Agro-climatic classification systems for estimating the global distribution of livestock numbers and commodities

David H White[1], Godfrey Lubulwa[2], Heping Zuo[3], William Wint[4] and Jan Slingenbergh[5]

[1] ASIT Consulting, PO Box 328, Hawker, ACT 2614, Australia
[2] Australian Centre for International Agricultural Research, GPO Box 1571, Canberra, ACT 2601, Australia
[3] National Land and Water Resources Audit, GPO Box 2182, Canberra, ACT 2601, Australia
[4] Environmental Research Group Oxford (ERGO), PO Box 346, Oxford, OX1 3QE, England
[5] Animal Production and Health Division, Food and Agricultural Organization of the United Nations (FAO),
Viale delle Termi di Caracella, 00100 Rome, Italy

Abstract Investment in agricultural research in developing countries is being increasingly targeted at those agro-climatic zones and issues where the economic and environmental benefits may be expected to be greatest. This first requires that the zones themselves be defined, along with information on domestic livestock numbers and commodity output within agro-climatic zones in different countries. Different methods for classifying agro-climatic zones were compared. These included methods based on estimated length of growing period (LGP) using rainfall and temperature data, the ratio of precipitation to potential evapotranspiration, and on more detailed agronomic models, remote sensing data and land use information. Zonation based on LGP has already been linked to existing national livestock data. By defining agro-climatic zones and relating concentrations of livestock populations to those of humans, it is possible to make realistic estimates of livestock populations and the production of livestock commodities for most developing countries. Detailed agro-climatic analyses of mainland east Asia and Sri Lanka have recently been undertaken using the GROWEST agronomic model. Using this model as the basis of agro-climatic classification appears to be significantly superior, particularly in temperate environments, to approaches based solely on LGP. Different ways of subdividing countries and continents into agro-climatic or agro-ecological zones are reviewed in this paper. In addition, we show how the numbers of, production and commodities from domestic livestock can be allocated to such zones. We also indicate how some of this information can be applied.

1. INTRODUCTION

This paper describes the first stage of a larger study aimed at developing a global livestock commodities database and technology transfer matrices [White 1998] to help improve the allocation of research resources by the Australian Centre for International Agricultural Research. ACIAR aims to aid agricultural production within developing countries, whilst being fully aware that the more research funds it invests on say improving livestock health or production, the less it can invest on fisheries, forestry and crops [Davis and Lubulwa 1995].

Agro-climatic and agro-ecological zonation schemes are standard tools for prioritising agricultural research because they offer relevant, available information about target environments [Corbett 1996]. A proper description of the target environment also enables research efforts to be more clearly focussed at local issues and needs.

Agro-climatic zones or regions have a characteristic inter-relationship between agronomy or farming systems and climate. Agro-ecological regions have a characteristic inter-relationship between agronomy or farming systems and various environmental features, not just climate. These definitions have been adopted by Australia's SCARM (Standing Committee on Agriculture and Resource Management) Working Group on Sustainable Agriculture.

2. AGRO-CLIMATIC AND AGRO-ECOLOGICAL CLASSIFICATION SYSTEMS

The number of bioclimatic, agro-climatic, ecoclimatic and biogeographic classifications is very large [Le Houérou *et al.* 1993]. Some are of general use while others are focussed towards particular global regions.

2.1 Köppen climate classification system

Until recently the most widely used system of climate classification has been that of the German climatologist Köppen [1936]. The Köppen (or Koeppen) classification is based on monthly rainfall and temperatures, including the following five inputs: average temperature of the warmest month; average temperature of the coldest month; average thermal amplitude between the coldest and warmest months; number of months with temperature exceeding 10°C; winter and summer rains.

Le Houérou *et al.* [1993] and others rejected the Köppen [1936] and similar classifications because they were based on the 'empirical and somewhat obsolete, albeit fairly efficient, relationship between precipitation and temperature as a criterion of water stress/water availability, and on mean annual temperature as a criterion of cold or heat stress, which lacks accuracy, sensitivity and efficiency'. In summary, the Köppen system is a static, empirically based descriptive system that was appropriate for the pre-computer era.

2.2 Agro-bioclimatic classification of Africa

Regions in Africa have been categorised using simple, rational and reliable parameters to represent water and temperature requirements and constraints [Le Houérou *et al.* 1993]. The discriminating values of these parameters were selected on the basis of agronomic and ecological criteria of the distribution of native vegetation, wildlife, crops and livestock.

This classification combines a rather large number of climatic, biological, agronomic and geographic criteria. The actual number of occurring combinations is about 200. Some of these occupy very large areas, such as the hyper-humid equatorial lowlands (~9 million km^2), or the extra-tropical, winter rainfall, cold hyper-arid lands (~5 million km^2).

The large number of classes in this classification system was found to be impractical for use in estimating the benefits within and between regions and countries from agricultural research. It also requires a digitised dataset containing the boundaries and details of the wide range of agro-ecosystems. Considerable resources would be required to apply it to other regions of the world.

2.3 Classification based on length of growing period

Probably the first serious attempt to use computers to help integrate climate, soil and plant information in order to determine agro-ecological zones throughout the world was that reported by FAO [1978-81]. Agro-ecological zones were determined by overlaying climatic inventories for different sites on soils maps, soil characteristics being used to provide an assessment of land suitability for different crops. Climate data were used to estimate the length of the growing period (LGP), the time available when water and temperature permit plant growth, based on estimates of soil water balance. For a crop to be growing it was assumed that monthly rainfall had to at least equal 50 *per cent* of potential evapotranspiration (PET) for crop growth to be achieved, and that the mean daily temperature during the growing period had to exceed 5°C. The distinction was made between the humid and non-humid parts of the year, according to when precipitation exceeded PET.

A new approach to LGP-modelling better integrates temperature- and moisture-related constraints and makes the concept more suitable for a global climatic resources inventory [Fischer *et al.* 1995]. The temperature threshold for a growing period remains, as in the standard LGP approach, a mean temperature of 5°C, but moisture depletion rates are treated as a function of moisture availability. Allowance is also made for the fact that in temperate and cold areas rainfall can be in the form of snow.

2.4 Agro-climatic classification for Mainland East Asia

Mainland East Asia, as classified by Zuo [1996], includes the countries of China, Vietnam, Laos, Thailand, Kampuchea and Peninsula Malaysia. These are some of the most densely populated areas in the world. With more than one fifth of the world's population living on less than one tenth of the world's land, in areas mostly covered by high mountains, plateaux and deserts, the resource deficiencies are often obvious and very serious.

A Geographic Information System (GIS)-based agro-climatic classification was developed for Mainland East Asia [Zuo 1996; Zuo *et al.* 1996a, 1996b]. This was based on regular grid data sets at a resolution of 1/20th degree and agro-climatic indices simulated by a general plant growth model GROWEST [Fitzpatrick and Nix 1970; Nix 1981]. These indices represented plant growth responses to light, temperature and moisture. The climatic data sets were developed using climatic surfaces interpolated by ANUSPLIN [Hutchinson 1984, 1991] and a digital elevation model (DEM) calculated using ANUDEM [Hutchinson 1989a, 1989b]. The classification attributes were all those simulated using the GROWEST model at a weekly time-step for each of the grid cells across Mainland East Asia. Thirty-nine GROWEST attributes were selected as classificatory variables for each grid cell. Fourteen agro-climatic zones were developed using the ALOC module of the numerical taxonomy package PATN [Belbin 1987].

Growth Degree Days (GDDs) were important in refining these categories. These help to discriminate between plants that have different temperature requirements in reaching maturity. GDD values were calculated by Zuo [1996] for mesotherm, megatherm C$_3$ and megatherm C$_4$ plant groups using mean daily temperatures for the number of days that the recorded mean temperature was within the temperature range bounded by the low and high temperature thresholds of the plant for growth. The temperature values were the mean daily temperatures simulated for each weekly time step accumulated during the growth period within the predefined temperature range. Zuo used ranges of 3°C to 35°C for mesotherm plants with an optimum temperature for growth of 19°C; 8°C to 40°C for megatherm C$_3$ plants with an optimum temperature of 28°C; and 10°C to 45°C for megatherm C$_4$ plants with an optimum temperature of 32°C.

This method has defined agro-climatic zones that have varying suitability for a range of agricultural systems and that are consistent with mapped vegetation patterns of Mainland East Asia. A similar classification has been done for Sri Lanka [Kannangara 1998].

3. RELATING LIVESTOCK DATA TO AGRO-CLIMATIC ZONES

3.1 FAO livestock classification system

FAO has been evaluating a livestock system classification using three clusters based primarily on length of growing period and temperature [Seré *et al.* 1996]. These are arid and semi-arid (less than 180 growing days); humid and sub-humid (more than 180 growing days); and temperate and highland (temperature constraint). It is therefore a coarse aggregation of the LGP concept. Three livestock production systems: grazing systems; mixed rainfed systems; mixed irrigated; equals 3 x 3 = 9 land-based systems. Two land-detached systems for monogastrics and ruminants were also included. For the purposes of the study of White [1998], having only three clusters based on length of growing days and temperature was considered too coarse a level of aggregation.

Ruminant animals are, of course, more strongly influenced by agro-ecological conditions than non-ruminants Thus the arid and semi-arid zones of sub-Saharan Africa, which together have 54 *per cent* of the land area, account for 57 *per cent* of the ruminant livestock measured in tropical livestock units (TLU) [Anon 1992]. The humid zone, making up 19 *per cent* of the land mass, has 6 *per cent* of ruminant TLUs. The largest share of goats (38 *per cent*) and sheep (34 *per cent*) and nearly all of the camels are found in the arid zone. Most cattle are in the semi-arid zone (31 *per cent*) and the sub-humid zone (23 *per cent*). Pigs are mostly found in the humid and sub-humid zones. Poultry are evenly distributed over all zones except the arid zone. Pigs and poultry are also produced in intensive commercial livestock systems that are influenced more by proximity to population centres and ports than by agro-ecological conditions.

3.2 Quantitative framework of global livestock production

FAO Animal Production and Health (AGA) Officers have been engaged in defining a global, quantitative analysis framework for livestock systems and associated livestock mapping software applications [FAO 1996a, 1996b; Slingenbergh and Wint 1997].

Many of the Division's current activities require at least a continental, but preferably global, appreciation of livestock distributions in relation to agro-ecological factors and human demographic patterns. A consultancy involving ERGO was used to explore and demonstrate the possibilities of using GIS techniques to produce a data base containing information on global livestock distributions, human demographic data, and agro-ecological information [FAO 1996a, 1996b]. This enables maps to be derived from these data; and possible avenues for future development to be investigated.

FAO animal population data are available only for whole countries, and not for agro-ecological zones within national boundaries. In contrast, global human population data are available, in image format, at a resolution of approximately 10 km^2. By applying image processing and GIS techniques, these can be used to produce human population numbers for each agro-ecological zone (AEZ) within each country.

There is a close statistical link between livestock numbers and human population levels within continents that can be quantified for each continent using regression analyses on the national data. These relationships have been applied to the AEZ human population data to predict animal biomass in each AEZ. It is then a relatively simple step to estimate the numbers of each domestic livestock species within each AEZ. In this way maps of the global distribution of cattle, sheep, goats, pigs and chickens, and commodities from these, have been produced [FAO 1996b].

3.3 Remote sensing studies in Africa

The work of Wint and colleagues on African ecozones and farming systems is continuing [FAO 1997, 1998]. Satellite data of land-surface and atmospheric characteristics are being used in the search for more ecologically based criteria for zonation, including:

a) the Normalised Difference Vegetation Index (NDVI), commonly used as an indicator of vegetation cover;

b) a measure of ground surface temperature, derived from one of the thermal infra-red channels (Channel 4; 10 day composite) on the satellite platform (NOAA AVHRR data; 1km x 1km resolution) by the NASA Global Inventory Monitoring and Modelling Systems (GIMMS) group; and

c) a measure of surface rainfall, the Cold Cloud Duration (CCD), derived from the METEOSAT satellite (8 km x 8 km resolution).

In addition, Digital Elevation Model (DEM) data were obtained from a 0.083 degree resolution elevation surface for Africa, produced by the Global Land Information System (GLIS) of the United States Geological Survey, Earth Resources Observation Systems (USGS, EROS) data centre.

Farming systems in Kenya have corresponded quite closely with ecological zonations based on length of growing period [FAO 1998]. Two sets of ecozones were identified, one with 11 zones and the other with 16 zones. The major effect of increasing the number of zones was to split the drier areas into more categories. Elevation was found to be an important determinant of the ecozones, but as Hutchinson [1989a, 1991] has shown, that would primarily be through its impact on rainfall and temperature, the influence varying with latitude.

For example, the most consistent predictors of cropping percentage in Kenya and Ethiopia appear to be human population number and elevation, as befits heavily populated areas concentrated in extensive highlands [FAO 1997]. In Somalia, Sudan and Uganda, the predictors are more diverse, with rainfall and to a lesser extent vegetation cover being common determinants of farming systems.

Length of growing period relates closely to the satellite-derived ecozones [FAO 1998]. The primary discriminating predictors were maximum temperature, minimum rainfall, mean NDVI and elevation, with the remainder being largely rainfall related. The AVHRR data were able to discern relatively slight variations within more arid areas, but were comparatively poor in discriminating between zones in the higher rainfall areas.

3.4 Cattle density distribution in Africa

The International Livestock Research Institute (ILRI) in Nairobi has been collecting country-level cattle census data to create livestock distribution maps, starting with a cattle density layer for a GIS of sub-Saharan Africa [Kruska *et al.* 1995]. The primary aim is to obtain information on the distribution of host populations (such as cattle) to aid animal health studies. They now have cattle density distribution data for sub-Saharan Africa, more-or-less at the third administrative level (depending on country), held as an integer type file in ARC/INFO GRID format. The cattle density layer continues to be improved as new information becomes available.

ILRI is currently starting to put together crop and livestock distribution coverages for eastern and southern Africa [P. Thornton, pers. comm.]. Given that ILRI now has a global mandate, it is interested in obtaining similar crop and livestock coverages for Asia.

3.5 Estimating technology spillovers between zones

The ACIAR study [White 1998] used six agro-climatic zones classified according to the estimated length of the growing period (LGP). These zones were designated desert, arid, semi-arid, dry sub-humid, moist sub-humid and humid [FAO 1996a, 1996b; Slingenbergh and Wint 1997]. This approach is consistent with ongoing work by FAO and others on LGP, complemented by satellite and other data, and estimates of total livestock biomass [Slingenbergh and Wint 1997].

FAO and ERGO [Wint, pers. comm.] kindly provided estimates of total livestock biomass for each domesticated livestock species within each agro-ecological zone within each country in an Excel worksheet. Whereas the FAO [1996a, 1996b] studies were based on national data on livestock numbers for 1994, White [1998] used national data for 1996 from the FAO Waicent database. A series of 20 spreadsheets was prepared containing estimates of livestock numbers, productivity (meat, wool, milk, eggs) and manure production within different agro-climatic zones in each country. White [1998] assumed that the proportions of each livestock species within each agro-climatic zone would be the same as in the FAO studies.

Quantitative estimates were made of pre-harvest and post-harvest technology spillovers from one agro-climatic zone to another [White 1998]. The distinction was made between agronomic, animal health and animal production technologies with ruminants, and between health and production with pigs and poultry. Post-harvest technology spillovers tended to be more independent of agro-climatic zone, so that technology benefits could flow more easily between zones. Perishable livestock products presented greater challenges in terms of technology spillovers between climatically dissimilar zones than relatively enduring products such as wool.

Estimates were also made of the basic and adaptive research capability to assist agriculture in 50 countries and regions, particularly focussing on Asia and Africa. This included summarising details on agricultural research, animal health services, and expenditure on education in most countries around the world.

The next stage involves estimating the economic significance of these spillovers, assuming that there is a 5 *per cent* reduction in costs from employing a new technology [Lubulwa *et al.*, in preparation]. Emphasis will then be on determining the likely economic benefits from specific technologies.

4. OPPORTUNITIES FOR FUTURE RESEARCH

Opportunities for and constraints to improving the productivity, sustainability and viability of farming systems are often specific to particular agro-climatic (and agro-ecological) zones. Most of these zones traverse many countries, so that research that is relevant to a particular zone and country may well be relevant to many other countries. It is therefore important that the boundaries of the different zones, and the soil and vegetation types, livestock populations and human activities associated with each zone, are clearly defined and documented. The advent of new technologies such as remote sensing and geographic information systems are powerful tools for facilitating this process.

National and regional data are not necessarily accurate, and whilst they are the best available, some efforts should be made to gather field information to substantiate them. This is because wide ranging decisions are likely to be based on this information, and on studies such as this one that have relied heavily on FAO and associated data. There is also an increasing need for accurate subnational data, as projects targeted to specific regions and issues become more common. This may well require more field work, but the highest priority is to use technologies that can predict, interpolate and/or extrapolate resource distributions from available data.

It is important to appreciate that the choice of agro-climatic zones in the study of White [1998] was very influenced by the fact that the FAO [1996a, 1996b] studies provided livestock data that could be linked to these zones. The use of human population density data has been a useful step in providing initial estimates of livestock density distribution within countries, and for the most part these estimates appear to be sufficiently accurate to provide information to aid in the targeting and prioritisation of agricultural research. These estimates will be least accurate where the quality of the national data are low, where environmental regulations limit the location of livestock industries (e.g. intensively housed livestock units and feedlots), and where climatic extremes, land degradation or alternative land uses have a greater effect on livestock densities than on those for human populations.

Definition of agro-climatic (and agro-ecological) zones will improve through applying digital elevation models, climate surfaces, plant growth models such as GROWEST [Nix 1981; Zuo 1996], field and remote sensing data, and geographic information systems [e.g. FAO 1997, 1998]. The use of the GROWEST model as the basis of agro-climatic classification appears to be significantly superior, particularly in temperate environments, to approaches based simply on length of growing period.

The collection of land use and livestock density data in Africa [Corbett *et al.* 1995; Kruska *et al.* 1995] and Latin America [G. Hyman, pers. comm.], complemented by local data at the sub-national level, means that before too long it will be useful to revisit the data on livestock density distribution in the light of new and more relevant zonations. Already, subnational livestock, crop and human distribution data are being used to delineate farming systems. GIS systems to link this information to satellite imagery and the output of agronomic models will enable exploitation levels and areas of agroecological vulnerability to be better defined. Data on the distributions of livestock, land use and tsetse fly are integral components of the Programme Against African Trypanosomiasis (PAAT) [W. Wint, pers. comm.].

5. CONCLUSIONS

Agro-climatic classification systems have evolved from empirical descriptions based on raw climate data, to systems based either on estimates of length of growing period, or agronomic models that describe plant responses to light, temperature and moisture. Satellite imagery and field data are being used to improve the goodness of fit of these different zonation schemes. Estimates of the global distribution of domestic livestock and livestock commodities, and crop distribution data have evolved from annual data at the national level, to estimates based on human population density. The next step involves increased use of agronomic models and satellite imagery. International collaboration in assembling and integrating these data sets and models is expected to have major benefits in improving the targeting of research, and land management practices that benefit both the environment and resident human and livestock populations.

6. REFERENCES

Anon. Assessment of animal agriculture in sub-Saharan Africa. Morrilton, Arkansas, Winrock Institute for Agricultural Development, 162 pp, 1992.

Belbin, L. The use of non-hierarchical allocation methods for clustering large sets of data. *Australian Journal of Computing*, 19, 32–41, 1987.

Corbett, J.D., The changing face of agroecosystem characterization: Models and spatial data, the basis for robust agroecosystem characterization. *Proceedings of the Third International Conference on the Integration of GIS and Environmental Modeling*, Santa Fe, New Mexico, January 1996. http://www.sbg.ac.at/geo/idrisi/GIS_Environmental_modeling/sf_papers/corbett/corbett.htm

Corbett, J.D., R.F. O'Brien, R.J. Kruska and E.I. Muchugu, Agricultural environments of the Greater Horn of Africa – a database and map set for disaster mitigation. 9pp., 31 maps, plus database, 1995.

Davis, J. and G. Lubulwa, Integration of research evaluation analysis into research institution decision-making: an overview of progress at ACIAR. Australian Centre for International Agricultural Research, Working Paper No. 17, 1995.

FAO, *Reports of the agro-ecological zones project.* World Soil Resources Reports No. 48, Vol. 1 - Africa, Vol. 2 - Southwest Asia, Vol. 3 - South and Central America, Vol. 4 - Southeast Asia, Food and Agriculture Organization, Rome, Italy, 1978-81.

FAO, Livestock Geography: A demonstration of GIS techniques applied to global livestock systems and populations. Consultant report by William Wint, Food and Agriculture Organization, Rome, Italy, April 1996, 77 pp, 1996a.

FAO, Livestock Geography II; A Further Demonstration of GIS techniques applied to Global Livestock Systems, Populations and Productivity. Consultant Report by William Wint, Food and Agriculture Organization, Rome, Italy, August 1996, 90 pp, 1996b.

FAO, Ecozones, farming systems and priority areas for Tsetse control in East, West and Southern Africa. Consultant Report by W. Wint, D. Rogers and T. Robinson, Food and Agriculture Organization, Rome, Italy, February 1997, 44 pp, 1997.

FAO, Predictions of cattle density, cultivation levels and farming systems in Kenya. Consultant Report by W. Wint and D. Rogers, Food and Agriculture Organization, Rome, Italy, January 1998, 23 pp, 1998.

Fischer, G., E. de Pauw, H. van Velthuizen, F. Nachtergaele and J. Antoine, A provisional world climatic resource inventory based on the length-of-growing-period concept. Paper presented at the NASREC Conference, 5-12 November 1995, Wageningen, Netherlands, 1995.

Fitzpatrick, E.A. and H.A. Nix, The climatic factor in Australian grassland ecology. In Milton Moore, R. ed. *Australian Grasslands*, Australian National University Press, Canberra, pp. 3–26, 1970.

Hutchinson, M.F., *A Summary of Some Surface Fitting and Contouring Programs for Noisy Data. Consulting Report No. ACT 841.* Canberra: CSIRO Division of Mathematics and Statistics and Division of Water and Land Resources, 24pp, 1984.

Hutchinson, M.F., *A new objective method for spatial interpolation of meteorological variables from irregular networks applied to the estimation of monthly mean solar radiation, temperature, precipitation and windrun.* CSIRO Division of Water and Land Resources, Technical Memorandum 89/5, Canberra: CSIRO, 10 pp, 1989a.

Hutchinson, M.F., A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. *Journal of Hydrology*, 106, 211–232, 1989b.

Hutchinson, M.F., The application of thin plate smoothing splines to continent-wide data assimilation. In: Jasper, J.D. ed. *Data assimilation systems*, Bureau of Meteorology Research Centre Research Report No. 27, Bureau of Meteorology, Melbourne, pp. 104–113, 1991.

Hutchinson, M.F., H.A. Nix and J.P. McMahon, Climatic constraints on cropping systems. In: Pearson, C.J. ed. *Field Crop Ecosystems of the World*, Elsevier, Amsterdam, pp. 37–58, 1992.

Kannangara, Ratnaseeli, An agro-climatic analysis of Sri Lanka. PhD thesis, Australian National University, Canberra, 1998.

Köppen, W., Das Geographische System der Klimate. In: *Handbuch der Klimatologie* I., Gebrüder Borntraeger, Berlin, C, pp. 1–44, 1936.

Kruska, R.L., B.D. Perry and R.S. Reid, Recent progress in the development of decision support systems for improved animal health. In: *Proceedings of the Africa GIS '95 meeting, "Integrated Geographic Information Systems Useful for a Sustainable Management of Natural Resources in Africa"*, March 6–9, Abidjan, Ivory Coast, 1995.

Le Houérou, H.N., G.F. Popov and L. See, Agro-bioclimatic classification of Africa, FAO Meteorology Series No. 6, 227 pp., 1993.

Nix, H.A. Simplified simulation models based on specified minimum data sets: the CROPEVAL concept. In: Berg, A. ed. *Application of remote sensing to agricultural production forecasting*, Balkema, Rotterdam, pp. 151–169, 1981.

Seré, C., H. Steinfeld and J. Groeneweld, World livestock production systems: current status, issues and trends. FAO Animal Production and Health Paper No. 127, 1996.

Slingenbergh, J. and W. Wint, Livestock geography and land use. Proceedings of the Livestock & Environment Conference, June 1997, Wageningen, Netherlands, 1997.

White, D.H. A global agro-climatic analysis of the distribution and production of livestock commodities. Economic Evaluation Unit Working Paper No. 30, Australian Centre for International Agricultural Research, 1998.

Zuo, Heping, Agro-climatic analysis for mainland east Asia by a GIS approach. PhD thesis, Australian National University, 264 pp, 1996.

Zuo, H., M.F. Hutchinson, J.P. McMahon and H.A. Nix, Developing a mean monthly climatic database for China and south-east Asia. In: Booth, T.H. ed. *Matching trees and sites, ACIAR Proceedings No. 63*, pp. 10–17, 1996a.

Zuo, H., J.P. McMahon, H.A. Nix and M.F. Hutchinson, A GIS-based agro-climatic classification for mainland east Asia. In *Proceedings of the second Australian Conference on Agricultural Meteorology*, The University of Queensland, 1–4 October 1996, pp. 98–101, 1996b.