SITE QUALITY FACTORS AFFECTING THE GROWTH AND VIABILITY OF BLACK WALNUT (*Juglans nigra* L.) IN AN AUSTRALIAN PLANTATION

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Summary: *Black walnut (Juglans nigra L.) is a valued hardwood for timber production mainly produced in the United States. Its cultivation is also experimented in other countries such as Italy, France, Australia, and New Zealand. The only substantial plantation of black walnut in Australia is located in Victoria.*
A research on growth and viability showed that black walnut timber production reaches competitive results. This encourages further research on site factors related to site selection for black walnut. Thus, climate, wind, cankers, premature leaf abscission, distance from water bodies, soil depth, texture, and color, depth and degree of mottling, calcium effervescence, acidity, the presence of gravel and /or sand in the soil profile, and understorey competition were investigated in order to determine if there was an association of such indicators with mean top height (Site Index). A regression where 91% of the mean top height variability depends on premature leaf abscission, clay content at 100 cm depth, mottling at 50cm depth, presence of gravel in the soil profile, and understorey competition, was found. Similar results were found when volume was used as a dependant variable instead of mean top height.
Site quality indicators found in the study could be used in most of the areas of cultivation and plantation development of black walnut. This approach avoids investigating a number of other possible site and soil indicators, and so reduces the cost of site analysis and selection and the risk of planting in mediocre or poor sites, which may instead be appropriate for other uses. At landscape level, reduction of homogeneity may result in higher ecological and biological diversity.

1. Introduction

Black walnut (*Juglans nigra* L.) (41, 46, 65, 98, 100) is a valued hardwood for timber production (10, 11, 19, 48, 52, 88, 31, 44) mainly produced in the United States (6, 19, 36, 96, 110) but experimented also in other countries such as Italy, France, Australia, and New Zealand (1, 4, 5, 14, 15, 18, 22, 32, 37, 67, 71, 76, 78, 80, 102, 103).
Site quality factors influencing the growth and viability of black walnut (*Juglans nigra* L.) in an Australian plantation were investigated in an attempt to identify the main site and soil indicators related to mean top height (Site Index) (3, 4, 5, 21, 23, 38, 40, 42, 49, 56, 57, 85, 89, 90, 91, 101). The only substantial plantation of black walnut in Australia is located in Victoria. A research on growth and viability showed that black walnut timber production reaches competitive results. This encouraged further research on site factors related to site selection for black walnut. The 28 hectare private plantation was established in 1971 and is widely known as “Walnut Island” (18, 71). Tree growth within the plantation at age 23 years was very variable, ranging from highly productive relative to plantations in the United States to very poor and appeared to reflect the high sensitivity of black walnut to microsite variations. The aim of this research was therefore to investigate the physical and biological factors affecting tree growth and development in an attempt to explain the variation in productivity across the site. Tests were made in an attempt to identify the main site and soil indicators correlated to black walnut site index. Thus, climate,

wind, cankers, premature leaf abscission, distance from water bodies, soil depth, texture, and color, depth and degree of mottling, calcium effervescence, acidity, the presence of gravel and /or sand in the soil profile, and understorey competition were investigated in order to determine if there was an association of such indicators with mean top height (Site Index). A regression where 91% of the mean top height variability depends on premature leaf abscission, clay content at 100 cm depth, presence of mottling at 50cm depth, presence of gravel in the soil profile, and understorey competition, was found. Similar results were found when volume was used as a dependant variable instead of mean top height.

The research shows that site and soil indicators and related properties correspond to the principles ones suggested by international research. Identification of microsite variations that appear to affect plantation growth contributes to the selection of suitable sites for black walnut plantations in Australia. Site quality indicators found in the study could be used in most of the areas of cultivation and plantation development of black walnut. The implementation of the method of site selection allows a rapid measurement and correlation of site indicators with mean top height to test if they are applicable or not. This approach avoids investigating a number of other possible site and soil indicators, and so reduces the cost of site analysis and selection and the risk of planting in mediocre or poor sites, which may instead be appropriate for other uses. Only in case of such site suitability indicators fail to produce reliable results further analysis may be pursued.
At landscape level, reduction of homogeneity may result in higher ecological and biological diversity. The possibility of identifying site factors that determine growth variability enables more appropriate selection and management options. Black walnut cultivation can be initiated only on sites that can achieve the expected results.

2. Material and methods

Preliminary analyses

Preliminary analyses indicated that the highest values of stocking in 1988 (79) were found on the plots with the highest mean top height and these were little different from the initial stocking at the time of planting (625 stems/ha) (18, 71). This suggests that no thinning has been carried out on these plots other than that due to mortality. On the other hand, plots with the lowest stocking in 1988 had very low levels of mean top height. While such apparently low levels of site productivity might also account for somewhat higher mortality, the low levels of stocking did not seem consistent with mortality alone but there was no way of clarifying the thinning history prior to 1988. A deliberate thinning was carried out in 1994 on 13 plots out of 24. For those plots that were thinned, percentage of trees were removed varied greatly, from –23.6% to –79.2%.

Mean top height as a site quality indicator

Mean top height is widely used as a site quality indicator in plantation forestry. A comparison of the mean top height of Walnut Island plots with the site index/mean top height curves of New Zealand (78) and United States is shown in Figure 1. A large number of plots are clustered around the highest site index curves.

Because the preliminary analyses gave rise to some concerns regarding the influence that mortality and thinning may have had on mean top height, regressions of mean top height on stocking in 1994 were estimated. An F-test for the regression indicated the model was not significantly different from zero (R^2 0.18; p-value 0.04). This strongly suggests that mortality and thinning had little or no effect on mean top height.

Volume Productivity

The association of standing plot volume in 1994 with mean top height and stocking was tested using multiple linear regression. This model was significantly different from zero and the two slope coefficients were also significantly different from zero at the 95% probability level (R^2 0.95; p-value $9.70e^{-14}$).

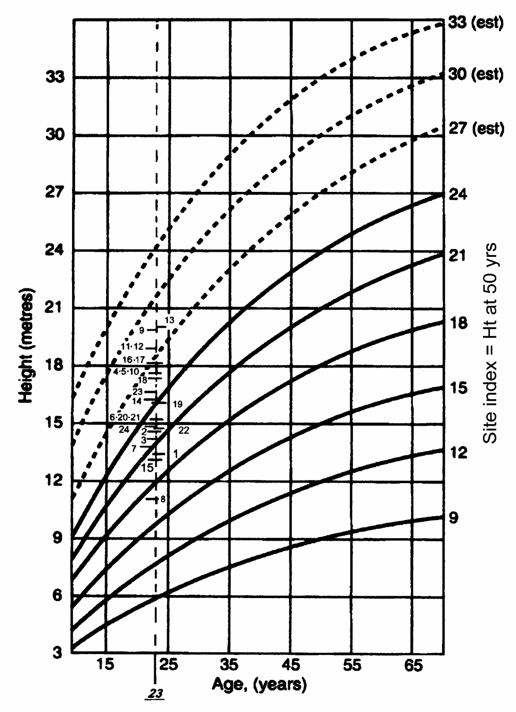

Fig. 1. Mean top height of the plots at Walnut Island at age 23 on mean top height curves of New Zealand and the United States.

Other tree growth and performance indicators

Other tree growth and performance indicators such as natural regeneration, pasture growth, allelopathy, intercropping, and management (17, 25, 34, 49, 51, 74, 82, 83, 86, 93, 106, 107, 109) , were also tested.

Site and soil indicators

Site indicators such as different periods of leaf colouration and abscission (leaf predawn) in different plots, leaf predawn and density of trees, frequency of stem cankers against leaf predawn, and canker frequency and distribution, were tested. Regard to soil indicators, depth, texture, color, acidity, and calcium content of soil were classified at 20cm, 50cm, and 100cm level of depth. Leaf predawn was regressed on distance from nearest water body, mottling at different depth on texture class, and texture class on distance from nearest water body. All of levels of site indicators were tested against the others in an attempt to identify any association. Site factor indicators were also regressed against colour and density of foliage, and distance from nearest water body. Despite the number of models fitted (n. 94), only a few cases showed a statistically significant correlation.

Foliar analysis

Foliar nutrient concentration is a diagnostic methodology that contributes an evaluation of both soil fertility and phytopathology associated with macro- and microelements deficiency (33, 47, 81, 87, 92). The Forest Research Institute of New Zealand undertook such an analysis in 1988 (79).

Colour and density of foliage

Different periods of leaf coloration and abscission (leaf predawn) were observed in different plots in early April 1998, during the period of leaf colouring.
Leaf coloration and abscission of plots were grouped in three classes where the first contained plots with green foliage and no defoliation, the third had plots with coloured (yellow) leaves and advanced

defoliation, and the second one was an intermediate class where walnuts had both green and yellow leaves and progressing leaf abscission. A linear regression of class of leaf coloration and defoliation of plots on site index was estimated.

Canker frequency, distribution, and development

The presence of stem cankers at Walnut Island was mapped before foliation started, in early spring 1997 (2, 7, 8, 24, 29, 50, 54, 58, 59, 69). All the trees on the plots were checked in order to verify any visible symptom of disease, especially cankers, decay, and carpophora. The position of previously thinned trees was also identified, and the cankered trees were checked and mapped on all the plots. As many cankered trees had specifically been thinned because of diseases (71), it is possible that testing a correlation between number of cankered standing trees, diameter classes, and tree density produce misleading results. The frequency of stem cankers was regressed against mean top height, mean diameter, number of stems per hectare, and colour and defoliation of foliage to verify whether any association occurs. The frequency of stem cankers was also regressed against distance from nearest stream.
The comparison of data available for the year 1997 with those measured in 1991 (Meggitt, 1991) provided an estimation of the variation of the incidence of cankers. The percentage of trees affected by both stem and headed cankers varied in the period 1991-1997. It is not possible to indicate whether headed cankers regressed and stem cankers appeared, or the latter used the wounds and anomalies of tissues caused by the former to enter the tree.

Site and soil variables and tree productivity

Black walnut seems to have the apparent capacity to tap the water table for moisture during the summer (26, 43, 57, 61). Mapping of the water table under Walnut Island was beyond the resources available for this study. Nevertheless, an attempt was made to test whether mean top height, as a measure of site productivity, was associated with distance of trees from water bodies, being a likely proxy for the depth of the water table.
Two transects, T1 and T2 were established to sample the distance from river. Because the planting density was 4m x 4m throughout the plantation, the distance between T1 and T2 was 28m, that is, 7 lines. The distance of trees from the river was measured by fixing a reference point, which was perpendicular to both transects and the river. Trees along the transects were selected on by random sampling and height and distance from river were recorded for each such tree.

Soil and related variables

The following independent variables were also tested in various multiple regressions against mean top height: texture class at 100cm depth, class of mottling abundance at 50cm depth, colour and density of foliage, competition with understorey in one plot, presence of gravel along the soil profile of two plots (3, 5, 6, 12, 20, 21, 22, 27, 28, 30, 33, 35, 37, 42, 45, 55, 56, 57, 60, 62, 66, 68, 75, 78,84, 89, 90, 91, 95, 99101, 103, 109).

Texture at 100cm depth was grouped according to clay content, the classes being determined on the basis of clay content percent. Initially the classification was based directly on that used by McDonald, *et al*. (70). However, tests using a simpler classification shown in Table 1. in which the McDonald class with clay content 35-45% was amalgamated with that for below 35% suggested that the simpler classification was slightly more precise and enabled a somewhat simpler interpretation.

The criterion of presence/absence of mottling is a directly measurable indicator of conditions producing mottling, namely the probable periodic lack of aeration associated with a high water table. Mottling was initially measured according to the methods recommended by Charman and Murphy (20) in which less than 10% mottling is separated from equal to or greater than 10% mottling. However, tests showed that recognition of a third class (0-2%, 2-10%, >10%) (Table 2.), as is done in Australian and Italian field sampling procedures (70, 111), in some case was more effective in precision and interpretation.

Table 1. Classes of soil texture of plots according to clay percent at 100 cm depth.

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Plot N.	Clay %	Texture Class	Plot N.	Clay %	Texture Class	Plot N.	Clay %	Texture Class
1	35-45	1	9	> 55	3	17	45-55	2
2	35-45	1	10	“	“	18	20-30	1
3	35-45	1	11	“	“	19	45-55	2
4	45-55	2	12	“	“	20	35-45	1
5	45-55	2	13	“	“	21	45-55	2
6	5-10	1	14	45-55	2	22	20-30	1
7	> 55	3	15	45-55	2	23	> 55	3
8	35-45	1	16	> 55	3	24	20-30	1

Table 2. Classification of mottling abundance at 50cm depth in the Walnut Island plantation (Class 1 = 0% -2%, Class 2 = 2% -10%, Class 3 = > 10%).

Plot N.	%	Mottling Class	Plot N.	%	Mottling Class	Plot N.	%	Mottling Class
1	2-10	2	9	20-50	3	17	(20)-50	3
2	0	1	10	“	“	18	10-20	3
3	0	1	11	20	“	19	< 1	1
4	< 2	1	12	20	“	20	0	1
5	> 20	3	13	(10) 12	3	21	0	1
6	20 (30)	3	14	2-10	2	22	2-10	2
7	20 - 50	3	15	20	3	23	2-10	2
8	0	1	16	20	3	24	20	3

Presence of understorey and presence of gravel along the soil profile in the respective plots were also implemented.

Correlation between tree performance and site quality indices

The correlation of site factors, which were estimated by indicators such as texture, soil depth, mottling, Munsell color chart, pH, and calcium effervescence, with mean top height (MTH) as a site index was tested through multiple linear regression.
The field analysis sampled at three different depths, that is, 20cm, 50cm, and 100cm depth, and each factor was partitioned into classes (levels). As noted earlier, linear regressions of each factor against the others at both same and different depths were fitted to explore if any significant correlation, influence, or dependence was evident. Then, MTH of plots was regressed against every soil factor at different depths, and non-significant relationships were discarded.

A multiple linear regression model of MTH on all the site factors that are significant was fitted, and single independent variables, that is, site factor levels (depths), were dropped while the model remained significant.

Finally, the effect of thinning, that is, number of stems per hectare of plots was added to the model, in an attempt to identify eventual effects on productivity.
Multiple linear regression was used to test the correlation of MTH with site factor indicators, which were the independent variables of the regression equation.

3. Results

Associations between site indicators

Soil Depth

Soil depth was at least 120 cm in all the 24 plots. However, such depth does not seem to limit black walnut growth (21, 37, 41, 49, 56, 76, 78, 85, 89, 91). Therefore, the relationship between soil depth and growth was not tested. Different texture and sandy and/or gravely layers were found at different depths in some plots within a depth of 120 cm.

Soil Texture

Soil texture varied from clay sand to medium heavy clay at Walnut Island. It also varied down the soil profiles. For example, there were plots with similar texture at the three different depths sampled (20cm, 50cm, and 100cm), plots with heavier texture in the surface soil, plots with lighter texture in the surface soil, and plots where abrupt variations of texture, usually sandy or gravely, can be found at different depths. Some plots without sand and/or gravel in the soil profile or as strata but with similar soil texture and distance from water bodies to others, appeared to have higher levels of site productivity based on their values for site index. Because of the relatively limited number of plots, it was not possible to test these hypotheses properly and the summary presented simply represents a preliminary set of hypotheses which should be tested further.

Depth to Mottling

Depth to mottling varied widely across plots. In different plots, mottling occurred at 50cm and 100 cm depth, at 20cm, 50cm, and 100cm depth, at 0cm and 100cm depth, at 20cm and 50cm depth. One plot showed mottling only at 20cm depth, and only one did not show mottling at any depth tested.

Mottling abundance ranged from just 2% to roughly 50%, with bands in the range 5-15 mm and contrast faint, distinct, or prominent. Boundaries may be sharp, clear, or sometimes diffuse, and Munsell color changed widely within the dominant hue 10YR and the secondary hue 7.5YR. Dark brown, brown, yellowish-brown, reddish-brown, and reddish were main colors observed.
When mottling was present, its abundance varied from just 2% to 50% according to different plots and depths. Contrast was also reflected in all of the three possible classes, that is, faint, distinct, and prominent. Mottling abundance did not seem to be associated with contrast. Most plots had two different types of mottling. Higher abundance, slighter lower than average contrast, and lower differentiation of mottling color in relation to soil color characterize a first pattern, in which less abundant.
Three main groups of plots based on mottling abundance and contrast at 50cm depth were identified. One group had no mottling, another group had abundance less than 10% and/or faint contrast, and the remaining plots had mottling abundance over 10% and a distinct or prominent contrast.

Soil Colour

Soil colour is defined by value and chroma within the hue 10YR of the Munsell Colour Chart. Most representative colours at Walnut Island were those with 4/1, 4/2, 4/3, 5/4, 5/6, 6/3, and 6/6 value and chroma. These colors varied from dark brown to reddish brown, so that different conditions of humification and aeration seemed to be indicated. Plots were grouped in classes based on value and chroma. At 20cm depth, some had value 4 and chroma 3 or 4, some other plots had value 5 and chroma from 2 to 4, and a third group had value 6 and chroma from 2 to 6. In particular, one had an intermediate color between 5/2 and 6/2, another varied from 6.4 and 6.6 value and chroma, and another one had a value 5 but a more extreme chroma of six.

Plots may have different soil color at 20cm, 50cm , and 100cm depth, and soil color changes occur in different orders. A group of plots had similar value and chroma along the entire soil profile, a second group had a different soil color at 20cm depth, some plots changed at 100cm depth, some plots had a similar soil color at both 20cm and 100cm depth, and some other plots had different soil colors in all of the three depth levels.

Soil Acidity

Soil acidity was usually in the range 6.0-6.5 pH. Value was around 5.5 pH at 20 cm depth in about 50% of plots, and at 100cm depth in about 12,5% of plots. Only two plots maintained a pH of 5.5 at all of the depth levels, and one had a 6.0 pH at 20cm depth but 5.5 pH at both 50cm and 100cm depth. Soil acidity was within the 6.0-6.5 pH range in 69% out of the 72 acidity tests.
Finally, plots with uniform pH at every level tested were about 41.7%, those with pH changing from 20cm to 50cm depth were circa 29.2%, plots with a different pH value at 50cm and 100cm depth were 16.2%, and plots with a different acidity at every depth level were 12.5%.

Calcium content

All classes of calcium content were found at Walnut Island. Slightly, moderately, highly, and very highly calcareous levels of effervescence were present at different depths and plots. This variability of calcium content classes seemed to confirm that calcium content may vary from more than deficient to more than adequate. Ten plots out of 24 had a uniform calcium content class at the three depth levels sampled, seven plots had a different calcium content at 20cm depth, three plots hade a different calcium content class at 100cm depth, and other four plots had similar calcium content at both 20cm and 100cm depth level. In addition, calcium content at 20cm depth was associated with calcium content at 50cm depth ($R^2 = 0.45$), calcium content at 50cm depth is associated with calcium content at 100cm depth ($R^2 = 0.44$), but no correlation was found between the 20cm depth and 100cm depth levels.

Foliar analysis

Foliar analysis compared foliar nutrient concentrations of Walnut Island with provisional foliar standards used in the United States to evaluate black walnut foliar nutrient analyses (97). According to data of the New Zealand Forest Research Institute, calcium, manganese, and magnesium were more than adequate to high, nitrogen was intermediate to low, phosphorus was nearly adequate to high, potassium was more than adequate to low, zinc was more than adequate to high, and boron was nearly adequate to low with respect to New Zealand standards (79).

Colour and density of foliage

A linear regression of leaf predawn onsite index was estimated:

$$COL = 5.48 - 0.24\ MTH \tag{3}$$

Model (3) was statistically significant (p-value 0.00008…), suggesting that leaf coloration and fall contributes an indicator of site productivity (R^2 0.51).

A linear regression of colour and density of foliage on tree density was not significantly different from zero.

Canker frequency, distribution, and development

Occurrences of stem and head cankers did not appear consistent over time and were further confounded by thinning. The percentage of cankered black walnuts was about 10.2% in 1997, while it was about 9.5% in 1991. Furthermore, the trees apparently recovered (circa 5.5%) in the same period suggested that a certain portion of them might be canker resistant.
The concentration of diseased trees in an area between three plots was quite evident. Such a specific distribution would suggest that susceptibility to canker and/or potential inoculum may be dependent on some environmental factor that stresses trees and/or creates conditions particularly favourable to pathogens (2, 3, 7,8, 17, 20,24, 26, 27, 29, 43, 45, 47, 49, 50, 54, 58, 61, 66, 75, 72, 98, 108). It is also possible that resistance and recovery of individual walnuts may have a genetic origin.

At Walnut Island, the frequency of stem cankers was higher in plots with lower mean top height and viceversa. A linear regression model of stem canker frequency on mean top height was estimated:

$$CKF = 24.49 - 1.30\ MTH \qquad (4)$$

where CKF is the percentage of stem cankers per plot, MTH is the mean top height of plots as a site index The model was significantly different from zero at the 95 % probability level (R^2 0.46; p-value 0.00027 ..).
Regressions of the frequency of stem cankers were also carried out against leaf coloration and fall but the coefficients were jointly not significantly different from zero.

Although all the indicators were regressed against each other, only a few are weakly associated. In particular, leaf coloration and fall is correlated weakly with distance from nearest water body (5a, 5b), mottling at 50cm depth with texture class at 100cm depth (6), and texture class at 100cm depth with distance from nearest water body (7).

$$COL = 0.40 + 0.47\ DS \qquad (5a)$$

where COL is class of leaf coloration and fall, DS is distance from nearest water body. The regression model was significant Multiple(R^2 0.46; p-value 0.00034 ..). One plot was omitted.

And

$$COL = 0.57 + 0.37DS + 1.30\ GV \qquad (5.b)$$

where GV is presence of gravel along the soil profile of two plots (R^2 0.57; p-value 0.00013..). No plot was omitted.

One plot behaved oddly in every model tested. The reason of its anomaly appeared to be due to the short distance from the billabong but a very low site index. In fact, height gradients of the plantation are mainly diminishing with distance from water bodies. In addition, the gravel (5-20mm) percentage increases with soil depth.

Mottling at 50cm depth and texture class at 100cm depth

A significant association was found between mottling at 50cm depth and texture at 100cm depth. Mottling classes were determined according to the “Soil Conservation Handbook for New South Wales” (Charman and Murphy, 1991).

$$MG50 = 0.46 + 0.51\ TX10 + 1.03\ SD \qquad (6)$$

where MG50 is classes of mottling: (Class 1) < 10%, (Class 2) > 10%; TX10 is texture class at 100cm depth, SD is presence of sandy strata or sandy texture in four plots.

The multiple linear regression was significantly different from zero (R^2 0.69; p-value 4.383 $e^{-006)}$.

Site and soil variables and tree productivity

Tree height and distance of trees from water bodies

A regression of tree height on distance from the river was fitted:

$$TH = 19.46 - 0.085\ DR \qquad (7)$$

where TH is tree height (m), and DR is distance from the river (m).

According to equation (7), about 61% of the variability of tree height is explained by distance from the river. This strongly suggested that mean top height may be a function of distance from water bodies.

Mean top height and distance from nearest water body

The distance of plots from the nearest water body was estimated using the plot diameter as a measurement unit. For example, a plot is about 2 plot diameters from the center of the billabong, where the measure is taken on the shortest straight line.

A regression of mean top height against distance from water was calculated:

$$MTH = 19.43 - 1.34 \ DS \qquad (8)$$

where MTH is mean top height of plots (m), and DS is the distance from nearest water body (multiples of plot diameter).

Equation (8) showed that the estimated coefficient for distance from water body is significantly different from zero at the 95% probability level (R^2 0.49; p-value 0.00018..). While this is an interesting result that supports the importance of distance from water bodies and associated soil properties, it is not an especially helpful one in the establishment of other plantations because it requires detailed site mapping of water bodies. The attempt was therefore made to develop the analysis further using variables reflecting the direct characteristics of the plots, especially those relating to soil and water.

Multiple regression of mean top height on soil and related plot variables

A multiple linear regression of mean top height against soils and related variables was calculated using all plots.

$$MTH = 13.67 - 0.90 \ COL + 1.22 \ TX10 + 0.84 \ MG5 - 5.16 \ WD - 3.22 \ GV \qquad (9)$$

where MTH denotes mean top height of plots as a site quality indicator.

One plot, which has clayey sand texture over 75-80cm of depth , is an outlier in the residuals of MTH.

The multiple coefficient of determination of model (9) is high (R^2 0.91) and coefficients are all individually significantly different from zero at the 95% probability level, providing a useful and precise predictive equation for mean top height (p-value $1.208e^{-008}$).

Regression of plot volume on soil and related variables

A multiple linear regression of plot volume against texture, mottling, understorey competition, presence of gravel, and number of stems per hectare was calculated.

$$Vol = -23.66 + 7.43 \ TX10 + 11.37 \ MG5 - 33.35WD - 40.70GV + 1.48NSH \qquad (10)$$

where Vol denotes net volume (m^3) of plots, TX100 denotes texture class (4 classes) at 100cm depth, NSH denotes number of stems per hectare (x/10).

None of the plots appeared to be aberrant on examination of residuals. Model (10) therefore seems to provide a useful predictive equation (R^2 0.89; p-value $3.683 \ e^{-008}$) for net volume at this age.

4. Discussion

Site productivity

Black walnut is a demanding species, especially with respect to moisture supply, soil aeration and drainage, and fertility (). The climatic pattern of Walnut Island is a Mediterranean type broadly comparable with that of Middle Italy. Dry summers, drought years, and strong winds are a major limiting factor for black walnut growth and timber production. Tree height was found to diminish with distance from the nearest water body and a general reduction of mean top height with distance from nearest water body was noted, probably reflecting a subterranean effect with respect to water supply and water table.

While this is an interesting result that accords with expectations from the literature, it may not be a useful predictive relationship for practical management because of the need to map the water bodies over the entire site in order to use it. Hence other multiple regressions of mean top height against soil and related plot variables were explored.
The results suggested that mean top height or site index provided a useful way of discriminating between various levels of site productivity. Hence, soil and other site variables were therefore investigated further.

Premature leaf abscission was associated with both site productivity and distance from nearest water body. Where premature leaf abscission occurred, water stress may have contributed to reduced tree growth and premature leaf abscission.
The association of premature leaf abscission with distance from nearest water body, which was stronger when presence of gravel in the soil profile was included, also supports the hypothesis of water stress determining leaf coloration and fall, and is consistent with the noted association of color and density of foliage with site index and stem canker frequency.
Stem canker frequency was associated with site productivity at Walnut Island, probably reflecting environmental stress. A limited availability of resources (i.e. moisture, nutrients, oxygen, etc.) not only reduces tree productivity, but can also predispose plants to infection because of the debilitation that may occur.
These results support the hypothesis that the investigated site and soil properties related to moisture supply influence black walnut growth, especially in absence of adequate rainfall during summers and drought years. However, further and more specific investigation of the soil and site properties influencing black walnut growth was pursued, in order to provide a more readily accessible guide to site selection and plantation management.

Effect of soil and site variables

On the basis of the previous results, soil depth to 120cm, soil colour, soil texture, degree and depth of mottling, acidity, and calcium effervescence were sampled and analyzed at 25cm, 50cm, and 100cm depth in each plot.
As noted earlier, the minimum soil depth (90-100cm) to gravel, coarse sand, or impervious layers suggested by the literature for siting black walnut corresponds with the minimum depth to gravel (1 m) at Walnut Island (CFTT, 1996). Soil texture classes were based on the clay content (%), as suggested by the literature review (quotes). On such a basis, clay content classes related to main pore space variations may be defined according to limits of 20%-30% or 30%-35%, 35%-45%, 45%-55%, and over 55% of clay content. In fact, above 55% of clay content micropores percent and total pore space appear closely correlated. The percentage of macropores, which reduce water yield, increases dramatically below 30% of clay, and intermediate classes are sensitive to variation of micropores on total pore space.
Mottling and clay content were not correlated with distance from nearest water body. This may reflect the presence of differently textured lenses or layers at different depth. Soil field analyses found a high variability of texture within and between soil plots, and literature reports that depth to the underlying gravel varies from 1m to 3m depth (CFTT, 1996).

At Walnut Island, mean annual rainfall is near the minimum acceptable to the species, and summers are often dry and very warm. Mottling seems to be due to soil saturation caused by rising of water table rather than water stagnation caused by difficult drainage. If this is true, the variable depth to gravel, lenses of clay or sand, and coarsely textured strata are likely to influence duration of water saturation at different depths, especially during periods when water table rises and falls, respectively. While some mottling was also present in apparently more coarsely textured soils, the most intense mottling (and presumably poorer drainage) was associated with the most clayey soils.
The association of mottling at 50 cm depth with texture class at 100cm depth corresponds to an increase of clay content. This association suggests that increasing impermeability at a deeper depth level is associated with more difficult drainage, as indicated by mottling, which accords with the literature cited earlier.
The colour of the mottling was often in the range of brownish yellow, yellowish brown, yellow, reddish brown, and brownish red, which indicates that there were periods when aeration was good. These results appear to be in agreement with similar French research (quote), which found that black walnut may grow on soils with a “gley” horizon which limits drainage, provided that the initial 40-50cm of soil was free for rooting. In addition, drainage at Walnut Island may be influenced by the variable depth to the underlying

gravel, contributing to different degrees and depth of mottling. Deeper clayey soils probably retain more water and are saturated for longer periods than shallow and/or more coarsely textured soils. Above all, soils with higher clay content are likely to have a slower drainage, such that processes causing mottling last longer under equivalent conditions. A short depth to gravel may allow for faster drainage and fewer and shorter periods of water saturation, but moisture availability is likely to be much more reduced during low rainfall periods. Hence, texture appears to be a major factor determining drainage, and availability, yield, and conservation of water and moisture.

As noted earlier, premature leaf coloration and abscission (leaf predawn) represents a response of black walnut to water stress, and mottling at 50cm depth and clay content at 100cm depth, presence of gravel, distance from nearest water body, canker frequency, and competition from understorey plants are related to drainage, water stagnation, porosity, water yield, and the chemical fertility of soil. Hence this set of independent variables is broadly consistent with the expected role of water relations and fertility.

Multiple linear regressions of mean top height against mottling at 50cm depth and clay content at 100cm depth, colour and density of foliage, competition with understorey in a plot, and the presence of gravel along the profile were calculated to test the relationship of site productivity to these variables. Among a number of models tested, one using premature leaf abscission, mottling at 50cm depth, clay content at 100 cm depth, presence of gravel and sandy layers, and understorey competition was significantly different from simpler versions and explained 91% of variability in black walnut growth at Walnut Island. Each of the individual coefficients was significantly different from zero at the 95% probability level and the final calculations yielded a very precise predictive equation.

A similar regression of net standing volume against site and soil variables yielded similar results, with number of stems per hectare replacing the premature leaf abcission variable. These results provide strong support for the complex role that soil variables play in determining site productivity and reinforce and extend the earlier results of Nicholas *et al.*, (1997) and those of Hansen and McComb (1958).

Soil properties correlated with tree growth

Clay content is reported by most authors as a main soil factor that influence black walnut growth. Interestingly, clay content classification used to test the association with mean top height in this research coincided with the classification of clay percentage in the soil that was supposed to define levels of soil properties dependent onto porosity, and proportion of different soil pore size itself.
It confirms the suitability of clay percentage as a strong indicator of soil properties related to tree growth. Mottling is also given as an important indicator of soil drainage and aeration, which are properties defined by a number of soil characteristics.

The association of mottling at 50cm depth with clay content at 100cm depth is in line with literature on relationships between soil texture and some of the related properties such as drainage and aeration (quotes). The dependency of mottling abundance onto clay content at Walnut Island enforced by the inclusion in the model of sandy strata or texture of some plots, which appear to indicate low or absent mottling because of higher drainage or shorter period of water stagnation in parity conditions. In model (10), clay content is strongly correlated with mean top height and indicates a static physical situation (texture) that influences soil properties such as drainage, aeration, water yield, cation exchange, and so on. Mottling, which is correlated to clay content at a deeper level, is a more dynamic indicator as it tends to estimate effects of clay content.
Both of two indicators are strongly associated with mean top height or site index. The presence of gravel in the soil profile, which is included in the model, strengthens the significance of mottling and clay content as indicators of the soil characteristics and properties above mentioned. The presence of gravel increases drainage and reduces water yield in spite of a good percentage of clay.

Lack of weed control reduces black walnut growth because of competition for water and/or nutrients. Foliar analysis (Par. 4.3.3.1) at Walnut Island seems to indicate no nutrient deficiency, and complements the other site and soil indicators.
As noted, the coefficient of the independent variable weed control (WD) in the equation is 5.16m, which is the average reduction of mean top height with a standard error of 0.85 m.

This result suggests that weed control is an important cultural practice at Walnut Island, especially in consideration of the dependency of water supply on the site and soil properties, and the limiting climatic features.

Comparison with other areas of plantation development

Tree growth at Walnut Island varies markedly but at least about 50% of plots reach the average standard as defined by the American Site Index. Furthermore, a good number of plots have higher values, that is, they are nearly the top class.
Such a positive result occurs in a site that can be defined as a mediocre one mainly because of the low mean annual rainfall, frequency of dry summers, drought, and warm, dry, strong winds. The very warm and often dry summer is likely to add further limitations to potential black walnut growth.

The high variability of tree growth in areas of plantation development makes difficult to compare the Walnut Island plantation. More trials should be tested throughout southern Australia before a definitive response can be given.
In Italy, there are plantations with both higher and lower productivity than the Walnut Island, and this depends on provenance, climate, and soil type.
French stands appear to have average values similar to most of plots at Walnut Island.
In Spain, *Juglans* species plantations are too young to provide comparable data.
Mean top height and standing volume of best plots at Walnut Island appear to be proportionally higher than best ones of a trial in Sloven.

5. Conclusions

Black walnut is a very high demanding species (41, 46, 65, 98, 100). The data above describe successful experimental results in cultivating black walnut for timber production at Alexandra. At least 50% of plots reaches competitive levels of productivity according to the United States Site Index (6, 19, 36, 96, 110). In addition, such a goal is particularly encouraging because Walnut Island appears to be a mediocre site, especially in comparison to some other Victorian areas (3,4, 9, 21, 22, 29, 41, 43, 46, 49, 52, 56, 57, 59, 61, 78, 81, 82, 88, 89, 90, 91, 103, 107, 110). Furthermore, no other provenance has been tested at Walnut Island except than those from Iowa, and there has been recent slowing of diameter growth, perhaps due to delayed thinning (71).

Walnut Island is possibly the only site in Australia that is sufficiently large and uniform to be suitable for this research. Unfortunately there is insufficient documentation of the establishment and management of the site to ensure that past management has been uniform over the full area and this may influence the results. Walnut Island shows that black walnut can successfully produce timber despite strong winds, dry summer, 1972, 1982, and 1994 droughts, and mean annual rainfall near the minimum required by the species (1, 13, 29, 61, 69, 77). The flat topography at Walnut Island not only simplifies harvesting and management, but also reduces or eliminates the effects of slope on both site variability and timber production. This is important in such experimental stages of the plantation because slope usually influences factors such as drainage, soil depth, organic matter content, and soil erosion also. Because of this, it may be used as a provisional indicator of site suitability for other Northern Hemisphere species to be cultivated in Australia for timber production.
So, appropriate experimental designs where different species, combinations, and provenances are tested in different environments are likely to produce positive results not only in timber production but also in other vocational sectors such as tourism, salinity tolerance, pasture and grazing improvement, landscape, and recreational area.
At Walnut Island, further research could be undertaken on the identification of provenance or genotypic means, and response to the site and soil indicators. It would allow genotypic means that produce better results to be selected in order to implement a forest tree improvement program for the production of a first selection of Australian cultivar(s) (18, 63, 64). Selection of best individuals and /or sub-populations should be accompanied by tests on mechanical and commercial characteristics of wood (9, 11, 15, 31, 75, 88). In fact, although the constancy of results over the variability of provenance within and between plots would suggest that site and soil indicators associated to mean top height or site index are consistent to major eco-physiological features of black walnut growth, a thorough provenance selection needs to be made before further experimentation with black walnut is undertaken.

A market investigation is also important to understand directions, limits, trends, characteristics, and potential demand, investments, and trade of walnut timber products for the development of an Australian production.

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