component 1 which is reflecting moisture availability. Altitude is strongly (negatively) correlated with component 2 which appears to be reflecting climatic stresses, particularly measures related to the cooler parts of the year. AWSC was strongly correlated with component 3 which mainly related to soil water-holding capacity. Component 4, not captured in the model, was strongly correlated with rainfall in the hottest 3 mo of the year.

The addition of measures of nutrition entailed reducing the size of the database, as not all sites had been sampled for chemical analysis. With the reduced data set, the addition of nutrient measures did not increase the predictive capacity of the growth model.

Discussion

Site index is commonly used as a measure of site productivity or site quality that is relatively independent of stand density (Hagglund 1981; Garcia 1998; Vanclay 1994; West 2004) and it has been used extensively in forestry (Grey 1989; West 2004). Site index is the top height at a prescribed age and has commonly been used in models that correlate site and soil characteristics with growth and yield predictions (Grey 1989; Mailly *et al.* 2004; West 2004). Site index at 20 y of age is often the base used for faster-growing species (Grey 1989). Height-growth curves map the change in height over the life of the plantation. The point in the life cycle of a forest when limiting factors may present themselves can significantly alter the shape of the growth curve (Fisher and Binkley 2000). The presence at one site of a higher growth rate at a given point in the plantation life compared with that seen at another site does not necessarily mean that that same relationship will be maintained subsequently.

Maximum mean annual volume increment (MAI) of a plantation is another relatively commonly used measure of productivity (e.g. Turvey 1983; Laffan 2000; Holz 2002; Wang and Baker 2007). It relates directly to production of wood volume at a site and therefore more directly to potential financial return. However, volume increment, unlike site index, is strongly affected by silvicultural management such as stocking and thinning (West 2004).

The measure of site productivity used in this study was height at age 10 y (SI_{10}). This age was chosen so that any extrapolation required in application of the model was modest and to ensure that the plots being modelled had reached an age when site limitations were determining growth rates. Ten years was also close to the intended age of harvest for a large portion of the plantations. This measure of growth was relatively well correlated ($R^2 = 0.619$) with three simple site variables (rainfall, water storage capacity of the soil, and altitude). As many soil and site surveys carried out before plantation establishment tend to be at a broad scale, a model based on simple predictors is desirable. The model does not apply to Vertosol soils, on which *E. dunnii* plantations have very low productivity.

A comparison of SI_{10} as predicted by the model:

$$SI_{10} = (-3.63 + 1.35 \times \mathrm{Ln(AWSC)} + 0.001 \times \mathrm{MAR} - 0.001 \times \mathrm{Altitude})^2,$$

with SI_{10} as determined at each site from extrapolation of site-specific growth curves returned a highly significant correlation with an R^2 of 0.64. The mean value of the difference between the SI_{10} predicted by the model and that derived from the growth curves, taken as a proportion of the model predicted value, was –12%. That is, the model under-predicted growth compared with the growth curves by 12% on average.

The error range of the model can be analysed by comparing the predicted value to observed value at each site:

$$\pm\sqrt{1+\frac{1}{n}}St_{1-\alpha/2}(n-1)$$

(Reynolds 1984, Equation 7), where n is the number of observations, S is the standard deviation of the proportional difference between the predicted and observed, and $t_{1-\alpha/2(n-1)}$ is the quantile of the t distribution with n-1 degrees of freedom. For the average of a number (k) of sites it is calculated as:

$$\pm\sqrt{\frac{1}{n}+\frac{1}{k}}St_{1-\alpha/2}(n-1).$$

Applying these formulae to the model at one plot the 95% confidence level would be from –58% to +34%, while the 95% confidence level prediction for many plots (where k is large) would approach –21% to –3%. These error estimates of ±12% are comparable to those determined by Osler *et al.* (1996) for two systems for estimating productivity that they examined (returning prediction intervals of ±11% and ±8% when applied over large areas).

The variables correlated with growth in this study relate to commonly-used growth indicators. AWSC is determined by soil variables such as depth to bedrock, depth to root-restricting soil layers, coarse fragment content and texture which have previously been correlated with growth (Turvey *et al.* 1986, 1990; Turvey 1987; Turner *et al.* 1990; Harper *et al.* 1999; Laffan 2000). A number of studies including Hunter and Gibson (1984), Harper *et al.* (1999), Snowdon *et al.* (1999) and Laffan (2000) have used mean annual rainfall as a useful predictor variable in growth models; actual rainfall figures are more appropriate than mean figures (Mummery and Battaglia 2004). The inclusion of evaporation and a measure of soil water storage capacity has the potential to improve predictive capacity over rainfall alone (Harper *et al.* 1999; Uzoh 2001).

Soil nutrients were not included in the final model even though their levels are commonly a strong determining factor in the productivity of Australian vegetation types (Adams 1996; McLaughlin 1996; Specht and Specht 1999) and plantations (Turvey *et al.* 1986; Laffan and Neilsen 1997; Harper *et al.* 1999). The use of soil nutrient analysis in predicting productivity of eucalypts is hampered to some extent by limited knowledge of the suitability of extraction methods in determining nutrient availability for the species and the soil types under consideration (Ryan *et al.* 2002). Methods commonly used in agricultural analysis appear less suited to native eucalypt species. The ability of tree species to access a greater volume of soil than most agricultural crops also needs to be considered (Ryan *et al.* 2002). The greater capacity of eucalypts to extract nutrients and the long rotations suggest that total levels of phosphorus, nitrogen and carbon (as well as exchangeable cations) may be better predictors than other measures of availability (Ryan *et al.* 2002). A larger data set with chemical analyses may provide a stronger correlation than we obtained.

The developed model compares favourably with an existing growth prediction model used by Forests NSW that was developed in 2002 (Holz 2002), using data that was available at that time. That model used ERD (an estimate of the effective rooting depth provided by a soil as determined by a wide range of soil characteristics) in a matrix with mean annual rainfall (decile 5) to classify sites into productivity classes according to estimated MAI. To compare the Holz model with that developed in this project, a function relating SI_{10} to Holz ERD and MAR was formulated:

$$(SI_{10})^{0.5} = 0.2515 + 0.006 \times \mathrm{Holz\ ERD} + 0.001 \times \mathrm{MAR}\ (R^2 = 0.35,\ P < 0.01).$$

A comparison of SI_{10} derived from growth curves and SI_{10} derived from the growth models is presented in Figures 4 and 5. No other site selection models for *E. dunnii* plantations in NE NSW and SE Queensland are publicly available for comparison.

The growth of plantations as measured by volume increment is a more useful measure of overall growth for many planning needs than a measure based on height. Direct modelling of volume growth can be a more accurate predictor of volume growth than the indirect use of basal area and height to predict volume (Leech 2007). In this study the information necessary to model volume directly was not available. It does appear, however, that SI_{10} of about 20, 24 and 28 are required to attain peak MAIs of 10, 15 and 20 m^3 ha^{-1}, respectively, within the first 20 y of plantation life (Henson and Vanclay 2004; Phil West, SciWest Consulting/SCU, *pers. comm.* 2009).

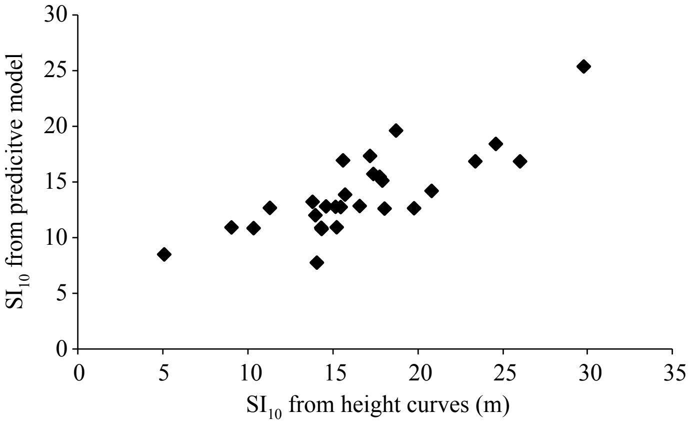

Figure 4. SI_{10} derived from growth curves plotted against SI_{10} estimated from the developed growth model

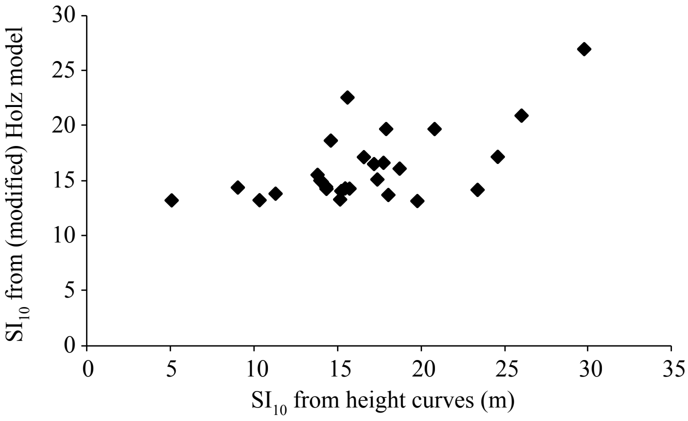

Figure 5. SI_{10} derived from growth curves plotted against SI_{10} estimated from Holz (2002) ERD and MAR

The estimates of SI at age 10 y across the growth plots are predicated strongly by the initial selection of a growth model, which in this case was a model that has been found to have general broad application (West 2004). It is desirable to confirm the applicability of this model to *E. dunnii* plantation growth, using data covering a longer part of the plantation cycle than was available to this study. The growth curves (Figs 1 and 2) illustrate the variability in annual height growth within a plot. As this annual variability strongly affects the shape of the growth curve, extrapolation beyond 10 y becomes increasingly precarious, as is illustrated by the unlikely maximum heights of 14.6 m and 28.5 m for those two sites. However, as the same growth curve (with site-specific constants) was applied to each growth plot, the same variables found to be predictive in this study would probably remain predictive under a different growth model.

The use of a limited set of sites to produce the model (28 sites with full growth data and site and soil description; fewer with complete chemical analyses) is a limitation of this study, as is the age of the trees in the plots (mean age around 6 y). A broad range of site and soil variables tested against growth were not found to be significantly correlated. It is likely that altitude, which was included in the three-variable model, is acting as a surrogate for a suite of climatic factors other than rainfall, such as evapotranspiration rates and temperature variables. The replacement in the model of altitude with a range of climatic measures including annual daily radiation and maximum and minimum temperatures of the hottest and coldest parts of the year slightly improved the correlation, but the simplicity of altitude alone made it a preferable component in the model. Altitude was also significantly correlated with a number of chemical characteristics (due to its relationship to geology and soil parent material in the area of the study). In particular, altitude was negatively correlated with available Al and positively correlated with base status and ECEC. Future refinement of the model using a larger data set will probably incorporate those individual climatic and soil chemical variables in place of altitude.

A more detailed study using a greater number of sites over a broader range of environments would probably permit greater discrimination using these variables, and incorporate measures of nutrient availability in an improved model. Such validation and refinement of the model with another set of plots is the logical next step in this research. The soil analyses carried out in this study were on samples taken from the growth plots at the time of soil description and not the time of the plantation establishment. Soil changes that occur over the life of a plantation can affect the levels of nutrients and organic carbon (Turner and Lambert 2000; Binkley and Stape 2004). Soil nutrient levels determined from established plantations as in this case should be seen only as indicative rather than prescriptive in a site-selection system such as that being developed here.

Site productivity research such as this is strongly enhanced when it is integrated with studies of wood properties as influenced by site and silviculture and the interaction with plantation genetics. Growth rates may be markedly increased by the use of genetically improved stock (Henson and Vanclay 2004) and when combined with an adequate site suitability classification system, acceptable growth rates and rates of economic returns should be possible on the ‘right’ sites.

Conclusions

The results from this study show that some relatively simple field assessments of soil (soil texture, horizon depth, stone content and total depth) and site (altitude) when combined with rainfall information (mean annual rainfall) can provide useful predictions of the growth of *E. dunnii*. These provide an important aid in the selection of appropriate land for establishment of *E. dunnii* plantations in north-eastern NSW and south-eastern Queensland and for the future management of those plantations. This model achieves relatively good correlation between growth and a simple set of site variables. However, the application of the model beyond the range of soils and climates included in this study is likely to lead to a lessening in the strength of that relationship. The introduction of more data and testing against an independent data set would further develop the model.

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Appendix 1. Soil nutrient analysis

Site	Horizon	Horizon depth (cm)	Texture	pH (1:5 water)		Organic C		Total N		Bray 1 P	
				Level	Rating[b]	(%)	Rating[b]	(%)	Rating[b]	(ppm)	Rating[b]
2	A1	0–10	ZCL	5.74	Mod. acid	3.47	V. high	0.35	High	1.73	V. low
2	B2	20–50	MC	6.58	Neutral	3.62	V. high	0.25	High	1.05	V. low
6	A1	0–10	SL	5.74	Mod. acid	2.55	High	0.15	Low	3.02	V. low
6	B21	70–85	SLMC	4.92	V. strongly acid	0.59	Low	0.05	Low	0.55	V. low
9	A1	0–6	LC	5.77	Mod. acid	3.48	V. high	0.28	High	5.04	Low
9	B21	6–70	MC	6.11	Slightly acid	1.23	Mod.	0.08	Low	1.33	V. low
10	A1	0–10	LS	5.54	Mod. acid	0.90	Low	0.07	Low	4.94	V. low
10	B1	40–65	SL	6.05	Slightly acid	0.22	V. low	0.01	V. low	1.14	V. low
11	A1	0–10	SL	5.53	Mod. acid	2.65	High	0.22	Mod.	7.15	Low
11	B2	50–80	LMC	5.32	Strongly acid	0.52	Low	0.06	Low	0.50	V. low
12	A1	0–10	LC	5.9	Mod. acid	3.24	V. high	0.25	High	2.78	V. low
12	B21	10–43	LMC	5.24	Strongly acid	0.92	Low	0.13	Low	0.86	V. low
13	A1	0–10	ZCL	5.62	Mod. acid	4.23	V. high	0.38	High	17.02	Mod.
13	B1	16–23	ZCL	5.69	Mod. acid	1.52	Mod.	0.14	Low	3.71	V. low
14	A1	0–18	ZCL	5.62	Mod. acid	4.71	V. high	0.38	High	13.41	Mod.
14	B1	18–36	CL	5.52	Mod. acid	2.19	High	0.15	Mod.	2.46	V. low
15	A1	0–6	SCL	5.46	Strongly acid	1.59	Mod	0.10	Low	1.38	V. low
15	B2	22–60	SMC	5.77	Mod. acid	0.38	V. low	0.03	V. low	0.93	V. low
16	A1	0–10	ZCL	5.33	Strongly acid	1.59	Mod.	0.14	Low	2.31	V. low
16	B21	15–40	MHC	5.09	Strongly acid	0.45	V. low	0.06	Low	0.37	V. low
16	B22g	40–80	MHC	5.24	Strongly acid	0.52	Low	0.06	Low	0.83	V. low
18	A1	0–10	CL	5.55	Mod. acid	3.05	V. high	0.26	High	2.34	V. low
18	B1	18–37	LC	5.7	Mod. acid	1.34	Mod.	0.14	Low	0.67	V. low
20	A1	0–10	LS	5.58	Mod. acid	1.23	Mod.	0.15	Mod.	2.13	V. low
20	B2	44–65	MC	5.43	Strongly acid	0.43	V. low	0.10	Low	0.53	V. low
21	A1	0–10	FSCL	5.78	Mod. acid	0.84	Low	0.07	Low	0.26	V. low
21	B21	37–80	ZLC	5.62	Mod. acid	0.53	Low	0.06	Low	0.26	V. low
23	A1	0–10	CL	5.8	Mod. acid	3.99	V. high	0.36	High	2.03	V. low
23	B2	0–40	MHC	6.1	Slightly acid	0.89	Low	0.14	Low	0.69	V. low
24	A1	0–11	SL	5.58	Mod. acid	1.18	Mod.	0.12	Low	1.32	V. low
24	A2	11–26	SL	5.89	Mod. acid	0.44	V. low	0.06	Low	0.45	V. low
24	B2	26–50	LMC	5.07	Strongly acid	0.48	V. low	0.07	Low	0.20	V. low
25	A1	0–10	SCL	4.81	V. strongly acid	1.91	Mod.	0.13	Low	4.07	V. low
25	B21	21–49	MC	4.43	Ext. acid	0.65	Low	0.05	Low	2.68	V. low
26	A1	0–9	CL	5.6	Mod. acid	2.48	High	0.16	Mod.	0.77	V. low
26	B21	15–37	MHC	5.35	Strongly acid	0.46	V. low	0.04	V. low	0.77	V. low
27	A1	0–10	SL	5.47	Strongly acid	1.49	Mod.	0.08	Low	1.58	V. low
27	B2g	28–55	SMC	5.67	Mod. acid	0.23	V. low	0.02	V. low	1.01	V. low
28	A1	0–10	LS	5.59	Mod. acid	1.41	Mod.	0.08	Low	2.10	V. low
28	B2	48–75	MHC	5.5	Mod. acid	0.43	V. low	0.03	V. low	0.92	V. low
29	A1	0–8	FSCL	5.46	Strongly acid	2.20	High	0.15	Mod.	1.33	V. low
29	B2	19–60	MHC	5.64	Mod. acid	0.46	V. low	0.03	V. low	0.88	V. low
30	A1	0–10	CL	4.7	V. strongly acid	4.28	V. high	0.50	High	2.29	V. low
30	B2	10–62	MC	4.21	Ext. acid	2.38	High	0.30	High	0.61	V. low
30	B3	62–150	MC	4.25	Ext. acid	0.58	Low	0.09	Low	0.16	V. low

[a] Ammonium acetate extract

[b] Ratings are based on Abbott (1985)

[c] Exchangeable sodium percentage—Isbell (2002)

Appendix 1 (continued). Soil nutrient analysis

Total P (ppm)	ECEC		EC (dS m^{-1})	Exchangeable cations (cmol$^+$ kg^{-1})[a]				ESP[c]		Base status	
	(cmol$^+$ kg^{-1})	Rating[b]		Ca	Mg	K	Na	(%)	Rating[c]	(cmol$^+$ kg^{-1} clay)	Rating[c]
351	22.9	Mod	0.12	12.17	9.35	0.76	0.33			69.6	Eutrophic
	61.5	V. high	0.09	34.48	24.56	0.50	1.84	3.0		122.7	Eutrophic
173	5.8	V. low	0.06	2.75	1.48	0.39	0.23			32.4	Eutrophic
	15.5	Mod.	0.07	0.16	3.52	0.32	0.18			9.8	Mesotropic
425	25.0	High	0.11	14.80	8.04	0.54	1.22	7.4	Sodic	65.6	Eutrophic
	33.6	High	0.27	17.61	12.60	0.41	2.49			66.2	Eutrophic
150	1.8	V. low	0.04	0.67	0.43	0.08	0.13			26.3	Eutrophic
	2.2	V. low	0.02	1.26	0.69	0.00	0.06			13.4	Mesotropic
315	5.3	V. low	0.07	2.54	1.45	0.40	0.15			30.2	Eutrophic
	6.7	Low	0.03	0.47	1.13	0.25	0.13			4.7	Dystrophic
325	25.0	Mod.	0.14	18.51	5.11	0.76	0.38			66.0	Eutrophic
	37.7	High	0.07	25.94	7.30	0.47	1.10	2.9		81.9	Eutrophic
	9.2	Low	0.16	5.93	1.41	0.76	0.15			25.4	Eutrophic
	3.9	V. low	0.08	2.91	0.12	0.17	0.04			10.0	Mesotropic
	11.3	Low	0.22	6.88	2.50	1.32	0.06			33.1	Eutrophic
	4.6	V. low	0.09	2.81	0.53	0.26	0.07			11.3	Mesotropic
	4.1	V. low	0.05	1.96	1.11	0.19	0.15			13.7	Mesotropic
	16.7	Mod.	0.05	0.27	4.89	0.17	0.78	4.6	Sodic	12.2	Mesotropic
	4.0	V. low	0.11	1.35	1.01	0.18	0.44			9.2	Mesotropic
	8.3	Low	0.09	0.37	2.88	0.17	0.92	11.1	Sodic	7.9	Mesotropic
	5.7	V. low	0.10	0.71	1.75	0.15	0.72			6.0	Mesotropic
354	10.6	Low	0.10	5.02	4.00	0.43	0.13			29.5	Eutrophic
	12.1	Mod.	0.06	5.42	5.44	0.15	0.18			29.9	Eutrophic
	5.0	V. low	0.08	3.64	1.05	0.15	0.01			96.8	Eutrophic
	11.3	Low	0.06	1.28	5.41	0.12	0.42	3.7		14.5	Mesotropic
213	7.4	Low	0.05	3.12	3.22	0.07	0.51			27.7	Eutrophic
	6.8	Low	0.04	2.59	3.09	0.05	0.51			16.6	Eutrophic
287	18.8	Mod.	0.14	9.38	7.92	0.52	0.61			56.7	Eutrophic
	35.5	High	0.18	12.17	19.79	0.31	2.89	8.1	Sodic	63.9	Eutrophic
	4.6	V. low	0.07	2.98	1.17	0.23	0.00			29.2	Eutrophic
	7.8	Low	0.03	4.37	2.90	0.29	0.06			50.7	Eutrophic
	8.4	Low	0.04	1.74	4.14	0.27	0.08			14.7	Mesotropic
	4.9	V. low	0.22	2.02	1.31	0.39	0.03			15.0	Eutrophic
	11.6	Low	0.10	0.96	3.61	0.29	0.23			10.2	Mesotropic
	8.8	Low	0.03	2.65	4.10	0.57	0.56			24.3	Eutrophic
	20.5	Mod.	0.12	0.82	9.51	0.47	2.07	10.1	Sodic	23.4	Eutrophic
	3.1	V. low	0.07	1.25	1.00	0.07	0.25			17.1	Eutrophic
	9.7	Low	0.12	0.01	6.43	0.09	1.19	12.3	Sodic	15.4	Eutrophic
60	2.8	V. low	0.05	1.13	0.81	0.04	0.20			43.4	Eutrophic
	14.8	Mod.	0.10	–0.01	6.92	0.05	1.79	12.0	Sodic	15.9	Eutrophic
191	5.5	V. low	0.07	2.33	1.73	0.44	0.24			19.0	Eutrophic
	19.4	Mod.	0.04	2.13	4.77	0.39	0.76			14.6	Mesotropic
	8.3	Low	0.12	2.43	2.80	0.56	0.18			18.4	Eutrophic
1563	6.1	Low	0.13	0.18	0.54	0.13	0.20			2.1	Dystrophic
	9.7	Low	0.10	0.27	0.98	0.04	0.16			2.9	Dystrophic