Developing a Site Classification System for Species Matching in Uganda

(Pt II)

III. A preliminary appraisal of the potential use of existing growth data in predicting growth potential of principal commercial species grown in Uganda.

IV. Towards a new site classification for species matching and predicting growth potential in Uganda: Initial refinements and revision of the classification system.

V. Towards a new site classification for species matching and predicting growth potential in Uganda: Data requirements and a framework for new species trials

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Introduction

The previous document outlined a preliminary basis for the further development of a site classification for species matching in Uganda. A relationship between temperature and altitude for a range of latitudes was described and linked to requirements of principal commercial species. The aim of this document is to ascertain the extent to which this approach can be taken further and refined by considering the following;

- A preliminary appraisal of the potential use of existing growth data in predicting growth potential of principal commercial species grown in Uganda.
- The use of additional climatic, soils and terrain information to refine and revise the proposed site classification system set out in the previous document.
- Make recommendations for obtaining growth and climatic data for better species matching and prediction of growth potential of principal commercial species in Uganda.

Methodology

In this study available growth data was sought with a view to relate it to site information to see if any discernible relationships were apparent. The minimum requirements for this exercise were geo-referenced plots or trials and dominant height of such stands. Additional site information was considered to be a bonus and in its absence was estimated from the location of the trial or plot.

Several sources of data were reviewed with a view to using it for this purpose;

- Kriek (1970)
- Alder et al. (2003)
- Eucalyptus hybrid trials (Epila-Otara and Ndhokero, 2009)
- SPGS permanent sampling plots (Jjumba, 2008)

Site information

Where geo-referenced information was limited or missing an attempt was made to locate the approximate area of the trials/plots by reference to the trial name or location. This was done establishing the approximate location of the trials/plots on Google Earth and obtaining latitude/longitude and altitude. Rainfall data was then obtained directly from the relevant report or in its absence by the Atlas of Uganda (1967). Mean annual temperature was obtained from the formula provided by Hardcastle (2003) relating MAT to altitude and latitude;

$$\text{MAT } (^{\circ}\text{C}) = 29.76 + (0.6248 \text{ Latitude}) - (0.007 \text{ Altitude}) \quad [1]$$

Evaporation and evapo-transpiration data was obtained from Dagg *et al*. (1970) and Rijks *et al.* (1970) which formed the basis of the figures found in the Atlas of Uganda (1967). In order to obtain a rudimentary estimate of regional water stress, annual moisture deficit was calculated using the equations of Kingston (1974; Equation [2]) and Hardcastle (2003; Equation [3]). This simply reflects the annual total of monthly differences between precipitation and evaporation when the latter exceeds precipitation. The equations used were;

$$\text{Annual moisture deficit (mm)} = 2492.6 - (8427.0/\text{Evaporation}) + (2143850.0/\text{Rainfall}) + (6.18201 \times 10^9/\text{Evaporation}^2) - (2.78204 \times 10^9/\text{Rainfall}^2) - (1.40809 \times \text{Evaporation} \times \text{Rainfall}) \quad [2]$$

$$\text{Annual moisture deficit (mm)} = 2484 - (0.593\ \text{Altitude}) + (91.338\ \text{Latitude}) - (1.084\ \text{Rainfall}) \quad [3]$$

Where;

Latitude is in degrees (decimal form), latitudes south being negative

Altitude in metres

Rainfall and evaporation in mm

A simple calculation of the ratio of rainfall to evaporation was also carried out. Evaporation was estimated from the Atlas of Uganda (1967) based on the results of Dagg *et al*. (1970) and Rijks *et al.* (1970) for 30 sites (19 in the Atlas of Uganda and 11 from the *Eucalyptus* clonal hybrid study). Additional information on latitude and altitude was determined using Google Earth.

Where possible the sites were allocated to the agro-ecological classification of Uganda (Government of Uganda, 2004).

Growth information

In each report an estimate of dominant height was sought since it is closely related to forest site productivity for a particular species and age (Skovsgaard and Vanclay, 2008). If dominant height is known at any age, it can then be projected to any age of interest in which case it is termed “site index” (e.g SI_{10} denoting dominant height at 10 years of age).

In order to facilitate further analysis for the *Eucalyptus* clonal hybrid study (Epila-Otara and Ndhokero, 2009) at each site, the clonal hybrid data was combined (GC as one treatment and GU as another). GU21 was also included in the GC dataset as the authors remarked that it had been wrongly identified as a GU clone when in fact it was a GC clone. Site index at 10 years was projected and volume estimated from dominant height and age based on Alder’s models for *E. grandis* (Alder et al. 2003). Since the measured heights are based on mean values and not dominant height, mean height was multiplied by a factor of 1.1 as it is commonly 90% of dominant height for *Eucalyptus* (Smith et al. 2005). Implicit in this approach is that Alder’s model for *E. grandis* in Uganda is also appropriate for *E. grandis* clonal hybrids which would obviously be subject to some error. Alder’s model was also rearranged to be solved for site index. It must be emphasized this was not carried out as a strict scientific exercise but as a preliminary study to elucidate broad relationships between site index and site criteria.

Statistical analysis

Statistical analysis was carried out using simple linear and multiple regression techniques in Genstat Version 10.2 (Lawes Agricultural Trust, 2007).

Results and Discussion

Using available growth data for predicting growth potential

A summary of growth data available for predicting site growth potential is presented in **Table 1**. A feature of all the studies is that only approximate locations are given in the reports published to date. It is possible that the exact locations of the PSPs of Alder et al. (2003) exist in a database and that the SPGS PSPs are also known or are easily obtained. The same should be true for the *Eucalyptus* clonal hybrid trials but no details are provided in either reports of these trials by either NAFORRI (2007) or Epila-Otara and Ndhokero (2009). The study of Kriek (1970) seemed to provide the most comprehensive of all datasets but for a number of reasons was the most the most difficult to comprehend (see next section). The PSP data presented by Jjumba (2008) was too young to make robust projections of site index at this stage and coupled with the lack of reported geo-references, the plots were not considered at this stage. However if more recent measurements of dominant height are available and the sites locations geo-referenced this dataset could prove useful. Of the remaining two studies each one is considered in turn. Further analysis was carried out on the data of Alder et al. (2003) and Epila-Otara and Ndhokero (2009) and is presented here.

The study of Kriek (1970)

This study is intriguing as it summarises a series of 78 trials that were implemented from 1953 onwards. In these trials over 59 species of *Eucalyptus*, 52 pines, 16 Acacia and species of numerous other genera were tested. The sites were placed into a framework based on altitude and "humidity" classes the latter based on a ratio of rainfall to evaporation. Regional approximations of mean, minimum, maximum and absolute minimum and maximum temperature as well as A-pan evaporation were given for each site. These were apparently obtained from the Atlas of Uganda (1967). An attempt was made to link the dominant height growth data to site data to evaluate whether systematic variations in site index at a reference age for typical species existed. In this respect *E. grandis* (*E. saligna* in the report) and *P. caribaea* were chosen since they had the most number of occurrences throughout the trial series. However, a number of shortcomings were apparent in the report which made any objective or even subjective analysis difficult;

- Although the sites are presented in an altitude/humidity class framework it is difficult to make out which sites are which.
- There was no information on initial spacing and final stocking
- Growth data is only presented graphically and the quality of the copy makes any information difficult to extract and extrapolate.
- It is very difficult to see which growth "curves" relate to which site.

- The document is structured in a very confusing manner which is not helped by the poor quality of the tables which are difficult to read.
- The exact method by which the humidity classes were calculated was not presented.

Because of this it was very difficult to extract meaningful data for analysis.

The study of Alder et al. (2003)

Growth and yield models were developed by Alder et al. (2003) for *P. caribaea* and *E. grandis*. The models for *P. caribaea* were based on 868 temporary sample plots and destructive sampling of 594 trees from a 1989 – 1993 plantation inventory funded by the Word Bank Forest Rehabilitation project. Alder et al. (2003) stated that there was a clear linkage between site index and altitude but that the relationship to rainfall was less clear. Even though the site index range is not wide and the data points few the data presented in **Figures 1 and 2** shows that there is a good relationship between site index and indices of moisture stress as shown in **Figure 1** by the ratio of rainfall to evaporation and in **Figure 2** when it is correlated directly to moisture deficit. The observations of Alder that site index increases with altitude are simply a reflection of less stress.

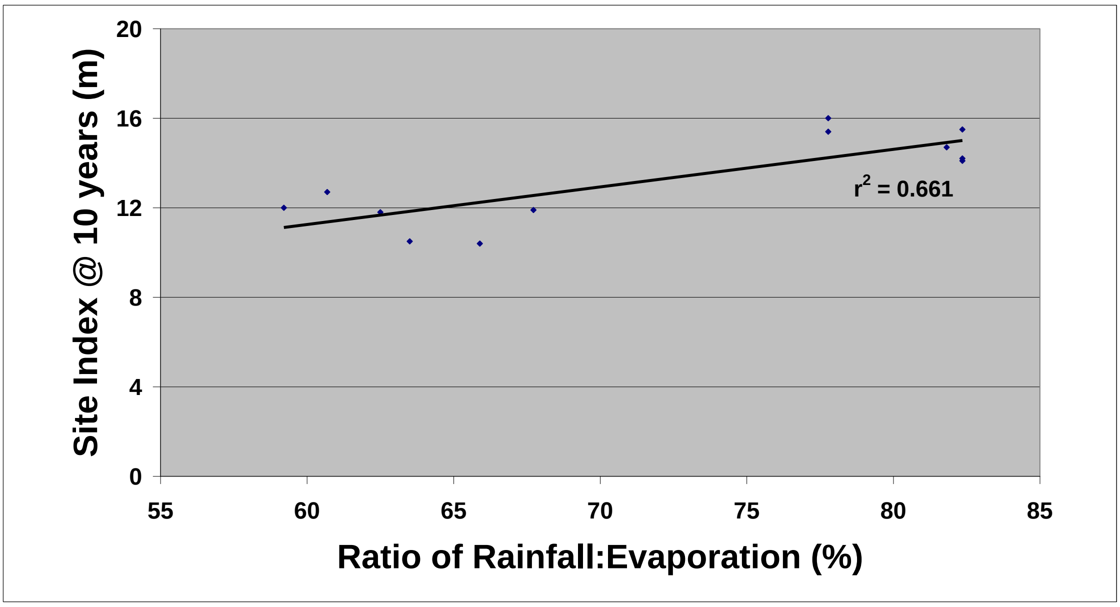

Figure 1: Site index at ten years of *Pinus caribaea* as a function of the ratio of mean annual rainfall and evaporation in Uganda. Growth data was derived from Alder et al. (2003)

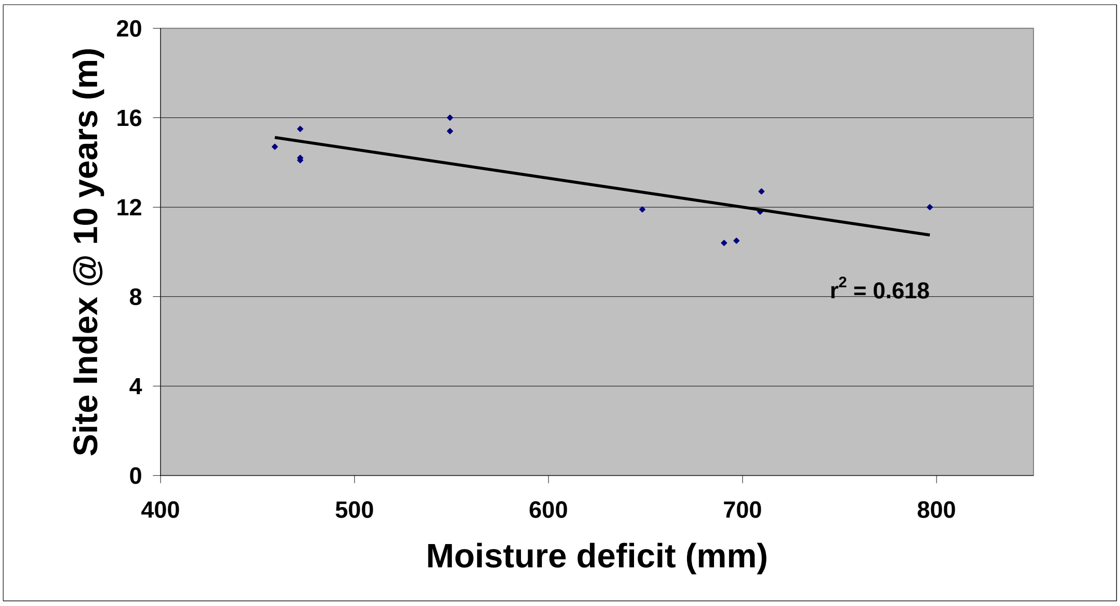

Figure 2: Site index at ten years of *Pinus caribaea* as a function of moisture deficit in Uganda. Growth data derived from Alder et al. (2003). Moisture deficit was calculated according to Equation [2] after Kingston (1974).

Alder et al. (2003) also developed models for *E. grandis* using growth and yield data from two series of permanent sampling plots established between 1989 and 1994 as part of the National Biomass Study and Periurban Plantation Project (PPP) and those of the Rwenzori Highlands Tea Company (RHTC). The PPP plots consisted of 36 PSPs covering plots from one to nine years old. The RHTC plots included 29 PSPs between two and eight years old. The latter were all located in the Fort Portal area and according to Alder et al. (2003) were generally well managed with a high level of silviculture at establishment. However it was not possible to model any of this data as it was not available at the time of writing. This would be a worthwhile exercise should it contain spatial referenced plots.

Eucalyptus hybrid trials (Epila-Otara and Ndhokero, 2009)

In an investigation of the performance of South African *Eucalyptus grandis* clonal hybrids in Uganda, twelve trials were established in 7 of the 10 agro-ecological zones of Uganda between 2002 – 2003. The trials consisted of six *E. grandis x camaldulensis* and five *E. grandis x urophylla clonal hybrids.* These were compared at each site to clonal *E. grandis* (TAG 5) and an *E. grandis* local land race. There are a number of features of the work that deserve critical attention although it is not intended to conduct a critical review of this work here. However attention should be drawn to the fact that mean individual tree volume was used as a criterion for selection which is problematic since individual tree volume (like dbh) is inversely related to survival.

It is clear from the relationships presented in **Figures 3 & 4** that the growth of the clonal *Eucalyptus* hybrids and *E. grandis* is closely related to either the rainfall:evaporation ratio or moisture deficit as predicted by Kingston (Equation 2) showing the best correlation. Only poor correlations between growth and moisture deficit were obtained when the latter was predicted by the Hardcastle method (Equation 3, data not presented).

When growth was plotted against rainfall no significant relationship was found (data not presented). It is clear that as rainfall becomes an increasing proportion of evaporative demand, growth improves markedly (**Figures 3 & 4)**. This seems to be more important for the GU clones and *E. grandis* than for GC clones which would be expected since the GC clones are known for their tolerance of drier conditions. *E. grandis* and their GU counterparts are generally known to be less tolerant of stress. Although the relationship is linear for the range of sites shown here as the rainfall and evaporative demand become similar (i.e. moisture deficits < 300mm, growth is unlikely to continue increasing linearly.

Although rainfall, evaporation and site index are all estimated and the dataset is relatively small, the results do confirm a strong relationship between growth potential and moisture deficit. The results also confirm the work of Kriek (1970) who showed good relationships between "humidity classes" and site index for a wide range of species in Uganda. Similarly, Kingston (1974) showed how a combination of altitude and moisture deficit zones could be used to define species zones and moreover showed good correlations with wood density.

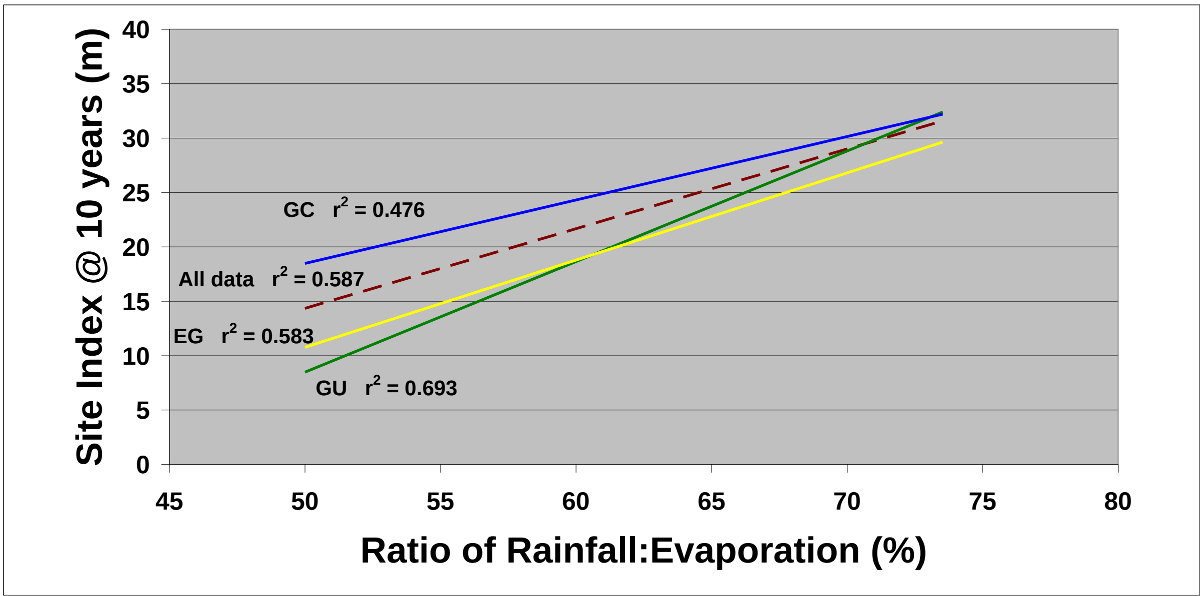

Figure 3: Projected site index at ten years of age for *E. grandis* (EG), *E. grandis x camaldulensis* (GC) *and E. grandis x urophylla* (GU) as a function of the ratio of mean annual rainfall and potential evaporation. All data (---) was obtained by averaging all the *Eucalyptus* growth data at each site. Growth data was derived from Epila-Otara and Ndhokero (2009).

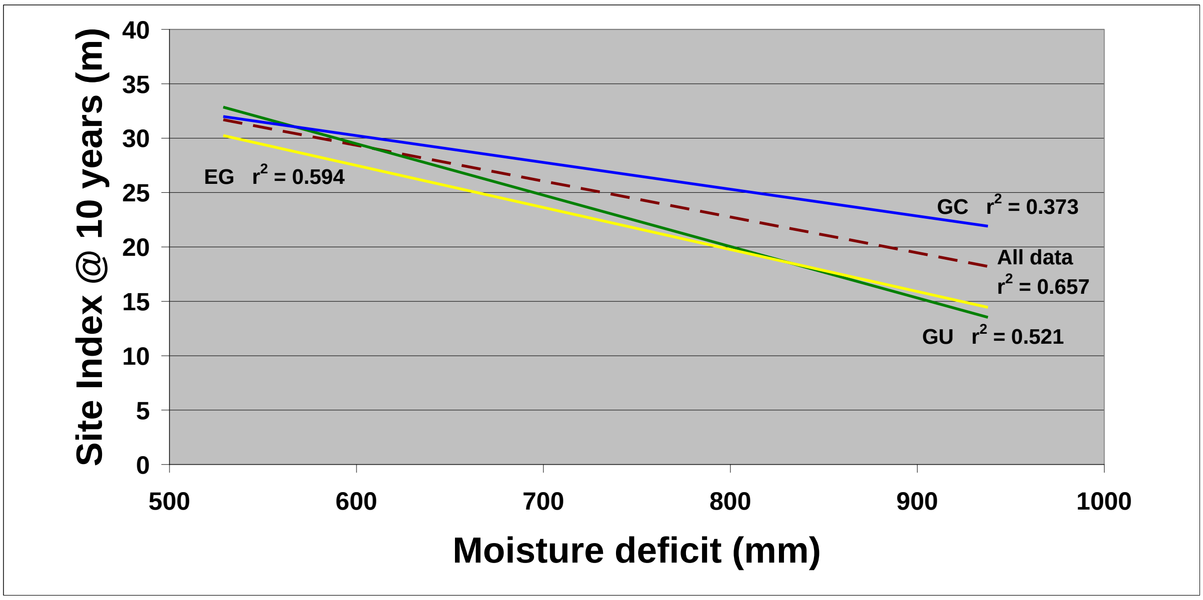

Figure 4: Projected site index at ten years of age for *E. grandis* (EG), *E. grandis x camaldulensis* (GC) *and E. grandis x urophylla* (GU) as a function of the ratio of mean annual rainfall and potential evaporation. All data (---) was obtained by averaging all the *Eucalyptus* growth data at each site. Growth data was derived from Epila-Otara and Ndhokero (2009). Moisture deficit was calculated according to Equation [2] after Kingston (1974).

Initial refinements and revision of the classification system

The data presented in the previous section have given an indication that predicting growth potential is most likely to be related indices of water availability as measured by rainfall and potential evaporation. It is clearly not good enough to use rainfall alone as an indication of productivity. For example potential evaporation (A-Pan) rates range from 1300 - 1500mm in the SW highlands of Uganda to 1700mm in much of the south of the country bordering Lake Victoria to 1900mm in the central area around Lake Kyoga and to 2100 – 2300mm in the north and north-east of the country (Atlas of Uganda, 1967; Dagg et al. 1970).

In terms of growth potential the data presented in the previous section suggests introducing a measure of site water balance as represented by the ratio of rainfall:evaporation or annual moisture deficits as a measure of growth potential. *Therefore, given that evaporation varies with latitude and altitude which are the basis for species zones, and that rainfall and evaporation combine to affect annual moisture deficits, it is possible to define rainfall thresholds for each combination of altitude and latitude that are correlated to threshold annual moisture deficits that broadly reflect growth potential.*

To construct such rainfall thresholds for each latitude/altitude combination the following procedure was followed;

1. A relationship was sought between evaporation and latitude and altitude
2. Annual moisture deficit ranges/thresholds were established that broadly approximate growth potential based on the results in the previous section

3. For a given latitude and altitude, and considering evaporation calculated by (1) rainfall thresholds were established that correspond to the rainfall: evaporation ratio or annual moisture deficit thresholds identified in (2).

The process for obtaining this information is as follows.

Defining a relationship between evaporation and latitude and altitude

The following equation was derived from 30 locations in Uganda.

$$\text{Evaporation} = 2287 + (191\ \text{Latitude}) - (0.488\ \text{Altitude}) - (0.0889\ \text{Latitude.Altitude}) \quad r^2 = 0.659 \ [4]$$

Annual moisture deficit and growth potential

The aim of defining broad annual moisture deficit classes is to define approximate growth potential and the likelihood of stress or risk occurring in a particular region or plantation. Definitive relationships between moisture stress and species grown under commercial conditions clearly would require a more in-depth study than this, but it is believed that the trends from the limited dataset presented so far are enough to define preliminary growth potential categories based on moisture deficit or a simple rainfall:evaporation ratio. These can be used as a basis and framework for further refinement and testing as more growth and site data becomes available for analysis.

It is clear that once rainfall is less than 55% of potential evaporation (corresponding to a moisture deficit of about 900mm per annum) growth is substantially reduced for *Eucalyptus* (**Figures 3** and **4)**. This would correspond to a site index at 10 years of less than 15m for *E. grandis* and the GU hybrids (an MAI of between 8 and 12 $m^3\ ha^{-1}$ annum). When rainfall is between 55 and 65% of potential evaporation (moisture deficits between 700 and 900mm) growth improves but is still relatively low, site indices being between 15 and 22m at 10 years for the GU hybrids and *E. grandis* (MAI = 12 – 16 $m^3\ ha^{-1}$ annum) and slightly higher for the GC hybrids (**Figures 3** and **4)**. This improves to moderate levels of productivity when the rainfall:evaporation ratio is between 65 and 75% (moisture deficits between 550 and 700mm) corresponding to site indices in the region of 25m for all *Eucalyptus* (about 25 – 30 $m^3\ ha^{-1}$ annum). Similar trends were apparent in the *P. caribaea* study of Alder et al. (2003; **Figures 1 and 2**). No data is available above a rainfall: evaporation ratio of 75% in the *Eucalyptus* hybrid study but productivity is likely to increase above this figure. For example, rainfall: evaporation ratios of over 90% are indicated at Entebbe and Fort Portal (**Appendix 1**) and according to Kriek (1970) the site index of *E. grandis* at Fort Portal has been reported to be above 40m at 10 years (MAI = 45 – 50 $m^3\ ha^{-1}$ annum).

It is therefore suggested, as a preliminary indication of forest site productivity/growth potential to establish rainfall thresholds for the various site classes based on 55, 65 and 75% rainfall: evaporation corresponding to moisture deficits of 900, 700 and 550mm respectively. Therefore four categories are contemplated as follows;

- < 55% not viable for commercial forest plantations

- 55 – 65% - low productivity, preferably only drought tolerant species
- 65 – 75% - moderate productivity
- 75% - high productivity

This is very tentative but could provide the basis for testing species in the new trial series and for refinement when new data becomes available from PSPs etc.

It is recognized that some species may tolerate annual moisture stress differently so that a high moisture deficit may limit one species more than another; therefore, knowledge of a species' basic physiological response to stress is clearly important. For example, Kingston (1974) suggested that the maximum moisture deficits in Uganda were 900mm for *P. caribaea*, 500mm for *P. patula* and 700 mm for *E. grandis*.

Defining rainfall thresholds that correspond to moisture deficits

Now that annual moisture deficit thresholds have been established through the application of the rainfall:evaporation ratio, the mean annual precipitation corresponding to those thresholds can be calculated for any combination of latitude and altitude. For each site class defined in the first report, a mean altitude was defined and using Equation [4] potential evaporation was calculated. From this rainfall thresholds according to 55, 65 and 75% were calculated for each altitude range in the species classification for one degree of latitude i.e. at 1^{o}S (-1), 0, 1, 2 and 3 where most of the forestry plantation zones are found in Uganda. An example of this for 1^{o}N is presented in **Table 2**. Values for other latitudes can be simply calculated in the same way.

Soil properties

Soil properties will affect total soil water storage or availability (such as soil depth, organic matter content and soil texture). However it was not considered introducing these at this stage since the emphasis in this study is to establish broad patterns of water supply and demand that are affected primarily by climate rather than by soil storage. It is suggested incorporating soil water storage parameters into the classification at a later stage once the climatic framework is in place for species matching and growth potential. This has the added advantage of being able to introduce factors that affect soil fertility and nutrition at the same time.

Rainfall variability

Although evaporation is fairly constant from year to year rainfall variation is a key consideration affecting the overall risk of the commercial enterprise. Rainfall variability affects growth in two ways; firstly intra-year or seasonal variability which is expressed by monthly rainfall distribution and secondly inter-year variability which is reflected in the long-term rainfall records.

Although Uganda is a relatively small country it has two distinct patterns of seasonal rainfall variability. North of a line (roughly above 1^{o}N), the rainfall distribution is distinctly mono-modal with the bulk of the annual rainfall falling between April to October with one long, hot dry season between November and March. This is one of the reasons for the much higher evaporation rates in the centre and north of the country. In the “south” of the country (roughly below 1^{o}N) the rainfall distribution is distinctly bimodal with rainfall peaking between April and May and again in October to November. Two short dry seasons occur between these periods. The slightly lower mean annual temperatures, absence of extremes and higher humidity due to the presence of Lake Victoria all play a role in the lower potential evaporation rates in the south.

Another important factor affecting species choice and growth potential is inter-year variability of rainfall. Annual rainfall distribution in the tropics has a typically skewed distribution caused by very wet years inflating the mean annual rainfall substantially. Thus average rainfall figures often “hide” the very dry years which nevertheless still occur even in high rainfall environments. Typically the median rainfall, which is often about 10% lower than the mean annual rainfall, is a better indication of rainfall expectation. For example, the Atlas of Uganda (1967) shows a map indicating the “20% probability of mean annual rainfall”. What this map indicates is the mean annual rainfall that is normally exceeded four years in five (or eight years in ten). So far example, if the mean annual rainfall is 1200 mm, it can be expected that 1000 mm can be exceeded four years in ten or looking at it another way, two years in ten can expect less than 1000 mm even though the average rainfall is 1200 mm! This is illustrated in **Figure 5** which shows the relationship between mean annual rainfall (x-axis) and mean annual rainfall that is exceeded four years in five or eight years in ten (y-axis). The 1:1 line been drawn to illustrate how much lower this expectation is compared to mean annual rainfall. The Atlas of Uganda (1967) also shows the expectation of mean annual rainfall nine years in ten and this indicates that one year in ten a drought of less than 750mm per annum can be expected within 80km north of Kampala (just north of Luwero) despite the mean annual rainfall being over 1100mm. This information is of great significance for the commercial forestry enterprise since trees are normally grown over 10 – 20 year rotations depending on species and regime. Now that the rainfall thresholds have been drawn up per climatic zone in **Table 2**, a grower can use **Figure 5** to indicate the likelihood of drought occurring for a given mean annual rainfall and thus give him/her an indication of risk for that area.

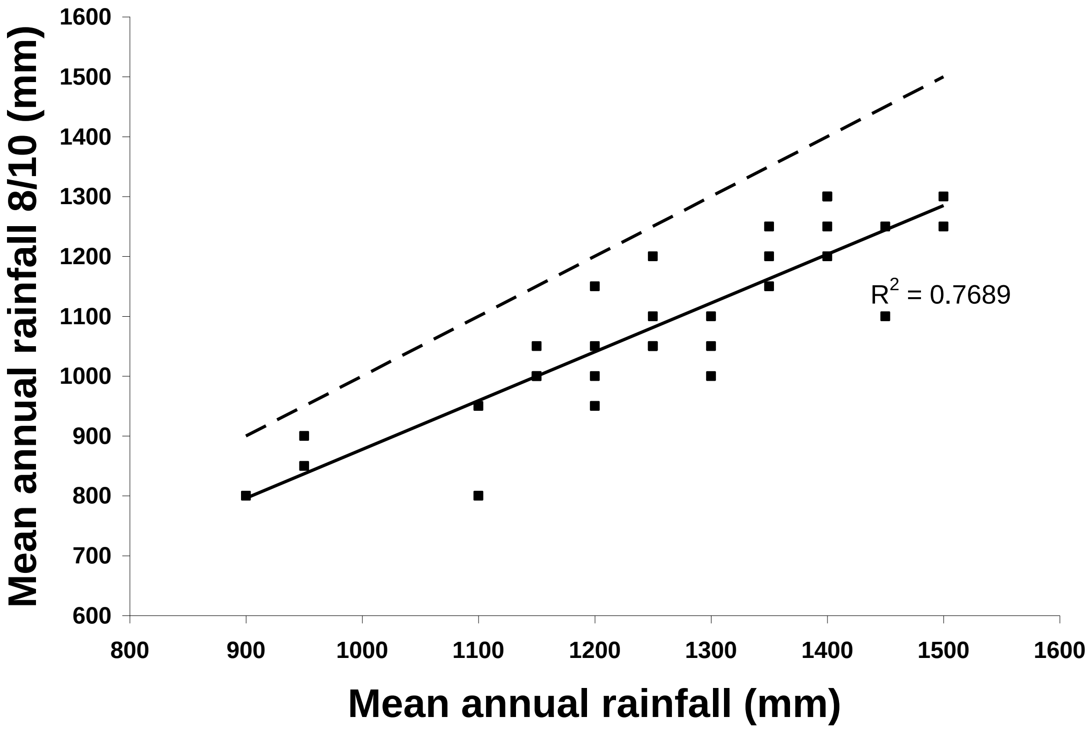

Figure 5: The annual amount of rainfall that will be exceeded 8 years in 10 (y-axis) for a given mean annual rainfall (x-axis). The dotted line indicates the 1:1 line if mean annual rainfall and expectation were the same.

The agro-ecological classification of Uganda

Since it has been used as the basis of the a number of studies, for example the tree biotechnology project (NAFORRI, 2007) and climate change study of the FAO (2010), it is important to evaluate the extent to which this classification reflects meaningful differences in environmental conditions that reflect commercial tree species criteria and forest site productivity.

The site criteria for the agro-ecological zones are very broad (**Table 3**). For example most zones are characterized by an altitude range of between 600 and 1500m. The range of rainfall regimes is less extreme usually varying within 300 – 400m within most zones except zones 4, 7 and 9 which show a rainfall variation of over 600 – 700 mm within one agro-ecological zone. Therefore a very wide range of species and productivity zones will exist in each zone. It is not specified what the temperature range refers to but is most likely the range of mean monthly maximum and minimum temperatures.

Each zone does have a useful description of rainfall season. However, the wide variations in the key parameters that affect species choice and forest site productivity suggest that this classification can only be used on a very broad scale. For example, the extrapolation of the results the *Eucalyptus* clonal hybrid trial series (Epila-Otara and Ndhokero, 2009) to the broad agro-ecological zone based on one trial per zone is very risky considering the variation in key growth parameters within each zone. Whilst the sentiments of Jjumba

(2008) that a minimum number of PSPs be established per agro-ecological zone in order to provide a site index per zone are understandable, the climatic and geographical variation within each agro-ecological zone may result in the latter not being the most effective stratification method to achieve this.

Conclusions

The development of a site classification system for growers in Uganda has a wide range of applications but, in the first instance as a means to assist them in species selection and predicting forest site productivity or growth potential. Such a system must also convey some information to the grower regarding the risk of a forestry enterprise in equal measure to providing knowledge on the benefits that may potentially be realized. This trade off between potential and risk is only possible when site information is properly interpreted. This document attempts to augment a proposed site classification for species selection (presented in the first report) by outlining a basis for predicting forest site productivity in Uganda. A feature of developing countries is the paucity of climatic and site data available to work with. However, it is frequently observed that available data is not always utilised to its full potential due to the lack of a clear vision as to its potential use in a practical forestry management context. This document attempts to show the value of the existing information, however imperfect, in the development of a species/site potential classification for commercial forestry in Uganda. An advantage of the method proposed is that the stratification of sites can be carried out with easily available or measured variables i.e. altitude and latitude (by using a GPS in-field or a topographical map). Although any additional weather information is always valuable, only mean annual rainfall is necessary, while it is possible to calculate MAT and evaporation based on altitude and latitude.

Recommendations and way forward

To be of use to a commercial timber grower, forestry management guidelines have to be presented in an easy-to-use format that provides the key information to assist in making decisions and providing choices that affect the commercial viability of their operation. At the same time a grower need reassurance that the information is of good pedigree and based on good science. Site classification is often a key link in technology transfer and conveying information in user-friendly manner. With this in mind it is suggested to break down the future recommendations into short, medium and long-term goals.

Short term (within 1 year)

As soon as possible SPGS growers need to have access to the site classification in order to have a better feeling of species choice and an indication of growth potential for their area. The successful implementation of the system will depend heavily on whether a grower tries to use it, the degree to which experience and local knowledge is added and the extent to which new information or science is added. The true test is user acceptance and trust.

Implementing the site classification

One of the best ways to see if a system works is to try and implement it. But before boundaries can be located on a map and drawn, a number of steps need to be taken;

- Locate the source of the data used in the production of the agro-ecological zones and obtain digitised copies.
- Digitize and copy the Atlas of Uganda (1967) before it falls apart.
- Use the altitude and latitude relationships to draw up initial boundaries for species zones and productivity classes.
- Develop a plan for implementing, monitoring and collecting daily rainfall and temperature information in key SPGS regions. These could be identified using the site classification.
- Create a basic GIS system to capture, store and present site information.

Obtain better growth data and link to site information

- Geo-reference all PSP plots and other trials of value such as the *Eucalyptus* hybrid trial series. The latter should be done as a matter of urgency before they get felled or thinned.
- Create a single database for all PSPs and standardize models and reference growth data (see last section).
- Ensure standard growth and site information is collected in the new species trials (see last section).

Medium term (within 3 years)

Obtain better site information

- Look to external sources of climate data such as the University of East Anglia Climate Unit.
- Compile and analyse climatic information collected in previous years.
- Determine the usefulness of available soil maps in terms of useful information for management and incorporate into the site classification.

Interpret growth data and link to site information

- Develop correlations between growth potential at specified reference ages for the commercially important plantation species and site conditions by using the PSP and trial information and linking with the site information collected at each site.
- Refine site classes for predicting growth potential.
- Improved growth models for predicting growth of principal species.

Implementing species trials

- Implement new species trials based on the various species and growth potential classes in the site classification.

Long-term (within 5 years)

A useful method of characterising growth potential of a particular area is by conducting site classification by maximum mean annual increment classes (Philip, 1998). Commonly, permanent sample plots are measured to define total volume production, dominant height at a particular age. Maximum mean annual increment volume production (MAI_{max}) is then modelled as a function of age and dominant height. The development of dominant height with age for various site qualities or yield classes can then be constructed in graphical or tabular form. This is the approach used by the British Forestry Commission (Edwards and Christie, 1981; Worrell and Malcolm, 1990). In terms of site studies the approach is useful since dominant height at a reference age (i.e. Site Index) can then be correlated to site factors such as climatic or edaphic variables and built into the growth models at some stage (e.g. Wang and Klinka, 1996; Woollons et al. 1997). Therefore growth prediction can be based on a framework of defining site classes that incorporate site quality. Although it is obviously easier to implement such an approach when good high quality growth data is available or when plantations have been established over many years, it is suggested that ultimately this is the type of outcome that should be sought in Uganda and that any growth data should be viewed through the lens of constructing such tables and models in a site-based framework.

Key requirements in terms of growth and site data

Stand information

- Surviving stems > 5cm dbh.
- Dominant height (the mean height of the 10% largest diameter trees in a plot or 100 largest diameter trees per hectare)
- Dbh and calculate basal area and volume.
- On felling develop tree volume equations for the various species.

Site information

- Accurate geo-referencing
- Altitude
- Monthly & mean annual rainfall.
- Mean annual temperature. If possible mean monthly minimum and maximum.
- Soil depth, horizon depth, texture and organic carbon content per horizon.
- Soil pH, Total N, extractable P (Bray-2), macronutrients (Ca, Mg, K, Na, S) and micronutrients (Co, Cu, Mn & Bo).
- Geology/lithology

References

Alder D, Drichi P and Elungat D (2003). Yields of Eucalyptus and Caribbean Pine in Uganda. *Consultancy report, Uganda Forest Resources Management and Conservation Programme*. Kampala, Uganda.

Atlas of Uganda (1967).

Dagg M, Woodhead T and Rijks DA (1970). Evaporation in East Africa. Bulletin of the International Association of Scientific Hydrology.

Edwards PN and Christie JM (1981). Yield models for forest management. *Forestry Commission Booklet No 49*. HMSO, London.

Epila-Otara JS and Ndhokero J (2009). Selection and site matching of Eucalyptus clones in Uganda. *Journal of East African Natural Resources Management xx: 18 - 25*

FAO (2010). The FAO guidance, intentions and commitment to climate change for Uganda (2010 – 2014). Food and Agriculture Organisation of the United Nations (FAO), Rome.

Government of Uganda (2004). Increasing incomes through exports. A plan for zonal production, agro-processing and marketing for Uganda. Government of Uganda, Kampala, Uganda.

Hardcastle, P.D. (2003). Report on a Silvicultural Classification of Uganda. *Consultant report by LTS International*. Consultancy report commissioned by SPGS, Kampala, Uganda.

Jjumba JN (2008). Assessing the growth and yield of some plantation species in Uganda. Consultancy report commissioned by SPGS, Kampala, Uganda.

Kingston B (1974). A climatic classification for forest management in Uganda. 10th Commonwealth Forestry Conference, September 1974. Forest Department, Entebbe, Uganda.

Kriek W (1970). Performance of indigenous and exotic trees in species trials: Report to the government of Uganda. *United Nations Development Programme Report No. TA 2826*. Food and Agriculture Organisation of the United Nations (FAO), Rome. 162p.

Lawes Agricultural Trust (2007). Genstat Version 10.2. Rothamstead Experimental Station, Wallingford, UK.

NAFORRI (2007). Clonal performance in various agro-ecological zones of Uganda. *Unpublished Report*. National Forest Research Institute, Kampala, Uganda.

Philip MS (1998). Measuring forests and trees. (2nd Edition) CABI International, Wallingford. 338p.

Rijks DA, Owen, W.G. and Hanna, L.W. 1970. Potential evaporation in Uganda. Water Development Dept., Ministry of Mineral and Water Resources, Government of Uganda.

Skovsgaard JP and Vanclay JK (2008). Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands. *Forestry* 81: 13 – 31.

Smith CW, Kassier HW and Cunningham L (2005). The effect of stand density and climatic conditions on the growth and yield of *Eucalyptus grandis. ICFR Bulletin Series 09/2005*. Institute for Commercial Forestry Research. Pietermaritzburg

The Republic of Uganda (2004). Increasing incomes through exports: A plan for zonal agricultural production, agro-processing and marketing for Uganda. Republic of Uganda, Kampala.

Wang GC and Klinka K (1996). Use of synoptic variables in predicting white spruce site index. *Forest Ecology and Management* 80: 95 – 105.

Woollons RC, Snowdon P and Mitchell ND (1997). Augmenting empirical stand projection equations with edaphic and climatic variables. *Forest Ecology and Management* 98: 267 – 275.

Worrell R and Malcolm DC (1990). Productivity of Sitka spruce in northern Britain. *Forestry* 63: 105 – 128.

Table 1: Summary of growth data available for predicting site growth potential

Study	Source of data	Species (no of plots or trials)	Measurements				Site information				Notes
			TPH	Dom height	BA/ Volume	Age	Geo-referenced	Altitude	Temperature	Rainfall	
Kriek (1970)	Species trials	78 trials 52 Pines 16 *Acacias* 59 *Eucalyptus* Many others	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Approximate climatic information only. Rainfall and evaporation used to calculate "humidity" class i.e. rough water balance
Alder et al., (2003)	Permanent and temporary sample plots	*E. grandis (65 PSPs)* *P. caribaea (868 TSPs)*	Yes Yes	Yes Yes	Yes Yes	Yes Yes	No No	No Yes	No No	No Yes	For *P. caribaea* sites identified according to forest reserve.
Epila-Otara and Ndhokero (2009)	*Eucalyptus* clonal hybrid study	*6 x GC clones* *5 x GU clones* *E. grandis TAG 5* *E. grandis LLR* 15 trials	Yes	Only mean height	Tree volume only	3.5 – 4.5 years	No	No	No	No	Approximate locations only. Selections done on tree volume but did not take into account stocking.
Jjumba (2008)	SPGS PSPs	*E. grandis* *P. caribaea* *P. oocarpa* *P. patula* *M. eminii*	Yes	Yes	No	2004 - 2006	No	No	No	No	Sites related to Agro-ecological zones Dominant height defined as maximum height

Table 2: A preliminary delineation of productivity zones as defined by rainfall thresholds for site classes based on mean annual temperature, altitude and potential evaporation. Due to the relationship between potential evaporation and latitude, rainfall thresholds are latitude dependent. This delineation is for 1^{o}N latitude

Climate zone	Warm temperate			Sub-tropical			Tropical			
MAT (^{o}C)	16 - 17	17 - 18	18 - 19	19 - 20	20 - 21	21 - 22	22 - 23	23 - 24	24 - 25	25 - 26
Latitude 1^{o}										
Altitude (m)	1970 - 1820	1820 - 1680	1680 - 1530	1530 - 1400	1400 - 1250	1250 - 1110	1110 - 970	970 - 820	820 - 680	680 - 540
Evaporation (mm)	1330	1420	1500	1580	1660	1750	1830	1910	1990	2070
Productivity zone	Rainfall thresholds (mm)									
High	> 1000	> 1060	> 1120	> 1190	> 1250	> 1310	> 1370	> 1430	> 1500	> 1560
Moderate	870 - 1020	920 - 1060	970 - 1120	1030 - 1190	1080 - 1250	1130 - 1310	1190 - 1370	1240 - 1430	1300 - 1500	1350 - 1560
Low	740 - 870	780 - 920	820 - 970	870 - 1030	910 - 1080	960 - 1130	1000 - 1190	1050 - 1240	1100 - 1300	1140 - 1350
Not suitable	< 740	< 780	< 820	< 870	< 910	< 960	< 1000	< 1050	< 1100	< 1140

Table 3: Site characteristics of Agro-ecological zones

Zone	Description	Altitude (m)	Temperature range (^{o}C)	Average rainfall and range (mm)	Rainfall season	Terrain	Soils
1	NE drylands	351 - 1524	12.5 – 32.5	745 (600 – 1000)	April - Sept	Generally flat with isolated hills	Moderate to poor
2	NE savannah grasslands	975 - 1524	15.0 – 32.5	1197 (1000 – 1300)	April - October	Generally flat with isolated hills	Moderate to poor
3	NW savannah grasslands	351 - 1341	15.0 – 25.0	1355 (1200 – 1500)	April - Nov	Generally flat with undulating hills	Good to moderate
4	Para savannahs	351 - 1341	17.5 – 32.5	1259 (800 – 1500)	March - Nov	Generally flat with undulating hills	Good to moderate
5	Kyoga plains	914 - 1400	15.0 – 32.5	1272 (1215 – 1328)	March – Nov (N) March – May (S) August – Nov (S)	Land flat and swampy	Poor - moderate
6	Lake Victoria crescent	1000 - 1800	15.0 – 30.0	1325 (1200 – 1450)	March – May August – Nov (E) Oct – Dec (W)	Undulating, hilly with flat wetland areas	Good - moderate
7	W savannah grasslands	621 - 1585	15.0 – 30.0	1270 (800 – 1400)	March – May August – Nov	n/a	Good - moderate
8	Pastoral rangelands	129 - 1524	12.5 – 30.0	968 (915 – 1021)	March – May Sept – Dec	Rolling hills with some flat areas	Moderate - poor
9	SW farmlands	129 – 1524	12.5 – 30.0	1175 (800 – 1500)	March – May August – Nov	Hilly	
10	Highland ranges	1299 - 3962	7.5 – 27.5	> 1400	March - Oct	Hilly to mountainous	Very good