Kyoto Mechanism and the Conservation of Tropical Forest Ecosystem
T. Okuda, Y. Matsumoto (Eds.), 2004

Using Bioclimatic Analysis to Assist Tropical Reforestation for Biodiversity and Carbon Sequestration Benefits

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Abstract
The Clean Development Mechanism of the Kyoto Protocol may provide some financial support for reforestation of tropical forest areas. This paper outlines bioclimatic analysis methods that can assist in identifying suitable species and areas for reforestation. Bioclimatic analysis methods can assist not only in identifying the potential distributions of tree species, but also the distributions of other plant and animal species important for biodiversity conservation.

1. Introduction

There have been dramatic losses of tropical forests in the last fifty years (Collins et al. 1991; Achard et al. 2002, Kashio, in press). It is hoped that the Clean Development Mechanism (CDM) of the Kyoto Protocol (Kirschbaum 2003), or some similar future arrangement, will provide financial incentives to encourage tree plantings to create carbon sinks and other co-benefits in developing countries. Restoration of forests for biodiversity conservation, perhaps with some limited selective logging for production of high value timbers, is an appealing CDM option as the forests may have greater long-term carbon sequestration benefits than short rotation plantations.

Whether tropical forest areas are to be restored primarily for biodiversity or commercial timber production it will be important to identify suitable species and areas for reforestation. Several years ago a global climatological audit of forest resources was proposed that would address the problems of climate change, conservation and deforestation (Booth 1991). Key objectives of the proposal, which could be built up from analyses of individual countries or regions, were as follows:

a) To develop interpolation relationships to allow mean climatic conditions to be reliably estimated for any location within a region of interest,
b) To collate information on tree species' natural distributions,
c) To collate information on trials of tree species outside their natural distributions,
d) To use information from natural distributions as well as trials to develop descriptions of tree species' climatic requirements, and
e) To develop climatic mapping programs to show where the species could be grown.

It was proposed that PhD candidates could carry out these stages for individual countries within about three years.

This paper outlines some of the progress that has been made in the last 12 years in the areas outlined above. The first section outlines one of the most complete demonstrations of

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the method showing how it can assist developing plans to restore dipterocarp forests in the Philippines. The following sections consider progress within each of the five stages outlined above. An example of work on forest seed deployment zones in Vietnam provides another example of how the five stages can be combined in one study. Issues such as sustainability and the development of criteria and indicators to monitor progress towards sustainability objectives are considered in the discussion.

2. Restoration of Philippine Dipterocarp Forest Ecosystems

Pangahas (2003) has used bioclimatic analysis methods to identify some priority areas for forest restoration in the Philippines. She developed long-term mean monthly interpolation relationships for temperature and precipitation using the ANUSPLIN package (Hutchinson 1999). These relationships enabled mean climatic conditions to be estimated reliably for any location in the Philippines. Geocoded (i.e. latitude, longitude and elevation) data describing the natural distributions of seven *Shorea* and *Parashorea* species were collated. Between 22 and 43 locational observations were obtained for each species. The BIOCLIM program conceived by Nix (1986) was used to estimate mean climatic conditions for 16 factors, such as mean annual temperature and precipitation of the driest quarter, at each of these locations and to thus determine the range of climatic conditions suitable for each species. GIS programs were used to map climatically suitable areas for each species for hundreds of locations across the Philippines by comparing the species' requirements with climatic conditions estimated for an approximately one kilometre grid across the whole country. These maps show core areas, which would be high priority for reforestation, as well as the broader range of areas climatically suitable for planting the selected species. The maps showing areas potentially suitable for species planting were also compared with maps of existing land use. Brushland areas, adjacent to existing forests but not entirely devoid of forest cover, provide good opportunities for reforestation projects to link existing forest remnants.

Though the Pangahas (2003) work is one of the most detailed applications of bioclimatology to tropical forest restoration there are several other pieces of work that could potentially contribute to addressing the problem.

3. Climatic Interpolation Relationships

The ability to estimate mean climatic conditions at any location within a country or region is fundamental to modern bioclimatic analysis methods. There has been considerable progress in the last 12 years in the development of interpolation relationships across the whole world including tropical areas. For example, Zuo et al. (1996) described the development of a mean monthly interpolated climatic database for China and mainland Southeast Asia. This includes tropical forest areas in southern China (e.g. parts of Hainan Island) as well as in Vietnam, Laos, Cambodia, Thailand and Peninsular Malaysia. Interpolation relationships have also been developed for Indonesia (Jovanovic and Booth 1996). These relationships could be used by programs such as BIOCLIM to analyse the climatic characteristics of South East Asian tree species in a similar way to the methods used by Pangahas (2003) for *Shorea* species in the Philippines.

Tropical forest areas in Africa were included in a continental analysis developed by Hutchinson et al. (1995). The interpolated data have only been released in the form of a gridded database at 0.05 degree resolution for monthly mean values of precipitation, daily maximum temperature and daily minimum temperature. The interpolation relationships used to create these grids could be used in the BIOCLIM program to analyse the distributions of species in Africa's tropical forests.

Climatic interpolation relationships for Central and South America have been developed by Jones and Gladkov (1999) as part of their FloraMap package. Geocoded data describing species distributions can be entered into the package, the genotype's climatic requirements are determined and maps are generated showing climatically suitable areas. The program uses fourier transforms and principal component analysis, which are more sophisticated than the BIOCLIM analysis. However, the basic concept is similar and could easily be applied to tropical tree species native to the Neotropics.

The Food and Agriculture Organisation has developed the LocClim (local climate) program (Grieser 2002) to provide an estimate of climatic conditions at locations in the developing world for which no observations are available. The program could be used to develop descriptions of species climatic requirements in areas where more sophisticated interpolation relationships are not available. The program interpolates using data from 28,800 stations included in the global agroclimatic database maintained by the Agrometeorology Group of FAO. Estimates of monthly, 10-daily and daily values of common climate variables can be produced. The variables include daily maximum, mean and minimum temperature, as well as precipitation, potential evaporation, sunshine fraction, windspeed and water vapour pressure. They are given together with error estimates, using a number of options to correct for regional variability, altitude dependency and horizontal gradients of the variables.

4. Data on Tropical Tree Species Natural Distributions

4.1. Some geocoded distribution records for tropical tree species are now available online.

For instance, Pangahas (2003) obtained records from the *Dipterocarpaceae* database at the Royal Botanic Gardens Edinburgh (www.rbge.org.uk). This includes records of specimens held at the RBGE and Royal Botanic Gardens Kew as well as the Rijksherbarium, Leiden and the State University of Utrecht. However, to obtain at least 20 location records for each species, Pangahas (2003) had to seek further data from the Philippine National Herbarium as well as herbaria in the United States and Australia.

5. Data on Trials of Tropical Tree Species outside Their Natural Distributions

The Center for International Forestry Research (CIFOR) began the development of the Tree Growth and Permanent Plot Information System (TROPIS, www.cifor.cgiar.org/publications/Html/AR-98/TROPIS.html) in the late 1990s (Vanclay 1998). The system is a metadatabase, or database of databases. It does not include primary data, but summarises where trial data have been gathered for particular species. It is designed to enable researchers to make contact with people working on particular species.

6. Descriptions of Tree Species Climatic Requirements

Descriptions of species climatic requirements are developed by estimating mean climatic conditions for a number of locations. For example, Booth (1985) collated latitude, longitude and elevation data for 84 sites of *Eucalyptus citriodora* in subtropical areas of Australia. For each of the 84 locations the BIOCLIM package was used to estimate 12 key climatic factors such as mean annual temperature and mean annual precipitation. Taking the hottest and coldest locations for mean annual temperature and the wettest and driest locations for mean annual rainfall starts to define the climatic requirements of the species. Determining these ranges for all the factors describes the species climatic envelope. If desired, percentile values can be used rather than the highest and lowest values to describe the climatic requirements of the species, based on an analysis of its natural distribution. Booth et al. (1988) showed how data from 17 successful *E. citriodora* trial sites in Africa could be used to refine the description of where the species might grow as an introduced species. Jovanovic and Booth (2002) analysed the climatic requirements of 27 eucalypt species using both natural distribution and trial information and mapped climatically suitable areas for planting in Australia.

Since 1991 probably the most significant development in tree species climatic requirements has been the preparation of the CAB International (2003) Forestry Compendium CD-ROM (www.cabicompendium.org/fc). This includes descriptions of the climatic requirements of 1200 species from all around the world, including many species native to tropical areas. These descriptions include the following climatic factors:

a) Mean annual rainfall (mm)
b) Rainfall regime (summer, uniform or winter)
c) Dry season length (consecutive months below 40 mm)
d) Mean maximum temperature of the hottest month (^{o}C)
e) Mean minimum temperature of the coldest month (^{o}C), and
f) Mean annual temperature (^{o}C)

This small group of factors is adequate for describing areas to which species may be introduced. A larger numbers of factors, such as the 16 factors used by Pangahas (2003), are generally required to describe a species' natural distribution reliably.

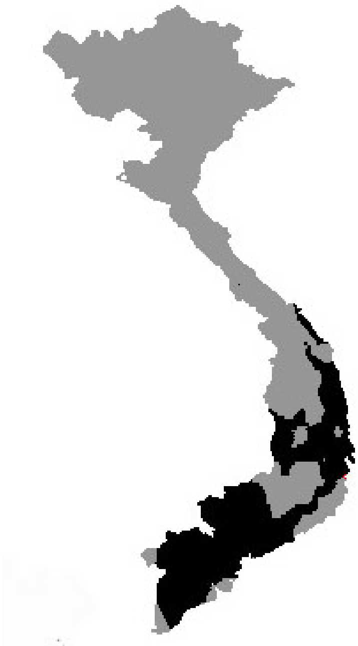

Fig. 1 Output from VIET climatic mapping program showing areas climatically suitable for *Dipterocarpus alatus* in black.

7. Climatic Mapping Programs

Climatic mapping programs use data from sources such as the CABI (2003) Forestry Compendium and show climatically suitable areas for growing particular species. CSIRO has developed climatic mapping programs for major regions such as mainland South East Asia, South America and Africa, as well as for individual countries such as the Philippines, Indonesia, Australia and Zimbabwe (see several papers in Booth 1996). Booth et al. (2002) have described a world climatic mapping program.

8. Forest Seed Deployment Zones in Vietnam

Work carried out in Vietnam by CSIRO for the Danish aid agency Danida demonstrates how climatic analysis could assist reforestation for carbon sequestration and biodiversity benefits in tropical areas. One of the aims of Danida's Vietnam Tree Seed Project is to promote higher species diversity in planting programmes, particularly through the use of native species. The old ecological zonation used by the project to assist seed selection simply divided the country into ten units.

To develop a new zoning system Booth et al. (2002) used monthly mean values of daily maximum temperature, daily minimum temperature and precipitation from 173 meteorological stations across Vietnam. The ANUSPLIN program was used to develop interpolation relationships and mean climatic conditions were estimated for a grid of nearly 17 000 locations across Vietnam. A mapping program was developed that can take in descriptions of the six climatic factors used in the CABI (2003) Forestry Compendium and show areas climatically suitable for growing particular species. Using the VIET climatic mapping program, as well as information about natural distributions and planting experiences of local organisations over many years, Dr Nguyen Hoang Nghia (Forest Science Institute of Vietnam) developed preliminary descriptions of the climatic requirements of 40 species, including 10 exotic species and 30 species native to Vietnam (see Figure 1). Simple descriptions of soil requirements were also prepared by Dr Nghia to assist species selection for particular sites, but soil data are not available for the 17 000 locations included in the climatic mapping program.

9. Discussion

Though no coordinated global climatological audit of forest resources as proposed by Booth (1991) has been undertaken, considerable progress has been made towards realising the objectives of the project proposal. Considering each of the objectives listed in the introduction the following progress has been made:

a) Climatic interpolation relationships are available for most parts of the world,
b) Many records of tree species natural distributions are available online,
c) The TROPIS database (Vanclay 1998) provides access to the results of many forestry trials,
d) The CABI (2003) Forestry Compendium provides descriptions of the climatic requirements of hundreds of tree species, and
e) Climatic mapping programs are available for most parts of the world.

In particular the work of Pangahas (2003) shows how detailed bioclimatic analysis can assist planning for tropical forest restoration. Identifying climatically appropriate locations for planting particular tropical tree species can make a small but significant contribution to establishing sustainable systems.

It's important to realise that bioclimatic analyses can assist with determining natural distributions not only of tropical tree species, but also other plant species as well as animal species, including highly mobile animals such as birds and mammals. For example, the BioRap package of tools (http://incres.anu.edu.au/biorap/) uses BIOCLIM-based tools to enable rapid assessment of biodiversity priority areas (Margules and Redhead 1995) and has been applied in Papua New Guinea (Nix et al. 2000).

BIOCLIM and other bioclimatic analysis methods can also be used to assess the likely effects of climatic change on flora and fauna. For example, descriptions of species' climatic requirements can be prepared in the usual way (see, for example, Booth 1985), and predictions of likely future distributions can then be mapped using grid-based databases including predicted climatic changes rather than current conditions (see, for example, Busby 1988). Williams et al. (2003) used bioclimatic analysis to predict significant reductions or complete loss of environment for all regionally endemic vertebrates in Australian tropical rainforests. Globally, Thomas et al. (2004) used bioclimatic analysis based on species-area relationships to predict species losses in tropical forests due to climate change up to 2050 at 4%, which is considerably less than in some other major biomes, but is occurring in particularly species rich areas and is additional to an extinction rate of 6.3% due to forest clearing. Bioclimatic analysis could be used to help select areas for restoration where species are at less risk of climate change. For example, if the aim is to conserve a particular dipterocarp species, restoration of the core areas identified by Pangahas (2003) may be preferable to areas at the warmer end of its distribution.

The use of bioclimatic analysis has its critics who correctly point out that other factors, such as species biotic interactions, can influence species distributions (Davis et al. 1998). There is a role for more complex dynamic landscape models, which can simulate interactions between species, to be used for detailed studies of particular areas (see, for example, Mackey and Su, in press). However, bioclimatic analysis methods are much simpler to apply. Pearson and Dawson (2003) have listed several alternative methods of bioclimatic analysis and concluded that they can provide a useful first approximation of species distributions.

Soil information can, of course, also help to account for plant species distribution, but it has been suggested that soil mapping at scales as fine as 1:5000 is required (Sollins 1998), so climatic analysis is better suited to identifying broad areas for reforestation. Soil assessments, along with social and economic considerations, may then assist in making the final selections of areas for reforestation within the broad priority areas identified using bioclimatic analyses.

Establishing sustainable tropical forestry systems, that may need to meet both commercial and environmental objectives, is complex. It requires the alignment of key attributes including ecological capacity of site, soil, water and environmental values as well as management intensity and economic benefit. Systems in which these variables are well aligned will have a low risk of failure and should be sustainable. Booth and Nambiar (2000) have discussed these issues in relation to plantation forestry in the tropics. A book on "Management of Soil, Nutrients and Water in Tropical Plantation Forests" (Nambiar and Brown 1997) considers many of the issues in detail. An international collaborative project coordinated by CIFOR is helping to apply the principles outlined in the book to develop sustainable tropical plantation forestry systems (Nambiar et al. 1999, 2000). Many of the ideas are also applicable to the management of natural tropical forest systems. For example, issues such as soil compaction and retention of nutrients on-site are likely to be important issues influencing the sustainability of natural as well as plantation forests.

To harmonise CDM and ecosystem conservation activities, criteria and indicators which describe and measure important forest values may need to be developed (CIFOR 1999, Prasad 2001, Raison et al. 2001). Example principles might involve statements such as "CDM projects are located in areas most likely to complement the biodiversity value of existing forest remnants" and "CDM projects are conducive to sustainable forest management". Sustainability objectives can be expressed in terms of C&I that describe important forest values. The bioclimatic and plantation sustainability work outlined here could help to provide practical analysis methods to underpin some of the criteria and indicators.

Restoring even a small fraction of the tropical forests lost over the last 50 years will involve extremely complex social, economic and ecological research issues (Okuda and Ashton 2003). However, there can be few ecological activities that are more important for the health of the planet. It is hoped that the CDM, or a similar future carbon sequestration instrument, can make a contribution to encouraging the restoration of some tropical forest ecosystems.

Acknowledgements

I'm very grateful to the symposium organisers for the invitation to attend this meeting and to the sponsoring agencies for supporting my attendance. John Raison and Nico Marcar provided helpful comments on the manuscript.

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