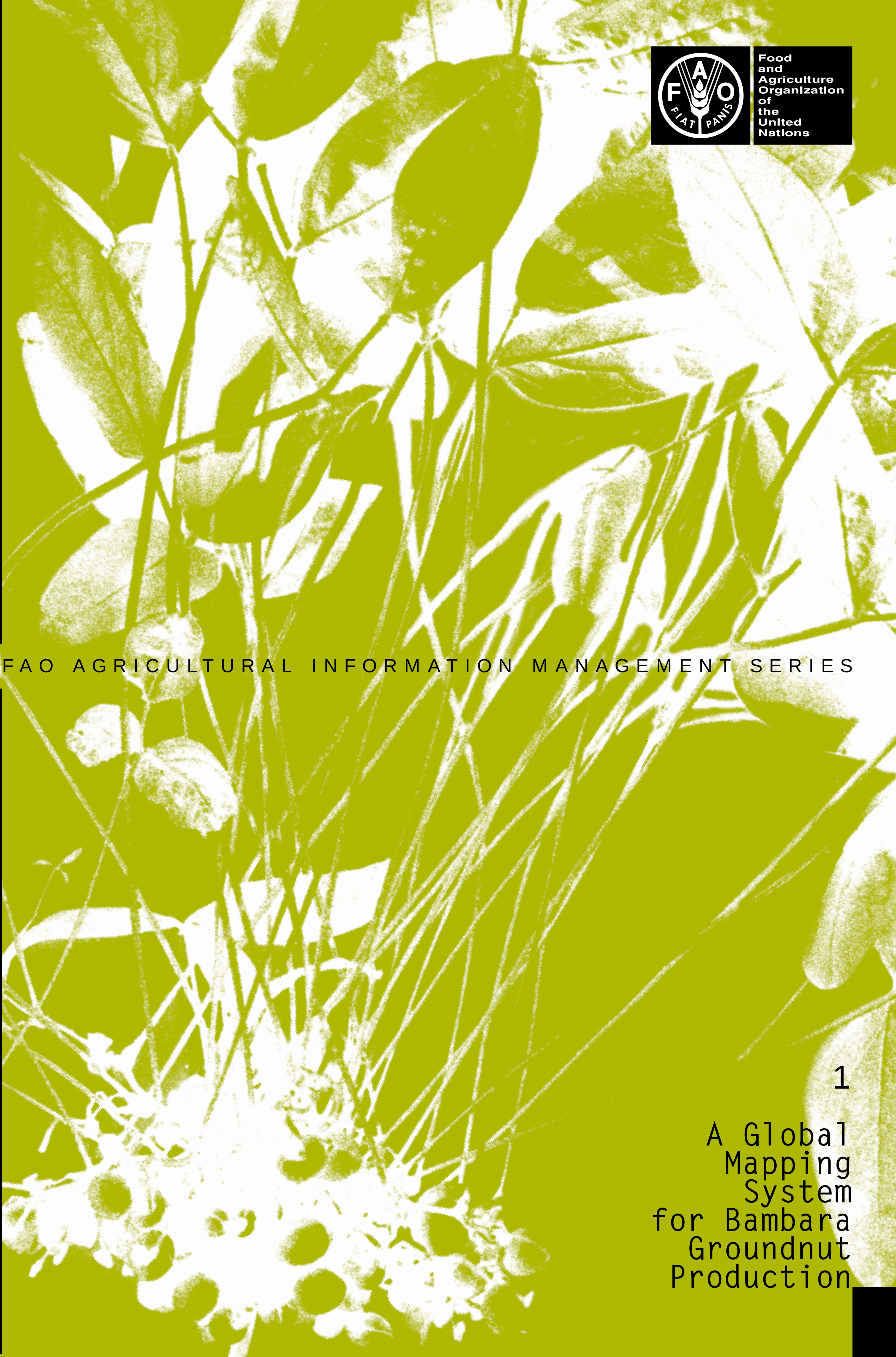

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1

A Global Mapping System for Bambara Groundnut Production

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1

A Global Mapping System for Bambara Groundnut Production

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Preface

This is the first study that estimates the potential production for any underutilised crop on a global basis. Our long-term aim is to demonstrate how this approach, initially for bambara groundnut, can be used to assess the potential productivity of many underutilised food crops at locations beyond their current distribution.

The most significant contributions from this study are the integration of a weather simulator and a crop simulation model into a Geographical Information System (GIS) to predict potential production of bambara groundnut over the globe. The integration came through a coincidence of interests. FAO needed to improve the knowledge and better use of underutilised crops that can contribute to the food security of the world's poorest people. For the University of Nottingham it was an opportunity to provide a geographic basis for their existing crop model that had been refined by the third author so that predictions of bambara groundnut potential could be extended to new sites.

Integration of the weather generator and model into a GIS was based on the experiences gained by the second author in using fish growth models to estimate potential for fish farming in Africa (FAO, 1998, available at www.fao.org/docrep/W8522e/W8522E00.htm).

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Abbreviations

AW1	Available water above pwp in layer 1 (mm)
AWmax	Available water at field capacity (mm)
D	Atmospheric saturation deficit (kPa)
DAE	Days after 50% emergence
DAR	Days after last rain or irrigation (d)
DAS	Days after sowing
Deficit	Water amount required to fill layer 1 to FC (mm)
DR2	Drainage from layer 2 to layer 3 (mm d^{1})
dRF/dt	Root front velocity (mm d^{-1})
Drrate	Relative drainage rate (d^{-1})
EEQ	Equilibrium evaporation (mm d^{-1})
ES	Daily soil evaporation (mm d^{-1})
ESO	Daily potential soil evaporation (mm d^{-1})
EVAPO	Potential evaporation (mm d^{-1})
F_Root	Daily fractional partitioning to roots
FC	Soil moisture at field capacity (volume %)
Fi	Fraction of radiation intercepted by leaves
Frs	Fraction of seed material converted to plant biomass
GrainW	Individual grain weight (g $seed^{-1}$)
Growth	Daily biomass assimilation (g m^{-2} d^{-1})
HI	Harvest index; pod:shoot weight ratio
Himax	Cut off point for maximum harvest index
K	Light extinction coefficient
L	Leaf area index
LeafW	Leaf weight (g m^{-2} d^{-1})
LLG	Radiation limited growth
LLP	Daily light limited photosynthetic rate (g m^{-2} d^{-1})
LSR	Leaf : shoot weight ratio
LSRi	Initial value of LSR
MOISTi	Initial soil moisture (volume %)
PodW	Pod dry weight (g m^{-2})
POP	Population density (plants m^{-2})
PWP	Soil moisture at permanent wilting point (volume %)
RD	Root density (m m^{-3})
Rlfactor	Root length factor (g m^{-1})
RootL	Total root length (m m^{-2})
RootW	Root dry weight (g m^{-2})
ShootW	Shoot dry weight (g m^{-2})
SLA	Specific leaf area (m^{-2} g^{-1})
Stindex	Stress index, genotype constant for stress tolerance
Stress	Drought stress
Tbase	Base temperature for crop development (°C)
Tfactor	Photosynthesis correction factor for temperature
Tmax	Daily maximum temperature (°C)

Tmean	Daily mean temperature (°C)
Tmin	Daily minimum temperature (°C)
Topt1	Lower optimum temperature for photosynthesis (°C)
Topt2	Higher optimum temperature for photosynthesis (°C)
TT	Thermal time (°C d^{-1})
TTemerg	Thermal time requirement for 50% emergence (°C d^{-1})
TT_pod	Thermal time for pod initiation (°C d^{-1})
Umax	Maximum relative water uptake rate (mmwater mm^{-1}soil d^{-1})
Upot	Potential transpiration (max uptake by roots) (mm d^{-1})
Uptake1	Actual water extraction by roots in layer 1 (mm d^{-1})
WLG	Water limited growth
WLP	Daily water limited photosynthesis (g m^{-2} d^{-1})
ε_s	Radiation use efficiency (g MJ^{-1})
Ω	Transpiration equivalent (g kg kPa^{-1})
θ	Actual soil moisture (volume %)

Summary

This report describes an approach to assess locations and areal expanses that have potential for the production of bambara groundnut (*Vigna subterranea* L. Verdc) across the world. The methodology was applied both to regions such as Africa, where the crop is widely cultivated but where experimental evidence is limited, and to new regions that have not previously been associated with bambara groundnut but where environmental factors are conducive for productive growth. A weather generator and a crop simulation model of bambara groundnut (BAMnut) were incorporated into a Geographical Information System (GIS) to predict, for the first time, bambara groundnut production for the world.

A gridded mean monthly climate dataset at a resolution of 50 km x 50 km for global land areas (excluding Antarctica), for the period 1961-1990, were used as input to the weather data generator to generate daily weather data. Simulation results from BAMnut in a suitable format were used as input to the GIS to provide the required maps and statistics. Given the time frame of the present study, neither the model nor the overall methodology attempted to account for the specific effects of soil type, pests or diseases on the likely productivity of bambara groundnut at any location. Similarly, the influence of daylength sensitivity for pod filling in many bambara groundnut landraces was not assessed in relation to potential yield. However, by scrutinising the world for bambara groundnut potential in relatively small sites, GIS technology provided a means to ask, "where is the best potential for growth, what is the likely yield threshold and over how much surface area of land are yields achievable"?

Each site that was evaluated was approximately a 50 km x 50 km (at the equator) grid cell, of which 62,482 cells corresponded to global land areas. Results show that bambara groundnut is likely to produce significant pod yields in many parts of the world beyond its current distribution with suitable areas of potential production in America, Australia, Europe and Asia as well as Africa. In fact, locations within the Mediterranean region show the highest predicted biomass, often exceeding 8.5 t ha^{-1}. The mapped predictions indicate that the productivity of bambara groundnut is likely to be influenced by the pattern of rainfall distribution as well as its annual amount and by the minimum and maximum temperature during the growing season. When factors such as the seasonal distribution of rainfall, daylength and range of temperatures during the growing season are accounted for, the potential yields of bambara groundnut within its current areas of cultivation can be significantly increased without high levels of agronomic inputs.

The preliminary identification of potentially suitable areas for production, based on the agro-ecological requirements of the crop, serve as a useful prelude to detailed field investigations on bambara groundnut to identify appropriate management practices and may provide a basis for a similar assessment on many other underutilised crops. The approach described here has implications for issues of food security since the methodology can be rapidly extended to assess the potential productivity of many subsistence food crops that contribute to the diets of the world's poorest people.

Introduction

OVERVIEW

For generations, agronomic experiments have been the conventional basis for cultivar selection and the evaluation of crop productivity in response to climate, soil and management options. However, agronomy is often limited by the availability of physical and human resources. All agronomic research is restricted to a limited number of sites, seasons and experimental combinations. Nevertheless, general recommendations for appropriate agronomic practices require an assessment of spatial and temporal variability, both within and between locations. This requirement is difficult to satisfy through conventional short-term experimentation on a limited number of sites. For the world's major crops, agronomic recommendations have been based on a long history of experiments and experience across a range of sites, seasons and management practices. By definition, major crops have an international significance and therefore research effort can be directed to long term and broad geographical objectives. In contrast, minor or underutilised crops often have important but regional or local significance. Since many of these crops are grown for subsistence and contribute to the food security of many of the world's poorest people, attempts to improve them rarely attract interest from international agencies or commercial sponsors. As a result, research on underutilised crops cannot afford the luxury of a long-term international effort and to make rapid progress alternatives to conventional agronomic experimentation must be sought. Recent developments in the use of computer-based analytical tools, such as weather data generators, crop simulation models, geographic information systems (GIS) and the Internet, provide exciting new opportunities to complement conventional agronomy and provide practical recommendations for appropriate agronomic practices outside the limited range of experimental conditions. One particular use of these new technologies is to assess the potential productivity of underutilised crops at locations beyond their current distribution.

OBJECTIVES

The objective of this study was to assess the potential productivity of bambara groundnut (*Vigna subterranea* L. Verdc) – an underutilised African legume – across the world. This global approach had two aims:

- To evaluate the productive potential of regions such as Africa, where the crop has been grown for centuries, but where experimental evidence is scant, incomplete or inaccessible.
- To define new regions not previously associated with the cultivation of bambara groundnut but where the combination of environmental factors indicate a potential for productive growth without recourse to costly inputs, such as irrigation.

BACKGROUND

Most human food requirements are provided by fewer than 20 crop species. There remains a vast repository of many hundreds of underutilised species that have been grown locally for centuries and which contribute to the food security of the world's poorest people. Many of these crops are cultivated in hostile, tropical environments by small-scale farmers without access to irrigation or fertilisers and with little guidance on improved practices and feasible alternatives. Any attempts to improve their germplasm or management practices depend on local experience and resources since most agricultural scientists and breeders have ignored or actively discouraged the cultivation of indigenous underutilised crops. The few efforts that have been made to evaluate these species by conventional methods have been slow and labour-intensive and research funds have rarely been directed to multidisciplinary research on such crops of unknown potential.

Furthermore, because many of these crops are grown for *subsistence*, little effort has been made to genetically or agronomically improve them or assess their nutritional, processing and economic potential. A major limitation of most research on underutilised crops is that, because of inadequate funding, it is confined to a single aspect, e.g. breeding, of the particular species in question. The lack of a multidisciplinary effort or comprehensive published literature on any particular underutilised species means that any research that is done may duplicate that being done elsewhere with no increase in overall knowledge or understanding of the crop in question. The lack of an overarching strategy for the improvement of different underutilised crops discourages the development of general principles that can be applied across species. This piecemeal approach reduces both the effectiveness of research on each underutilised species and the collective influence of those advocating greater efforts to increase agricultural biodiversity.

If there is to be an increase in agricultural biodiversity and a broader basis to food security policies, there is an urgent need to *co-ordinate* research on underutilised crops within a general and robust methodology that:

1) Disseminates recommendations to growers and advisors on management practices and end uses.
2) Defines physiological attributes and responses to environmental factors so that the agro-ecological requirements of each crop can be determined.
3) Identifies how knowledge and understanding gained on any particular species can rapidly be applied to increase our understanding of other underutilised crops.

This study, using our experience of bambara groundnut as an example, demonstrates how the integration of physiological principles, field research and crop modelling together with a weather data generator and GIS can provide a general and cost-effective means of rapidly assessing the potential of many underutilised food crops.

BAMBARA GROUNDNUT

Bambara groundnut *(Vigna subterranea L.* Verdc*)* is an indigenous grain legume grown mainly by subsistence women farmers in drier parts of sub-saharan Africa. The crop has advantages over more favoured species in terms of nutritional value and tolerance to adverse environmental conditions. In much of Africa, bambara groundnut is the third most important legume after groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) (Sellschop, 1962). The crop has a number of production advantages in that it can yield on poor soils with little rainfall as well as produce substantial yields under better conditions. It is nutritionally superior to other legumes and is the preferred food crop of many local people (Linnemann, 1990; Brough and Azam-Ali, 1992). Bambara groundnut is a rich source of protein (16-25%) and its seeds are valued both for their nutritional and economic importance. The seeds command a high market price, with demand far outweighing supply in many areas (Coudert, 1982). However, despite these important attributes, the agro-ecological and genetic potential of bambara groundnut have not yet been fully realised nor its full economic significance determined. The crop is still cultivated from local *landraces* rather than *varieties* bred specifically for particular agro-ecological conditions or production systems.

Recently, scientists in Africa and elsewhere have begun to accumulate agronomic and physiological knowledge about the crop and to link this with the indigenous knowledge and perceptions of farmers and their families. Between 1992 and 1996, the University of Nottingham, UK, co-ordinated a major European Union (EU) project to assess the agro-ecological potential of bambara groundnut. This programme linked field experiments in the United Republic of Tanzania, Botswana and Sierra Leone with experiments and analysis at Nottingham and Wageningen University in the Netherlands. The objectives of the EU Bambara Groundnut Project were to:

1) Define sites and seasons for bambara groundnut cultivation in the United Republic of Tanzania, Botswana and Sierra Leone.
2) Produce a validated, mechanistic model of bambara groundnut to predict total biomass and pod yield in contrasting soil and atmospheric environments.
3) Identify attributes associated with the ability to produce yields under semi-arid conditions.

4) Recommend management practices to stabilise crop yields under rainfed conditions.
5) Outline a methodology for applying a similar approach to rapidly assess the potential of other underutilised species.

A more complete description of the EU project appears in University of Nottingham (1997). A number of associated publications describe the growth and development of the crop (Collinson *et al*., 1996) its capture and use of solar radiation (Collinson *et al*., 1999) germination responses of seeds (Kocabas *et al*., 1999) and yield responses to sowing date (Collinson *et al*., 2000).

SIMULATION MODELS

Simulation models are robust tools to guide our understanding of how a system responds to a given set of conditions. Crop simulation models are increasingly being used in agriculture to estimate production potentials, design plant ideotypes, transfer agrotechnologies, assist strategic and tactical decisions, forecast real time yields and establish research priorities (Uehera and Tsuji, 1993; Penning de Vries and Teng, 1993; Bannayan and Crout, 1999). Although there are growth simulation models for a range of major crops, there have been few attempts to develop models for underutilised species for which the factors controlling growth and development are not well understood and the general literature is sparse. The BAMnut crop simulation model was designed as a part of the EU Bambara Groundnut Project to integrate our knowledge about the agro-ecological requirements of bambara groundnut across a range of locations in Africa. BAMnut is the first dynamic simulation model for bambara groundnut and therefore provides the first *predictions* of its pod yields in response to the use of environmental resources or responses to environmental stress. A major objective for developing BAMnut was to provide a means of integrating our preliminary understanding of the dynamics of crop growth as influenced by soil moisture and environmental variables. This allows the agro-ecological potential and resource requirements of the crop to be established. In particular, because BAMnut is a process-based model, it allows predictions of crop growth and yield to be generated and matched with current and potential production environments beyond those used in the development of the original model.

EXPERIMENTAL DATA

To develop BAMnut, functional relations were derived from experimental data collected in growth room or glasshouse experiments at the University of Nottingham (UK) in 1995 (Collinson *et al*., 1993, 1997and1999; Kocabas *et al*., 1999; Berchie, 1996; Babiker, 1989; Zulu, 1989) and field experiments conducted in Africa (Sesay and Yarmah, 1996; Karikari, *et al*., 1996;). A set of independent data from Nottingham and two years (1994, 1995) field data from two sites in the United Republic of Tanzania (Morogoro: 6° 49' S, 37° 4' E and Hombolo 5° 54' S, 35° 57' E) were used to evaluate the model.

For the 1995 glasshouse experiments, three contrasting landraces of bambara groundnut were grown as crop stands in controlled-environment glasshouses at the Tropical Crops Research Unit (TCRU), University of Nottingham. Each glasshouse has a cropping area of 35 m^2 containing a sandy loam soil overlying a gravely loam subsoil. This area is subdivided into two equal plots within which soil moisture can be independently controlled and monitored. The soil volume is lined to a depth of 1.25 m with butyl rubber to prevent natural water table fluctuations from affecting the rooting zone. The three bambara groundnut landraces were obtained from collaborating institutions in Sierra Leone ('LunT'), the United Republic of Tanzania ('DodR') and Botswana ('DipC'). In each glasshouse, one landrace was grown in each plot and received one of two soil moisture treatments. In the first, the soil was irrigated to 90% field capacity each week. In the second, the soil was irrigated to 60% field capacity until establishment (27 days after sowing (DAS)) with no further irrigation (Collinson *et al*., 1999). The crops received natural daylight with no supplementary lighting. Fertiliser was applied prior to sowing to achieve approximate soil nutrient contents of; N 150 kg ha^{-1}, P 40 kg ha^{-1} and K 150 kg ha^{-1} based on soil analysis. Crop growth measurements were obtained from seven sequential growth analyses taken during the growing period. More details of this experiment can be found in Collinson *et al.*, (1999).

Two of the landraces used in the 1995 glasshouse experiment (DipC and DodR) were also grown in a field study in the United Republic of Tanzania. In the field experiments, the crop was planted at three different dates; 4 January, 4 February and 4 March in 1994 and 1995 on a sandy loam soil. Experiments were arranged as a randomised complete block design with four replicates each containing six plots. Individual plot size was 5.6 x 5.6 m, each plot containing 16 rows 35 cm apart. Fertiliser was applied prior to sowing at a rate of 40 Kg N ha^{-1} using NPK compound fertiliser (25:5:5). Sequential growth analyses were carried out on six plants per plot on eight occasions throughout the season.

Chapter 1

Materials and methods

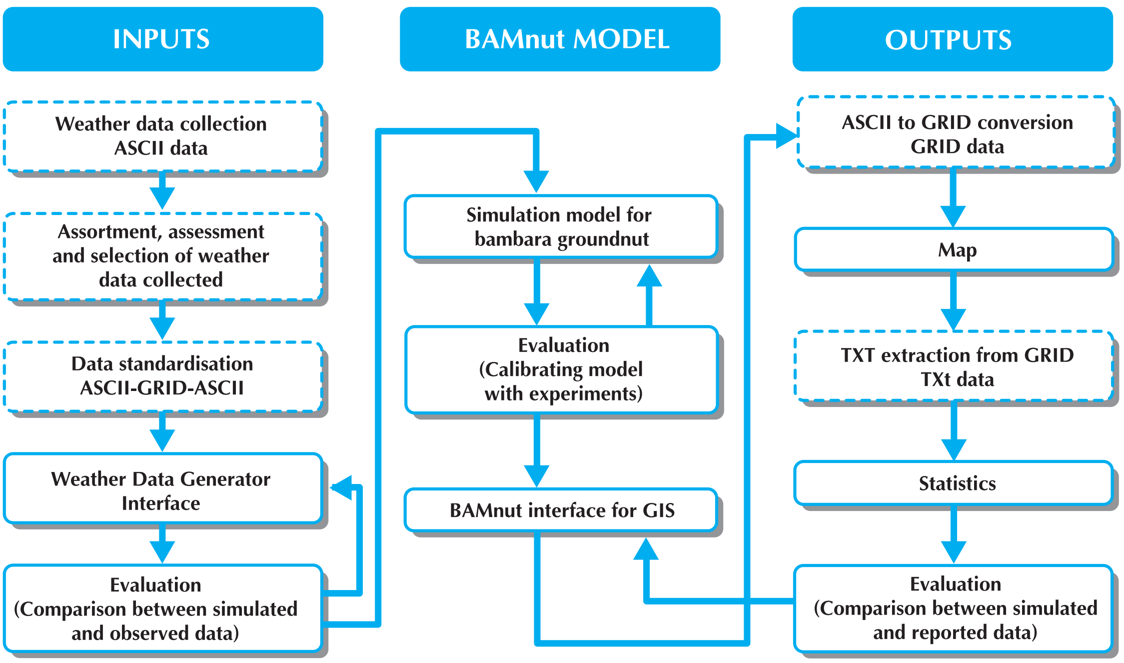
Agronomy is the science of crop management. It proceeds from a physiological understanding of the crop through to the prediction and verification of better management techniques. One possible means of achieving better agronomic management is the use of crop models. A crop model can be defined as a quantitative means of predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables (Monteith, 1996). A model has two important and related purposes: to improve our understanding of the crop and to predict how a crop will perform in defined agricultural environments, thereby aiding tactical and strategic decision-making.

This study examines how well sites across the globe satisfy potential biomass requirements for bambara groundnut and their likely yield thresholds in terms of pod production. In overview, there are two major analytical procedures in this study:

1) Integration of a weather generator into a GIS for the creation of daily weather data; and
2) Integration of BAMnut into a GIS;

BAMnut needs information and data on the most important factors that affect crop yields - the model inputs. After passing 'through' BAMnut, the inputs are converted to a number of outputs, such as maps and statistics of crop yields. A schematic diagram summarising the methodological framework developed in this study is shown in **Figure 1**.

Figure 1 - Schematic diagram describing the procedures involved in estimating and mapping the potential production of bambara groundnut



Note: Dashed boxes refer to GIS activities while solid boxes refer to the modelling activities.

BAMnut – A SIMULATION MODEL FOR BAMBARA GROUNDNUT

BAMnut DESCRIPTION

BAMnut is a process-oriented model developed at the University of Nottingham as a tool to simulate crop growth and yield in bambara groundnut. The model has been written in Visual Pascal, it simulates dry matter production and pod yield through numerical integration with a daily time-step. On each day, the resources of light and water are 'captured' and 'converted' into assimilated dry matter. Depending on the availability of these resources and the crop's ability to sequester them, growth (dW/dt) is considered as either light limited or water limited. **Figure 2** summarises the relations between the different modules within BAMnut, which are further described below. Radiation limited growth (LLG) is calculated from incoming radiation and the fraction of radiation intercepted by green leaves. Water limited growth (WLG) is calculated from potential water uptake rates and the amount of available water in the rooting zone. LLG and WLG are then compared to take the minimum of the two as the actual growth.

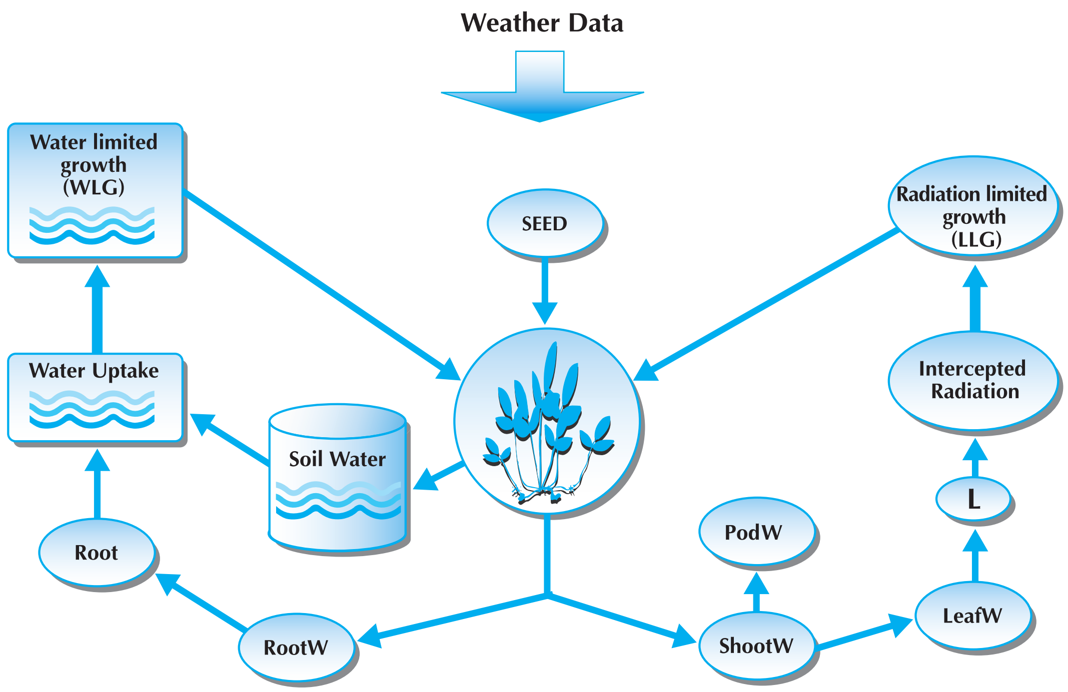
$$dW/dt = \text{minimum of } (LLG, WLG)$$

Where:

W = total dry matter ($g\ m^{-2}$)
LLG = radiation limited growth rate ($g\ m^{-2}\ d^{-1}$)
WLG = water limited growth rate ($g\ m^{-2}\ d^{-1}$)

Finally, pod yield is determined at crop maturity as the product of accumulated dry matter and a harvest index taken as a constant landrace-specific value.

Figure 2 - Relational diagram of the BAMnut model



Note: The water balance for growth under water limited conditions is represented in the left part of this figure. The right part of the figure represents potential growth of shoots and pods. L is the leaf area index, LeafW, PodW, RootW and ShootW represent the respective dry weights of crop components.

RADIATION LIMITED GROWTH (LLG)

Under optimal conditions (potential growth) a high proportion of variation in biomass production can be explained from intercepted radiation with a simple equation:

$$LLG = \varepsilon_s * Radiation * Fi * Tfactor$$

$Fi = 1- e^{-(K*L)}$

Where:

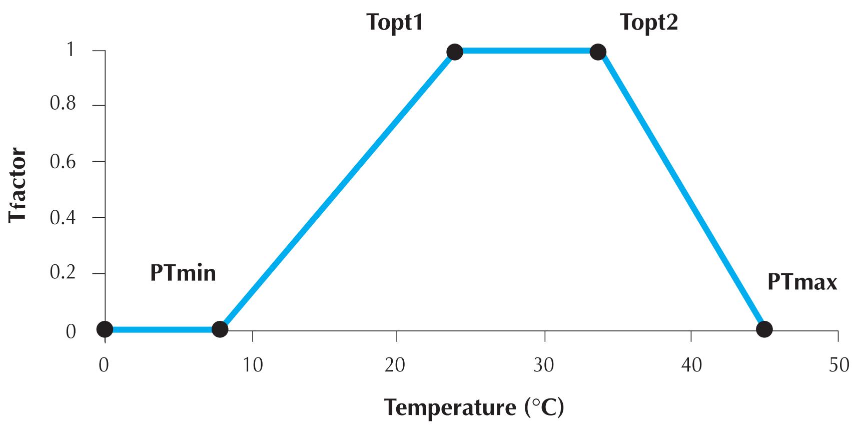
LLG = radiation limited growth
ε_s = radiation use efficiency (g MJ^{-1})
Radiation = incoming solar radiation above canopy (MJ m^{-2} d^{-1})
Fi = fraction of radiation intercepted by canopy
Tfactor = growth correction factor for temperature
K = light extinction coefficient
L = leaf area index

The approach described above was first defined by Monteith (1977) and Gallagher and Biscoe (1978). BAMnut follows the same approach with growth as the product of intercepted radiation and a conversion factor (radiation use efficiency, ε_s). The fraction, Fi, of radiation intercepted is calculated from the leaf area index, L, and the canopy extinction coefficient, K, using the Beer's Law approach (Squire, 1990), which states that fractional interception is related to the leaf area index of a canopy. Radiation limited growth (LLG) is calculated from solar radiation intercepted by leaves. BAMnut assumes a constant radiation use efficiency, (ε_s =1.2 g MJ^{-1}). This provides a conversion factor for radiant energy to plant biomass i.e. the ratio of dry matter produced to solar radiation intercepted during a defined period of growth.

Growth response to temperature (Tfactor)

The experimental data from the Nottingham glasshouse experiments showed that for bambara groundnut, ε_s remained constant across all experiments. The literature suggests that photosynthetic rate depends on the ambient temperature i.e. a temperature factor for the photosynthesis/light response (Goudriaan and van Laar, 1994). This concept is incorporated in BAMnut and a temperature factor (Tfactor) is calculated according to the temperature relation shown in **Figure 3**. The value of ε_s is reduced by Tfactor at tempera-

Figure 3 - The temperature factor for photosynthesis correction in BAMnut



Note: PTmin and PTmax are the minimum and maximum temperatures for photosynthesis. Topt1 and Topt2 are the lower and higher extremes of the optimum temperature range.

tures outside the optimum temperature range (Tfactor = 1) from Topt1 to Topt2 and falls to zero above the maximum temperature for photosynthesis (Tfactor = 0). BAMnut uses this temperature factor to adjust the crop growth response to temperature.

WATER LIMITED GROWTH (WLG)

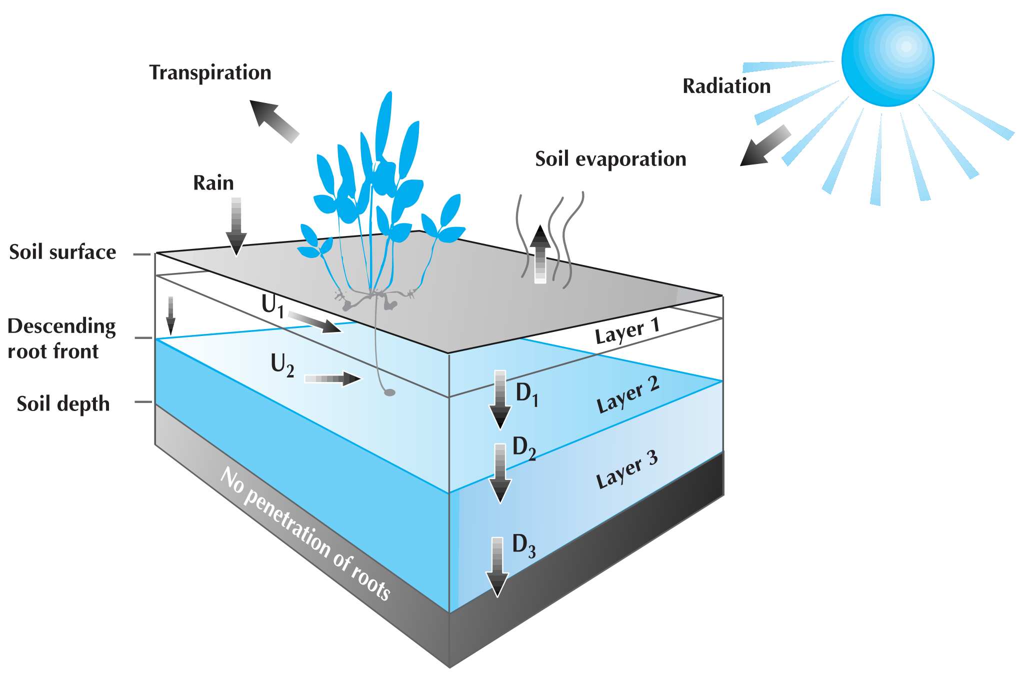
The water balance in BAMnut considers three soil layers (**Figure 4**). Changes in water content are calculated for each layer separately, from rainfall, drainage, soil evaporation and water uptake by roots. Water limited growth (WLG) is the maximum growth rate that the water uptake potential of roots allows for. When growth is water limited, transpiration equals potential water uptake (Upot) and:

$$\text{WLG} = \frac{(\text{Upot} * \Omega)}{\text{D}}$$

Where:

WLG = water limited growth
Upot = potential transpiration (maximum uptake by roots)
Ω = transpiration equivalent (g kPa kg^{-1})
D = drainage (mm d^{-1})

Figure 4 - Inward and outward water flows for the different layers considered in the soil water balance of BAMnut



Note: Un and Dn indicate the water uptake by roots and drainage from soil layer n.

Drainage

Drainage (D) occurs when the net flow of water into a certain layer is more than the amount required for that layer to reach Field Capacity (FC). The surplus water then drains to the deeper layer.

$$\text{D} = (\theta - \text{FC}) * z/100 \quad \text{for} \quad \theta \geq \text{FC}$$

Where:
D = drainage (mm d^{-1})
θ = actual soil moisture (volume %)
FC = soil moisture % at field capacity (volume %)
z = thickness of the soil layer (mm)

Potential evapotranspiration (PET)

PET is calculated using an equilibrium evaporation concept as modified by Priestley and Taylor (1972). This allows the calculation of approximate daytime net radiation and equilibrium evaporation, assuming that the stomata are closed at night and therefore that no PET occurs during this period. PET is calculated as 1.1 times the equilibrium evaporation to account for the effects of unsaturated air. The multiplier is increased above 1.1 to allow for advection when the maximum temperature is greater than 35°C, and reduced for temperatures below 5°C, to account for the influence of low temperatures.

Soil evaporation

Potential soil evaporation is the potential evaporation minus transpiration. The actual soil evaporation is the lowest of two values; potential soil evaporation and soil evaporation calculated for a soil that dries within the time period. This consideration is consistent with the two-stage concept of Ritchie (1972).

Soil evaporation = ESO (potential soil evaporation) if Ecum<Upot

Otherwise:
Soil evaporation = $\left(1.1*\sqrt{DAR}\right)-1.1*\left(\sqrt{DAR-1}\right)$

Where:
Ecum = accumulated soil evaporation (mm d^{-1})
Upot = potential transpiration (maximum uptake by roots)
DAR = days after the last rain (d)

TRANSPIRATION EQUIVALENT

Evaporative demand is defined as the amount of water transpired in order to realise a certain light limited growth rate. As both photosynthesis and transpiration are based on canopy gas exchange, BAMnut assumes a close relationship between transpiration and dry matter production. This is because changes in stomatal resistance will equally affect both carbon assimilation and transpiration.

Water limited growth is often calculated as the product of potential water uptake and a crop specific (constant) water use efficiency (WUE). BAMnut uses the transpiration equivalent, W (g kPa kg^{-1}), according to Azam-Ali *et al*, (1994). Water use efficiency is not treated as a crop specific constant but a variable that responds negatively to changes in atmospheric saturation deficit. Azam-Ali *et al*, (1994) defined W as a crop specific constant that relates to water use efficiency as follows:

$$\mathrm{WUE} = \frac{\Omega}{\mathrm{D}}$$

$$\mathrm{WLG} = \mathrm{Upot} * \mathrm{WUE}$$

Where:
WUE = water use efficiency (g kg^{-1})
Ω = transpiration equivalent (g kPa kg^{-1})
D = atmospheric saturation deficit (kPa)
WLG = water limited growth
Upot = potential transpiration (maximum uptake by roots)

Root distribution and water absorption

Roots tend to adopt a distribution that exponentially reduces with depth. This is similar to the inverse square root function used by Monteith *et al.*, (1989). BAMnut calculates a total root length from the root biomass using a specific root length factor, RL_{factor}. Root density is calculated as an exponential function of depth.

Before dealing with the actual water uptake, the potential water uptake must be known to determine whether growth is light limited or water limited. The water uptake by roots can then be calculated from the actual growth rate.

Potential transpiration equals potential water extraction from the soil by roots. Its magnitude depends on the depth and density of the root system and on the available soil water. A maximum uptake rate U_{max} in mm(water) per mm (soil) is defined with a given value dependent on crop and soil properties. This maximum uptake rate can be realised in a soil that is at field capacity and is fully exploited by roots. When either soil moisture or root density is below optimum the potential water uptake is reduced. The relative potential uptake rate U at a certain depth in the soil is calculated as:

$$Upot = \int_0^{RF} U_{max} \times \left(\frac{AW}{AW_{max}} \right)^2 \times \sqrt{\frac{RD}{RD_{sat}}}$$

Where:

Upot = relative water uptake rate (mm (water) mm^{-1} (soil) d^{-1})
U_{max} = maximum relative water uptake rate (mm (water) mm^{-1} (soil) d^{-1})
AW = available water above permanent wilting point (mm)
AWmax = available water at field capacity (mm)
RD = root density (m m-3)
RD_{sat} = maximum effective root density (m (roots) m^{-3})

Actual water uptake

Finally, the actual water extraction (U) in layers 1 and 2 can be calculated from the potential water uptake and the ratio of actual to potential transpiration.

$$Uptake = Upot \times \frac{LLG}{WLG}$$

Effect of stress on dry matter production

An unstressed crop is one that grows at a rate limited only by the availability of light. If water supply cannot match the transpirational demand, then the crop is said to be stressed and growth proceeds at a rate dictated by water availability. Water stress in the model is defined as the ratio of actual available water to potential available water in the soil. Water stress in the model affects L and shoot production. Another stress concept is defined in the model as the ratio of water limited growth to light limited growth. This correction factor affects the harvest index and fraction of dry weight allocated to roots.

MODEL EVALUATION

Table 1 shows the observed values of harvest index, pod yield and total above ground biomass across all the experiments involved in the development of BAMnut (Bannayan *et al.*, 2000). Due to yet unquantified genotype/environment interactions bambara groundnut, particularly in rainfed growing conditions, shows a high individual plant variability in harvest index and subsequently in pod yield. The simulated harvest index includes the range 0.01 to 0.58. The Root Mean Square Difference (RMSD) of harvest index simulation in this study is 0.19. However, ignoring the experiments (3 out of 11) with unexplained variability in harvest index would improve the RMSD of harvest index to 0.07 and P values would decline to 0.04. **Figure 5** shows the comparison of simulated against observed values of harvest index across all experiments shown in **Table 1**. **Figures 6** and **7** show the comparison of observed and simulated pod yield and shoot weight

TABLE 1
Shoot biomass, pod yield and harvest index of bambara groundnut across all experiments used in the development of the BAMnut model (Bannayan *et al.*, 2000)

Site	Landrace	Irrigated / Rainfed	Shoot biomass ($g\ m^{-2}$)	Pod yield ($g\ m^{-2}$)	Harvest index
Tanzania	DodR	Rainfed	279	55.6	0.20
Tanzania	DodR	Rainfed	215	29.7	0.14
Tanzania	DodR	Rainfed	61	2.4	0.04
Tanzania	DodR	Rainfed	144.6	35.9	0.13
Tanzania	DodR	Rainfed	121.2	47.4	0.39
Tanzania	DodR	Rainfed	78.8	5.4	0.05
Tanzania	DodR	Rainfed	192.5	77.8	0.17
Tanzania	DodR	Irrigated	575.3	332.9	0.19
Nottingham	DodR	Irrigated	535.8	284.4	0.53
Nottingham	DodR	Irrigated	661.6	310.9	0.46
Nottingham	DodR	Rainfed	118	3.8	0.03
Nottingham	DodR	Rainfed	111.9	0.3	0.0
Nottingham	DipC	Irrigated	761.9	443.4	0.58
Nottingham	DipC	Irrigated	565.3	274.8	0.48
Nottingham	DipC	Rainfed	105.4	12.4	0.12
Nottingham	DipC	Rainfed	156.9	18.4	0.12

respectively. The model is able to simulate pod yield and shoot weight with reasonable accuracy, with RMSD of 23.9 and 180.7 $g\ m^{-2}$ respectively. However, it is expected that with more experiments that examine crop partitioning during the reproductive stage and close monitoring of soil water, there is scope to substantially improve model simulation in all aspect of growth.

INCORPORATING BAMnut INTO A GIS

Agronomic models are traditionally used for point or site-specific applications. This is often because of limitations in data availability and computer technologies. Most process-based models have examined temporal variation using point data from specific sites and, again, provide outputs that are site specific. Because agriculture is a spatial activity, there is growing interest in placing site specific information into spatial and long-term perspectives. GIS facilitates the storage, manipulation, analysis and visualisation of spatial data (Hartkamp *et al.*, 1999). Therefore linking GIS with agronomic crop models is attractive because it permits the simultaneous examination of spatial and temporal phenomena. Spatial visualisation of the results from models significantly enhances our understanding and interpretation of simulation results (Engle *et al.*, 1997) and provides an opportunity for complex spatial analyses of the model results (Campbell *et al.*, 1989; Stoorvogel, 1995). By analysing the spatial patterns of simulated yield there is an opportunity to improve production estimates and highlight vulnerable areas, for example those that are prone to drought (Carbone *et al.*, 1996). However, the major drawback with such work is the limited availability of input climate and soil data that precludes the use of the more sophisticated simulation models.

Model adaptations for GIS integration

To integrate BAMnut into a Geographical Information System (GIS) it was first necessary to select and evaluate the data required as inputs to the model. Two important limitations were placed in this study to save costs. First, only already digitised or computer ready data could be used for the analysis and, second, the data had to be comparable world-wide.

Figure 5 - Comparison of observed harvest index with simulated values from BAMnut across all experiments for two contrasting landraces of bambara groundnut (10 D.F., $r^2 = 0.36$, $P = 0.10$)

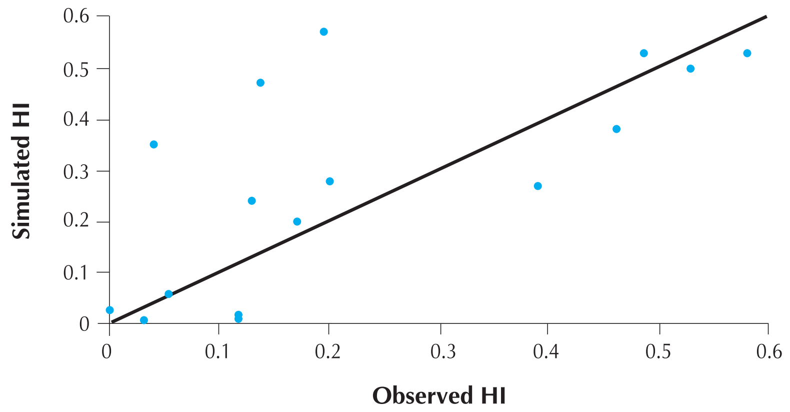


Figure 6 - Comparison of observed pod weight with simulated values from BAMnut across all experiments for two contrasting landraces of bambara groundnut (10 D.F., $r^2 = 0.43$, $P = 0.06$)

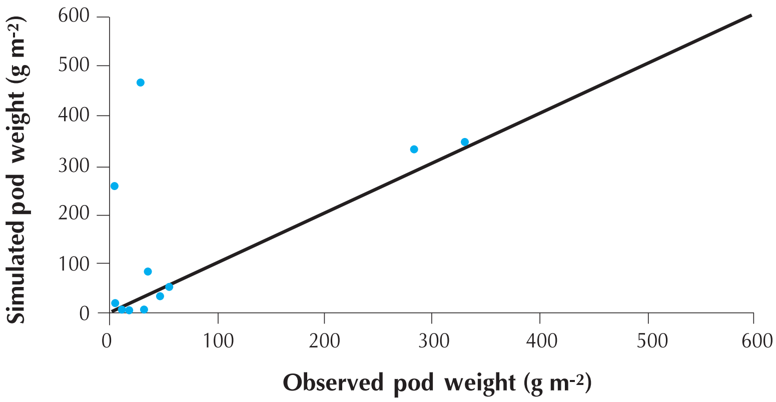
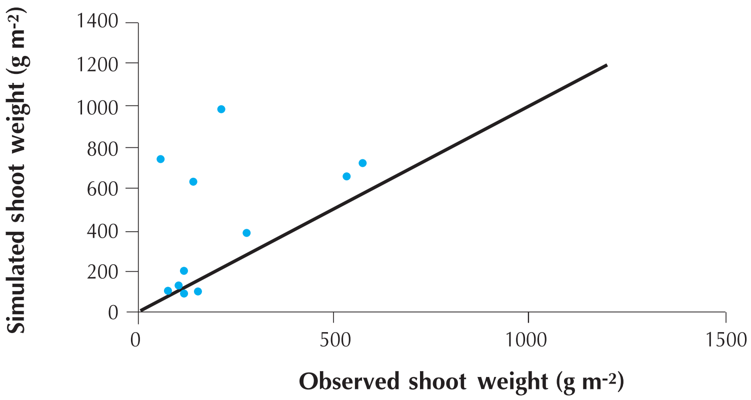


Figure 7 - Comparison of observed shoot weight with simulated values from BAMnut across all experiments for two contrasting landraces of bambara groundnut (10 D.F., $r^2 = 0.73$, $P < 0.05$)



Note: The relatively poor fit of the model (**Figures 5, 6** and **7**) illustrates the difficulties involved in modelling an underutilised crop for which there is little supporting data. Future studies will aim at identifying and modelling the causes of the variability which are likely to be genetic, i.e. within and between landrace variation.

To adapt the model for this study it is assumed that the crop does not begin to grow until the accumulated rainfall from the first day of the year is more than 10mm. Another assumption is that frost killing of the crop would occur at –10 °C, i.e. total absence of the crop in the areas where this temperature may occur. Unlike many major crops for which experimental evidence is available, the above assumptions on bambara groundnut growth were based on subjective interpretation and similar experimental evidence for pearl millet – a crop which grows in agro-ecological zones that are typical for bambara groundnut. In this study, the phenological characteristics of the Tanzanian bambara groundnut landrace Dodoma Red were used for model development. Therefore, total crop duration is assumed to be equivalent to a thermal time of 1900 °Cd.

Geographic Information Systems (GIS)

According to the GIS dictionary, maintained by the Association for Geographic Information (AGI), and the Web page of Edinburgh University Department of Geography (www.geo.ed.ac.uk/agidict/welcome.html), a GIS is a computer system for capturing, storing, checking, integrating, manipulating, analysing and displaying data related to positions on the Earth's surface. Typically, a GIS is used for handling maps of one kind or another. These might be represented as several different layers where each layer holds data about a particular feature. Each feature is linked to a position on the graphical image of a map.

Layers of data are organised to be studied and to perform statistical analyses. Uses are primarily government related, e.g. town planning, local authority and public utility management, environmental, resource management, engineering, business, marketing and distribution.

GIS portrays the real world. A view of the world as depicted on a map surface reveals that the surface consists of either points, lines or polygons. Thus roads would be lines, houses are usually points, and gardens or fields polygons. In a GIS there are two basic methods which the computer may use to store and display spatial data - 'vectors' or 'rasters'. These methods differ in the manner by which spatial data are stored and represented. FAO's Environment and Natural Resources Service of the Sustainable Development Department (SDRN) (www.fao.org/sd/eidirect/gis/chap3.htm) provide useful comparisons of vector and raster systems in summary form.

Analytical scope, reporting and visualisation

One of the powerful features of GIS packages is that statistical summaries of layers/coverages, model stages or outcomes can easily be obtained. Statistical data can include area, perimeter and other quantitative estimates, including reports of variance and comparisons among images. A further powerful analytical tool that aids understanding of outcomes is visualisation of outcomes through graphical representation in the form of 2D and 3D maps. For example, entire landscapes and watersheds can be viewed in three dimensions, which is very valuable in terms of evaluating spatial impacts of alternative decisions. Also, techniques have been developed to integrate GIS with additional tools such as group support systems, that allow interactive scenario development and evaluation and support communication among stakeholders via a local area network (LAN) (e.g. Faber *et al.*, 1997). Currently, there is also rapid development and deployment of Internet-enabled GIS tools, that allows a wider community of decision-makers to have instant access to spatial data. All of these tools are constantly being added to GIS packages and can be of great value.

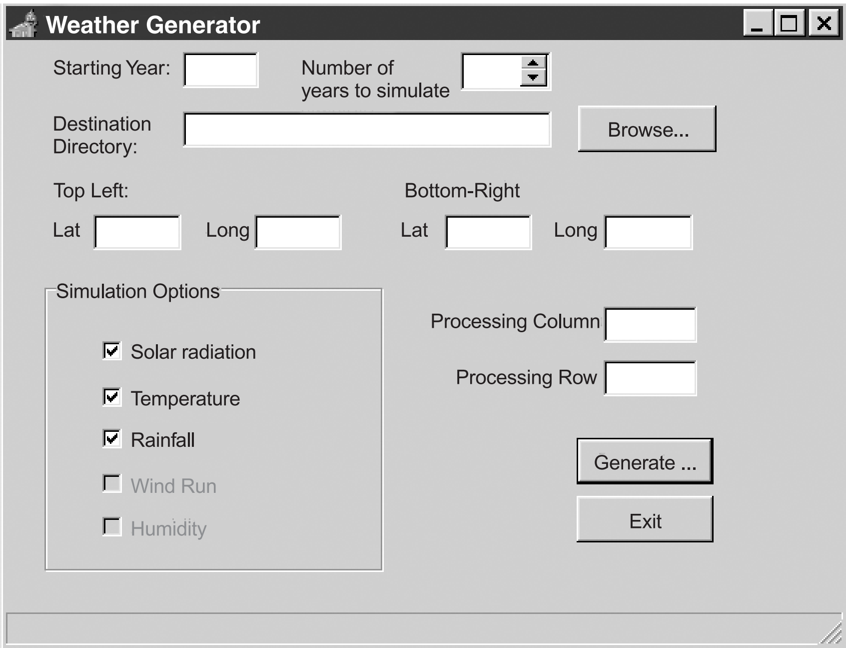
INPUTS TO BAMnut MODEL – WEATHER DATA

Weather has a major influence on a wide range of biological processes including agricultural production. The weather data often needed in relation to crop growth and yield include rainfall, maximum and minimum temperature, solar radiation, some measure of atmospheric humidity and wind. However, daily records that include all these elements are rare or are of insufficient duration for desired applications. In particular, in many regions of the world, distances between meteorological stations mean that it is difficult to assess the likely weather conditions at intermediate locations. Therefore, weather generator programs that are able to generate long series of weather records from limited existing data are useful. BAMnut requires daily weather data. However, these data are not available across the world. To solve this problem, a daily data weather generator (Matthews and Stephens, 1996) was used. Stochastic weather generators (Richardson, 1981; Geng *et al.*, 1986; Hutchinson, 1991; Racsko *et al.*, 1991) can use historical weather data from a site to provide daily sequences of the main weather parameters that are statistically similar to the observed data from which they were derived. This approach can then be used to provide weather inputs for crop growth models (Bannayan and Crout, 1999).

ADAPTATIONS TO WEATHER GENERATOR

In this study, the Turbo Pascal version of the weather data generator developed by Matthews and Stephens (1996) was adapted in Visual Pascal to generate the required daily weather data (**Figure 8**).

Figure 8 - The interface of the weather data generator developed for the present bambara groundnut mapping study



The observed climate data from the University of East Anglia Climate Research Unit (CRU) (www.cru.uea.ac.uk/) available through the Intergovernmental Panel on Climate Change (IPCC) Data Distribution (http://ipcc-ddc.cru.uea.ac.uk/cru_data/examine/have_index.html) was found to be the most comprehensive world climate data available and provided the main inputs to the weather generator. Data from the CRU included mean monthly climate data for global land areas, excluding Antarctica, for the period 1961-1990. The mean 1961-1990 climatology of seven variables were selected as inputs for the model developed in this study: Rainfall (mm d^{-1}), Radiation (W m^{-2}), Wet Day Frequency (Days), Maximum Temperature (°C), Minimum Temperature (°C), Vapour Pressure (kPa) and Wind speed (m s^{-1}). For full details of these variables please refer to the Data Description Pages - Climate Baselines - CRU Global Climate Dataset (http://ipcc-ddc.cru.uea.ac.uk/cru_data/examine/cru_climate.html). The procedure to import these files into Arc/Info (GIS software) is presented in the **Appendix**.

Based on the format of the Observed Climate Download files (http://ipcc-ddc.cru.uea.ac.uk/cru_data/datadownload/observed/climatology_download.html), the world is represented on a map in rectangular form as a GIS raster comprising 720 columns and 360 rows. Each raster cell has a resolution of 0.5º latitude by 0.5º longitude i.e. equivalent to 50 km x 50 km at the equator.

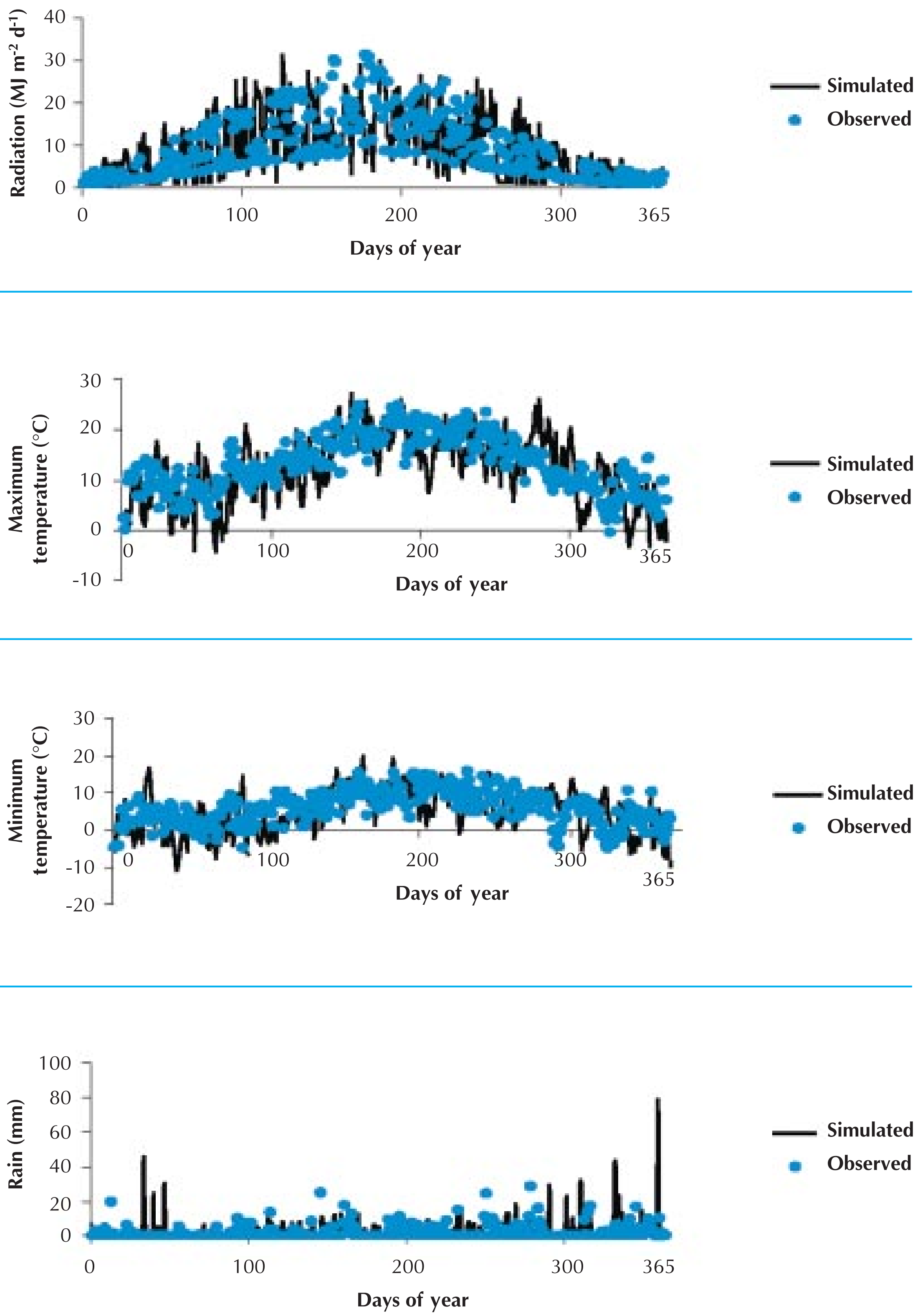
Based on the number of columns and rows, the total number of raster cells that comprise a single climate map are 259,200 i.e. 720 x 360 cells. Of these, 62,482 cells correspond to the land areas and the rest (196,718 cells) to missing values in the climate data (Antarctica, oceans and major inland water bodies).

Since most of the study was based on the CRU data, the cell size and geographic projection of one of these parameters was chosen as the base map to standardise map extensions. Thus, all map outputs derived from the model, have the same CRU map extensions.

Data inputs and outputs for the weather generator are based on the CRU climate map extensions. CRU climate data in ASCII form were downloaded, imported, converted to raster form and prepared using UNIX Arc/Info GRID i.e. the raster module of Arc/Info. Once prepared, the data were reconverted to ASCII form (see **Appendix** for details). The prepared ASCII data reside in a single directory in a PC. The adapted weather generator is able to create data by user-defined coordinates by defining the latitude and longitude values for the top left and bottom right corners of the desired area. For example, the settings for an area comprising the United Republic of Tanzania and adjacent land areas, would be top left latitude 0, longitude 28, and bottom right latitude -12, longitude 41. Computer memory problems were encountered due to the number of files that the generator had to create (i.e. 62,482). However, because the model comprised user-defined coordinates, the desired results were obtained by splitting the world into 30 sections.

The weather generator only processed those rasters that represented land areas. Missing values in the climate data (Antarctica, oceans and major inland water bodies) that were assigned integer values of –9999 were not processed and thus retained their original value. For each raster containing a single monthly climate value, the generator creates a file with 365 daily weather records. Each record is automatically labelled with an ID (e.g. 90001) that corresponds to its geographical location in the CRU map, and each contains daily data on solar radiation (SRAD), maximum temperature (TMAX), minimum temperature (TMIN), rainfall (RAIN), evapotranspiration (EVAP), vapour pressure (MNVP), windspeed (WIND) and CO_2 (ACO2) (see **Appendix**). As an example, **Figure 9** shows the comparison of one year simulated weather data for Sutton Bonington in the UK with observed weather data at that site, for radiation, minimum and maximum temperature and rainfall. The general pattern of both generated and observed data is similar.

Figure 9 - Comparison of simulated and observed weather data for Sutton Bonington, UK (52° 49′ 48″ N, 1° 15′ 0″ W)



Chapter 2
Results and discussion

OUTPUTS FROM BAMnut MODEL – CROP BIOMASS AND POD YIELDS

The outputs of multiple simulations of the model for both biomass and pod yield have been classified into four representative ranges of suitability as shown in **Table 2**. Although these categories are arbitrary, they help to simplify the analyses and provide some basis for comparisons between regions. The levels, defined as very suitable (VS), suitable (S), moderately suitable (MS) and unsuitable (US), are based on reported pod yields for bambara groundnut at different locations in Africa. For example, the VS category with pod yields greater than 3000 kg ha^{-1} corresponds with reported pod yields of up to 3870 kg ha^{-1} in Zimbabwe (Johnson, 1968). Similarly, the MS category corresponds with the typical farmers' yields of 650-850 kg ha^{-1} in Africa reported by Stanton *et al.* (1966). Regions producing pod yields below 300 kg ha^{-1} are defined as unsuitable (category US) for bambara groundnut cultivation. Crop failure has not been included as it obviously has the definition of no yield.

Figures 10 and **11** respectively show the predicted biomass and pod yield of bambara groundnut across the world. The different suitability ranges defined in **Table 2** are shown in different colours to indicate the geographical distributions of each classification.

Figures 10 and **11** show that there is potential for bambara groundnut production in many parts of the world beyond its current distribution with suitable areas with potential in America, Australia, Europe and Asia as well as Africa. In fact, locations within the Mediterranean region show the highest predicted biomass, often exceeding 8.5 t ha^{-1}.

Figures 12.1-12.11 and **13.1-13.11** provide a more detailed analysis of bambara groundnut biomass and pod yield predictions based on continent and country scales. The combination of Figures 10 and 11 as biomass and pod yield ranges with Figures 12.1-12.11 and 13.1-13.11 as the percentage of suitable arable lands for major parts of the world provides an integrated assessment of the potential production of this crop.

Figure 12.1 describes the potential biomass production for each continent. Of these, it is interesting to note that almost 75% of South America and 25% of Asia, two regions of the world not previously associated with bambara groundnut, are classified in the VS, S or MS ranges, i.e. as at least moderately suitable for bambara groundnut cultivation. The comparable figure for Africa, where almost all bambara groundnut is currently grown, is 65%. It is also noteworthy that Europe, which has less than 10% of land that is classified as at least moderately suitable for cultivation, has the largest proportion (3%) within the VS category.

TABLE 2
Classification of suitability ranges for predicted biomass and pod yield of bambara groundnut

	Very suitable (VS)	Suitable (S)	Moderately suitable (MS)	Unsuitable (US)
Biomass (kg ha^{-1})	>8,500	4,500-8500	1,500-4,500	1-1,500
Pod yield (kg ha^{-1})	>3,000	1,000-3,000	300-1,000	1-300

Note: kg ha^{-1} refers to pod or biomass per crop and may not be restricted to one crop per year.

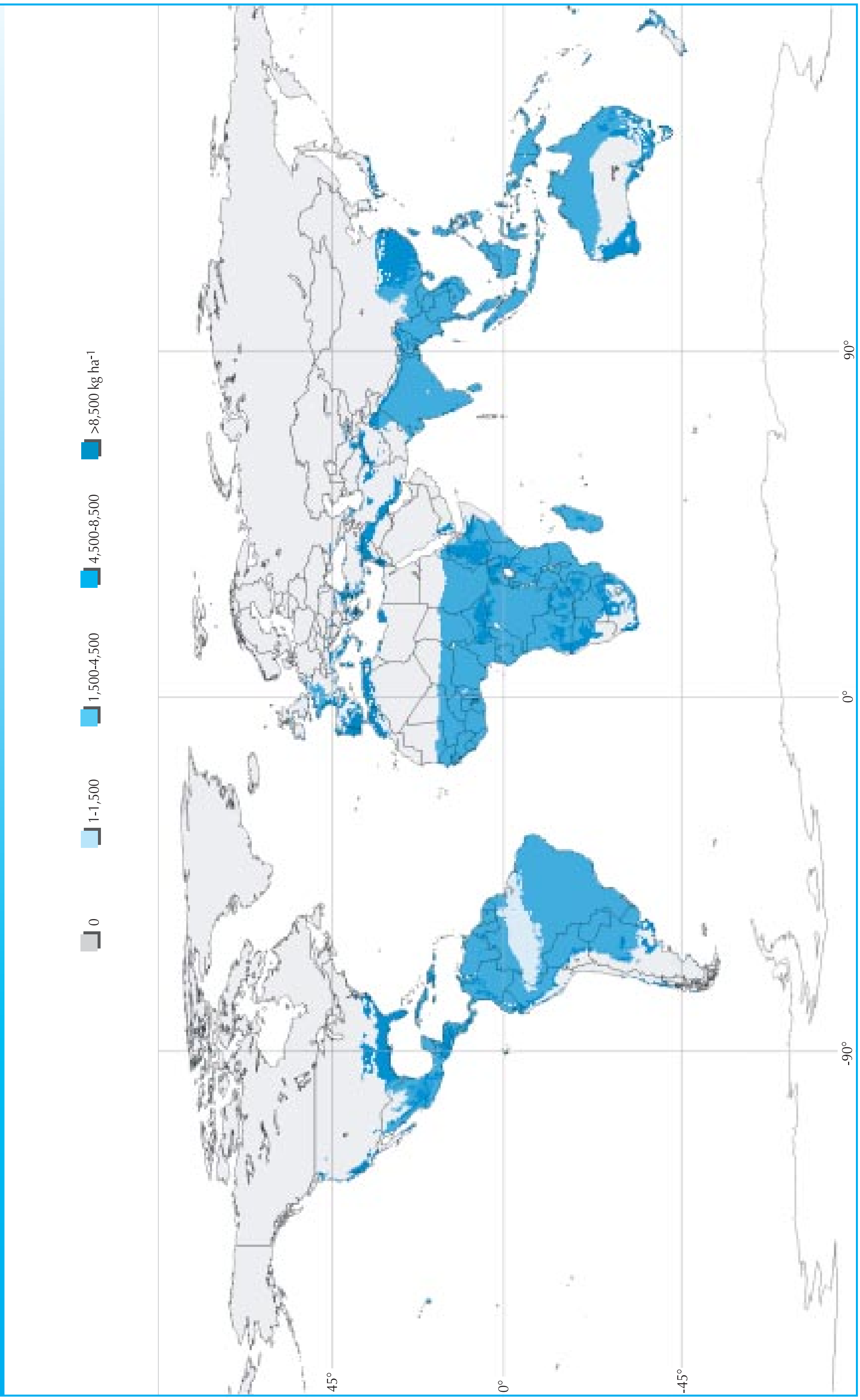


Figure 10 - Predicted biomass of bambara groundnut (kg ha^{-1}) across the world

Figure 11 - Predicted pod yield of bambara groundnut (kg ha^{-1}) across the world

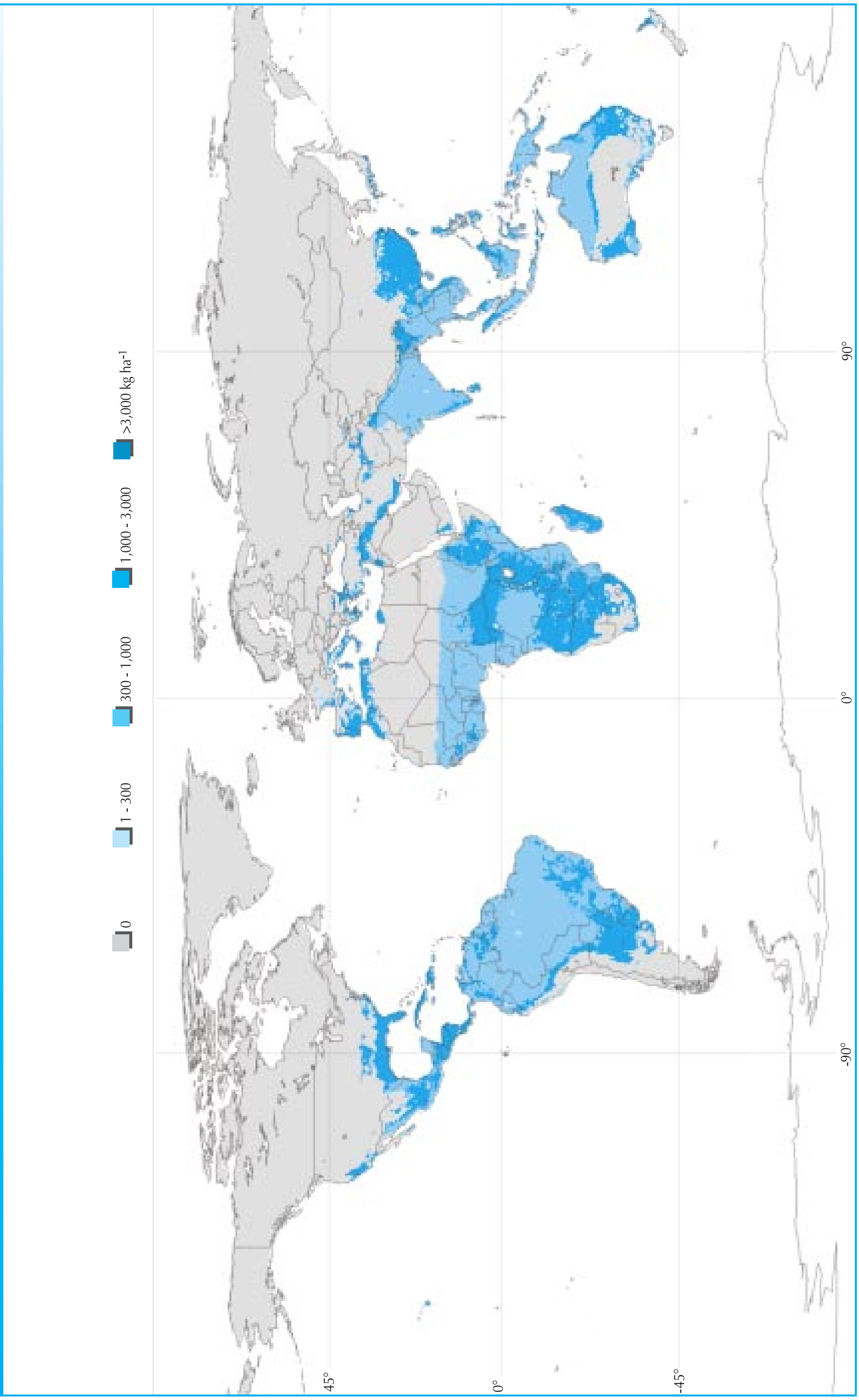


Figure 12.1 - Relative surface area with potential biomass for bambara groundnut CONTINENTS

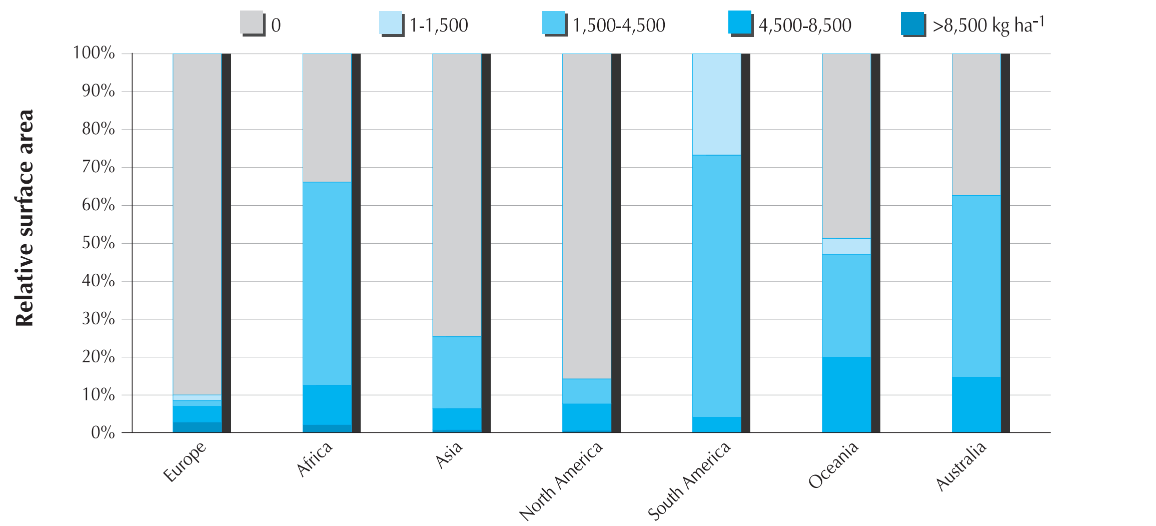


Figure 12.2 - Relative surface area with potential biomass for bambara groundnut NORTH AFRICA

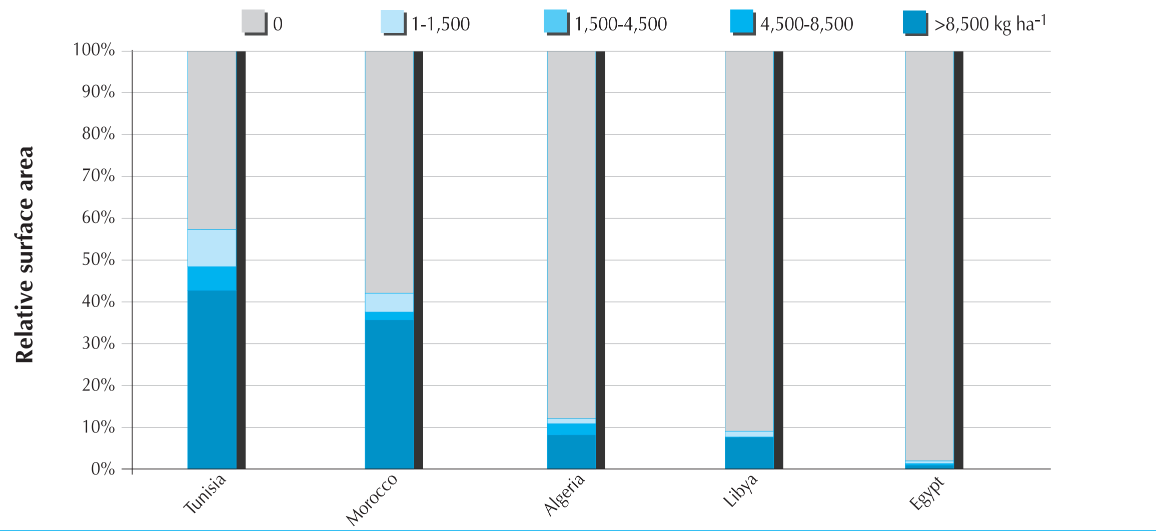


Figure 12.3 - Relative surface area with potential biomass for bambara groundnut CENTRAL AFRICA

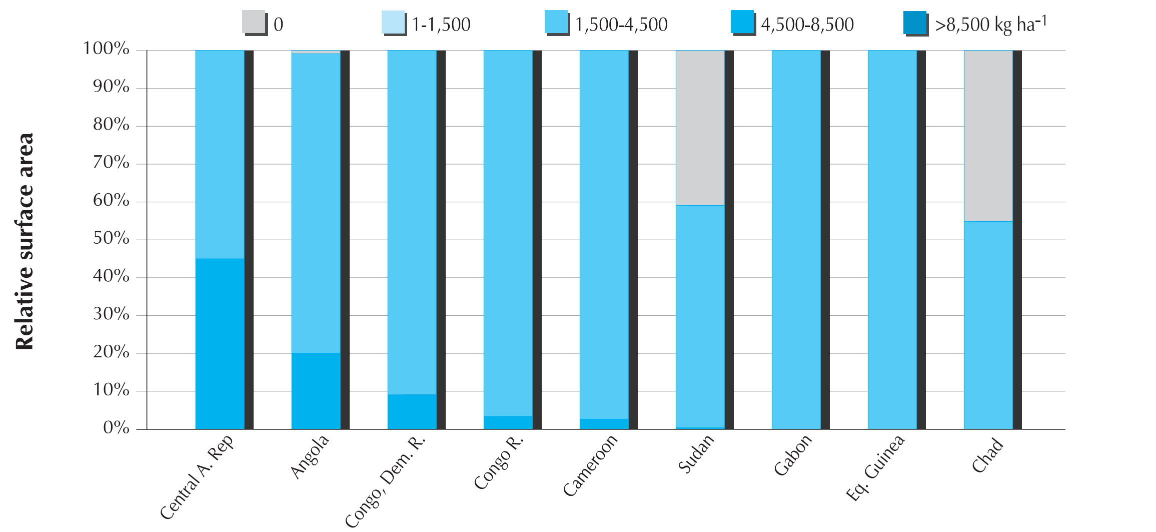


Figure 12.4 - **Relative surface area with potential biomass for bambara groundnut** SOUTH AFRICA

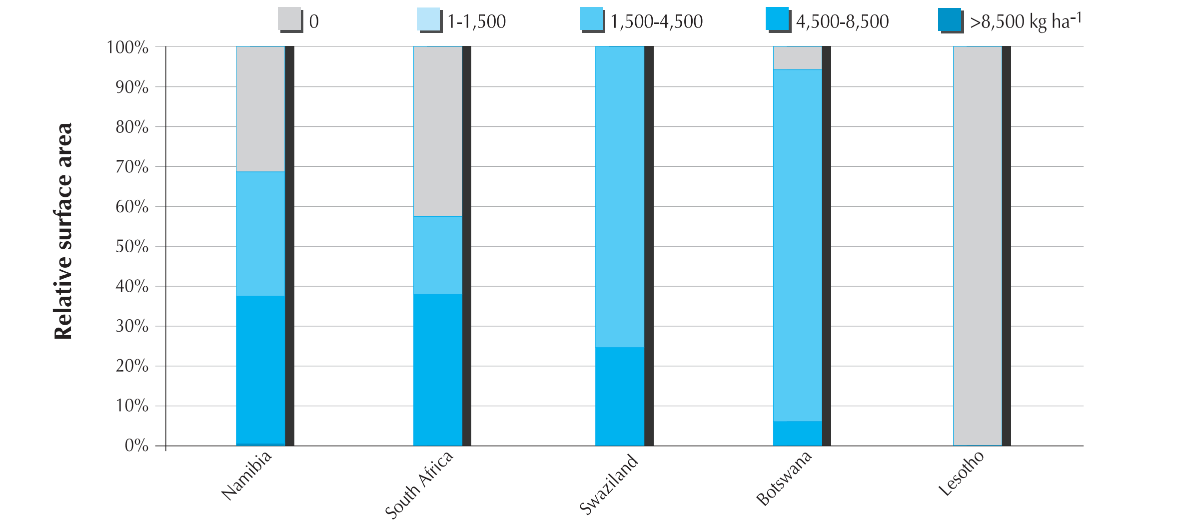
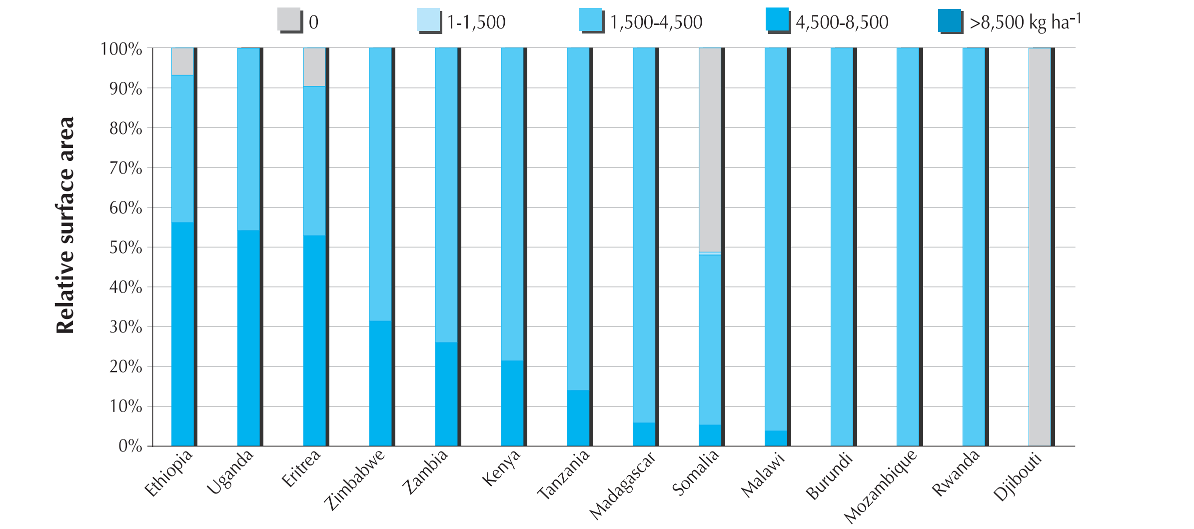


Figure 12.5 - **Relative surface area with potential biomass for bambara groundnut** EAST AFRICA



Figures 12.2-12.11 provide more detail on the biomass predictions for specific countries within each region. **Figure 12.2** shows that there is relatively little productive potential for bambara groundnut in Algeria, the Libyan Arab Jamahiriya and Egypt. In contrast 43% of Tunisia and 36% of Morocco are within the VS category for potential biomass.

Most areas in Central Africa **(Figure 12.3)** can be classified as moderately suitable. Although 45% of areas of Chad and 40% of the Sudan show crop failure, the whole of the Central African Republic can be classified within at least category MS for cultivation. Predictions indicate that bambara groundnut may be unproductive in some areas of southern Africa **(Figure 12.4)**. For example all of Lesotho is classified as unsuitable. In contrast, more than 90% of Botswana, more than 57% of South Africa and nearly 70% of Namibia are classified within at least category MS. All of Swaziland falls within the S and MS categories of suitability.

Figure 12.5 shows that, with the exception of Djibouti, all of East Africa is classified within categories S and MS for biomass production of bambara groundnut. Virtually the whole of West Africa **(Figure 12.6)** is classified within category MS. Surprisingly, there are no countries in this region that are within the VS or S categories. Nevertheless, complete crop failure is unlikely.

Figure 12.6 - Relative surface area with potential biomass for bambara groundnut WEST AFRICA

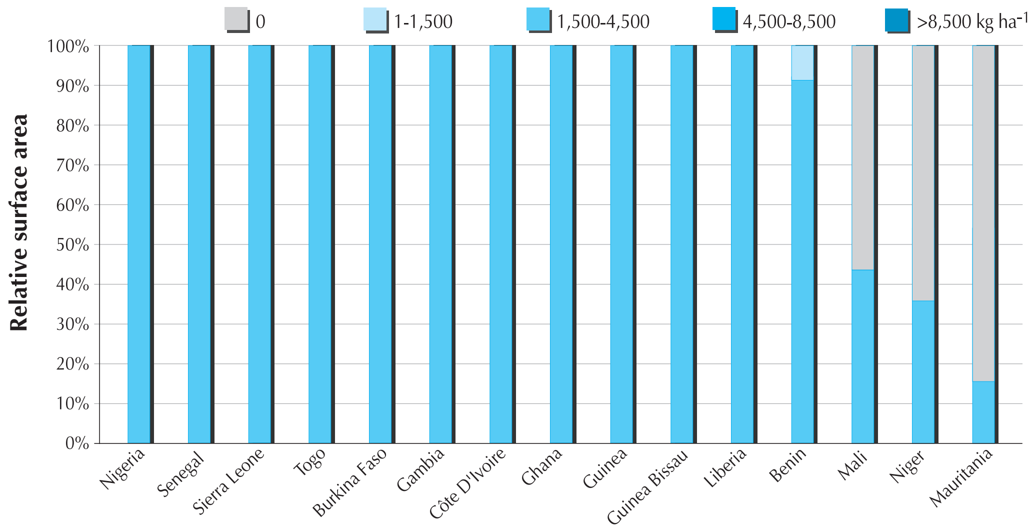


Figure 12.7 - Relative surface area with potential biomass for bambara groundnut AMERICA

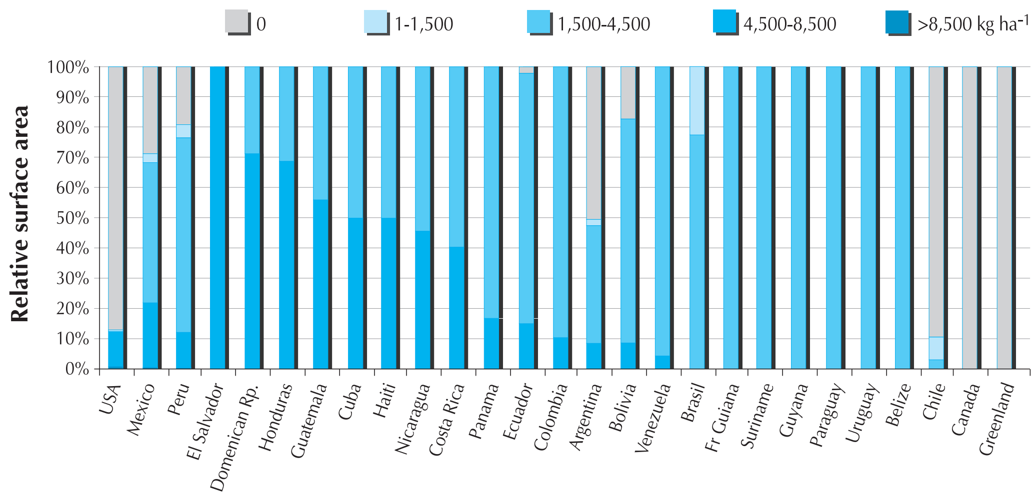
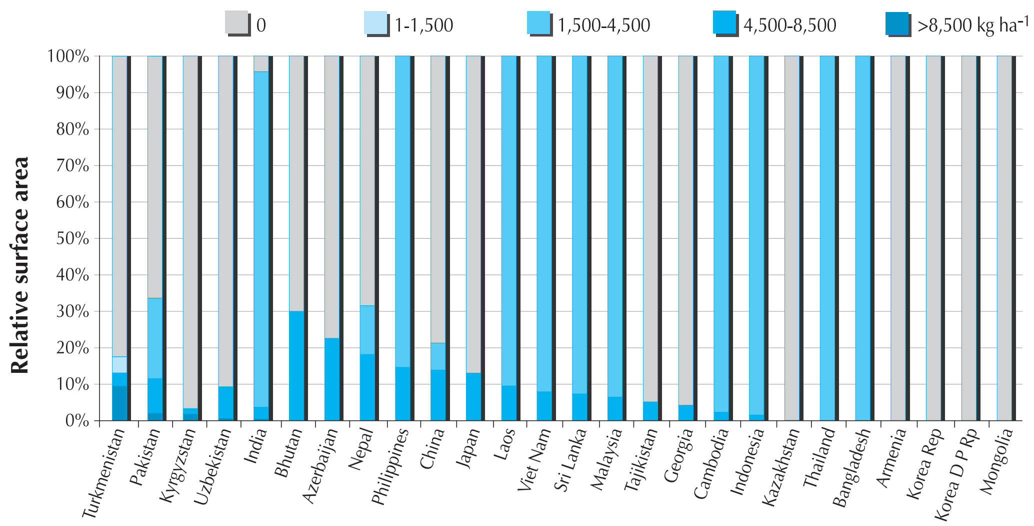


Figure 12.8 - Relative surface area with potential biomass for bambara groundnut ASIA



Despite its historical absence from this part of the world, a general assessment of the American continent **(Figure 12.7)** shows that there are many areas in this region that have high potential biomass productivity for bambara groundnut. In all countries in South America, with the exception of Argentina, more than 75% of the land area is within the S and MS categories of suitability. In contrast, 87% of the USA is classified as unsuitable for cultivation.

Within Asia **(Figure 12.8),** all of India, the Lao People's Democratic Republic, Philippines, Viet Nam, Sri Lanka, Malaysia, Cambodia, Indonesia, Thailand, and Bangladesh fall within categories S and MS.

Much of the Near East **(Figure 12.9)** is classified as unsuitable for cultivation of bambara groundnut, mainly because of low rainfall. However, for those countries with a more Mediterranean climate, there are potentially highly productive areas. For example 100%, 80% and 75% of Cyprus, Israel and Lebanon respectively fall within category VS of suitability.

The low potential productivity for much of Europe **(Figure 12.10)** is similar to that of the Near East but, for Europe, it is mainly low temperatures rather than soil moisture deficits that limit growth and development to only part of the year. However, in the Mediterranean countries of southern Europe there is considerable potential for cultivation. For example, 71% of Portugal, 60% of Greece, 57% of Spain and 49% of Italy are within categories VS and S. Where these appropriate environments are coupled with improved cultivation techniques there is considerable scope to achieve high yields of bambara groundnut (an indigenous African legume) within countries of the European Union.

Similarly, in Australia and Oceania **(Figure 12.11)** there are significant areas that are classified as moderately suitable for bambara groundnut cultivation. For example 62% of Australia is within categories S and MS.

Figures 13.1-13.11 provide the pod yields that correspond to the total biomass predictions in Figure 11. With the exception of Europe (6.5%), at least 10% of the land area of each continental region (Figure 13.1) can provide bambara groundnut pod yields within category S (1000-3000 kg ha^{-1}). As much as 30% of Africa falls within this category.

Within Africa **(Figures 13.2-13.6)** the largest potential yields occur in South, East and Central Africa. For example, 100% of Swaziland, 98% of Uganda, 95% of Zambia, 89% of Burundi, 84% of Zimbabwe and 79% of the Central African Republic have yield predictions within category S.

For America, **(Figure 13.7)** all of El Salvador, Honduras, Cuba and the Dominican Republic fall within category S for pod yield. Countries such as Uruguay, Panama, Haiti, Paraguay, Venezuela and Ecuador have land areas that are entirely within categories S or MS.

Within Asia **(Figure 13.8),** all of the Lao People's Democratic Republic, Malaysia, the Philippines, Sri Lanka, Viet Nam, Bangladesh, Indonesia, Cambodia and Thailand fall within categories S and MS. However, the country with the largest proportion of its area in category S is Tajikistan with more than 70% in category S.

In the Near East **(Figure 13.9)**, all of Cyprus, 80% of Israel, 75% of Lebanon and 70% of the Syrian Arab Republic are within category S.

For Europe **(Figure 13.10)**, Portugal, Greece, Spain and Italy have the greatest productive potential for bambara groundnut, with as much as 62% of Portugal in category S and more than 50% of the land area in each country within categories S and MS. There is even a small potential for bambara groundnut in France with over 12% of land area in categories S and MS.

Australia **(Figure 13.11)** has 60% of its land area within categories S and MS.

At this stage it is important to note the following limitations to the above analysis of potential pod yields in bambara groundnut. First, the methodology takes no account of specific soil types. Although the model requires inputs that depend on the physical characteristics of soil e.g. available water, there is no attempt to assess productivity in terms of soil classification for contrasting locations. Second, there is no allowance for the effects of pests and diseases on the capture and conversion of environmental resources and allocation to pod yield. Third, many bambara groundnut landraces have a specific daylength requirement for pod filling, i.e. allocation to yield will only begin at a particular daylength. In assessing potential productivity at each location, this daylength requirement has not been included.

Figure 12.9 - Relative surface area with potential biomass for bambara groundnut NEAR EAST

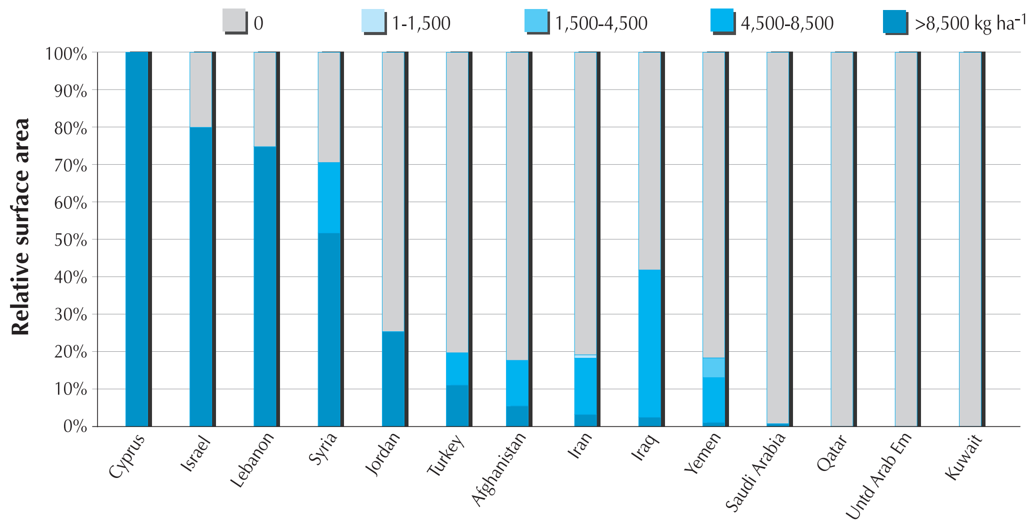


Figure 12.10 - Relative surface area with potential biomass for bambara groundnut EUROPE

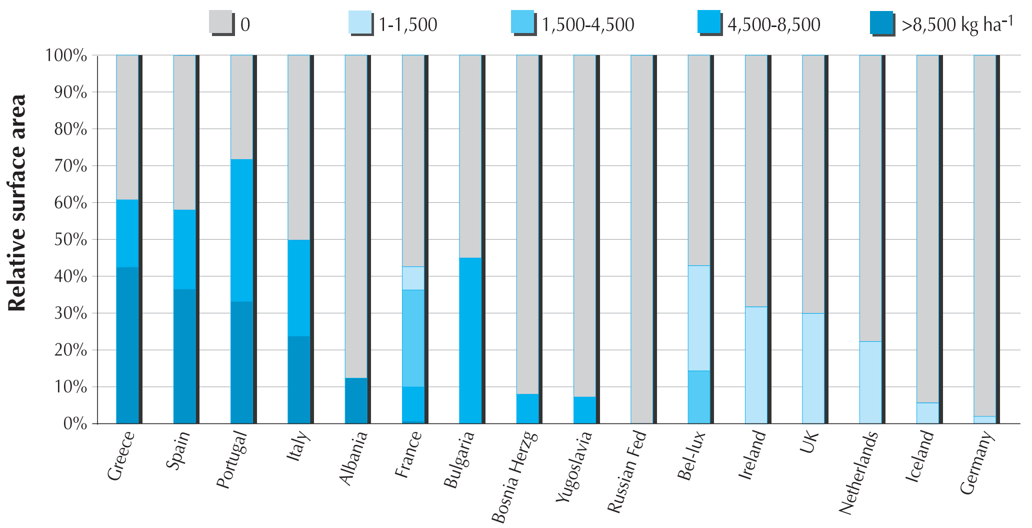


Figure 12.11 - Relative surface area with potential biomass for bambara groundnut AUSTRALIA & OCEANIA

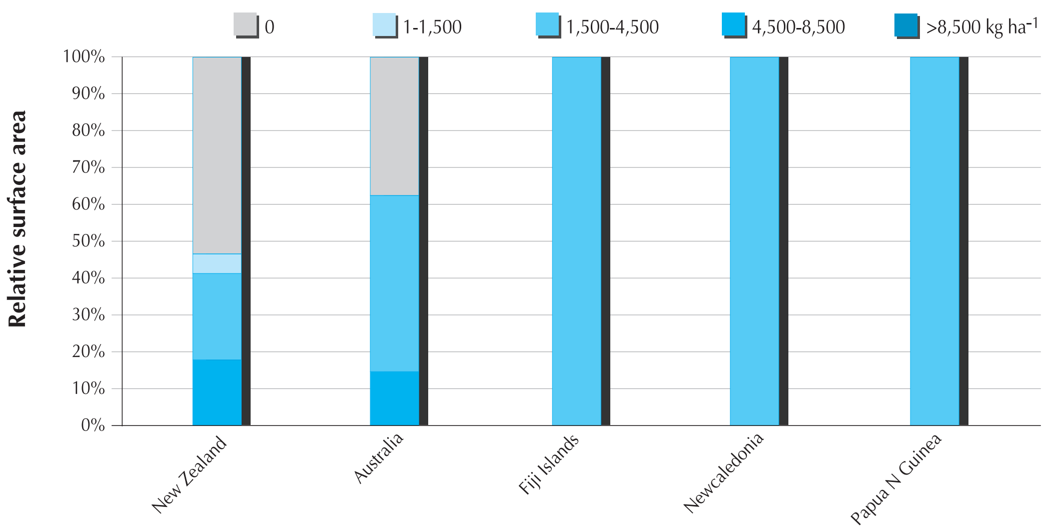


Figure 13.1 - Relative surface area with potential pod yield for bambara groundnut CONTINENTS

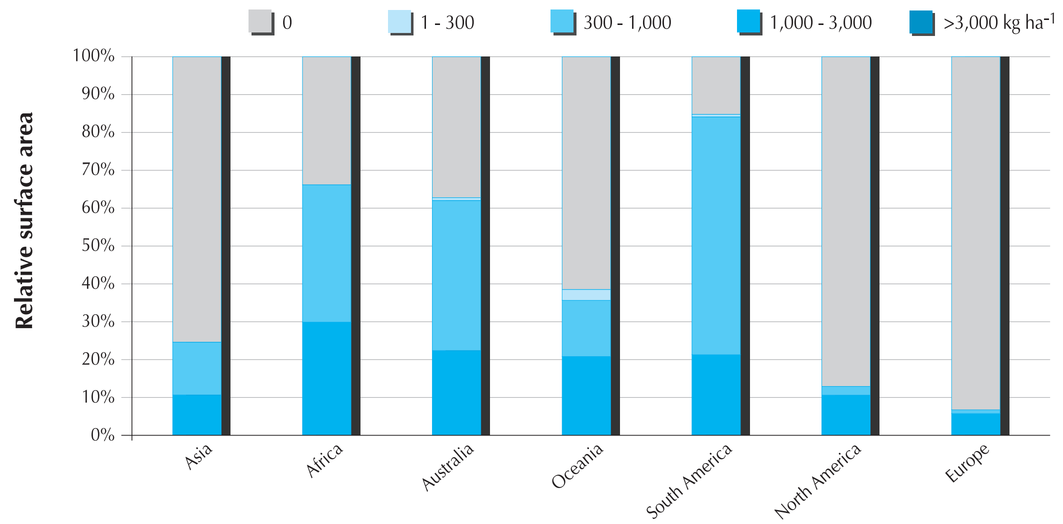


Figure 13.2 - Relative surface area with potential pod yield for bambara groundnut NORTH AFRICA

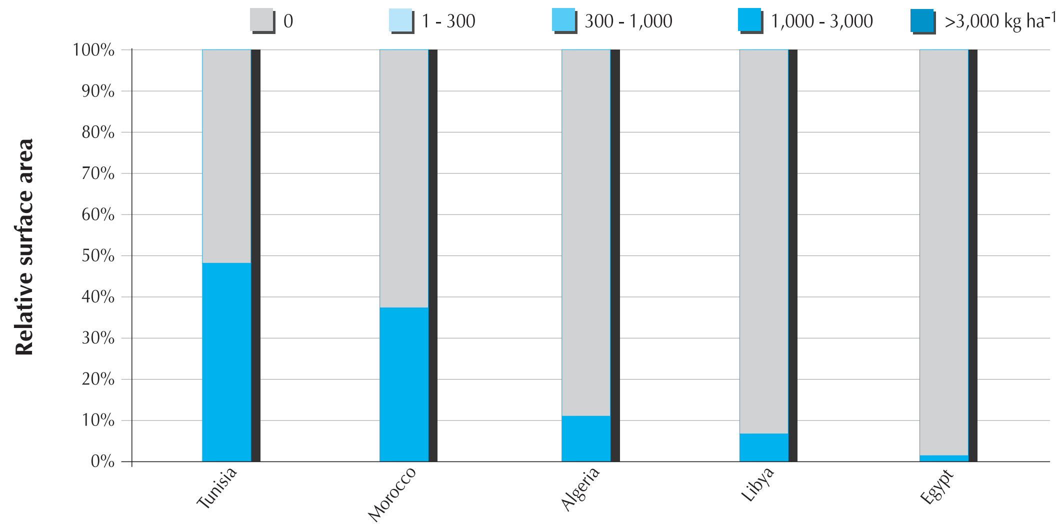


Figure 13.3 - Relative surface area with potential pod yield for bambara groundnut CENTRAL AFRICA

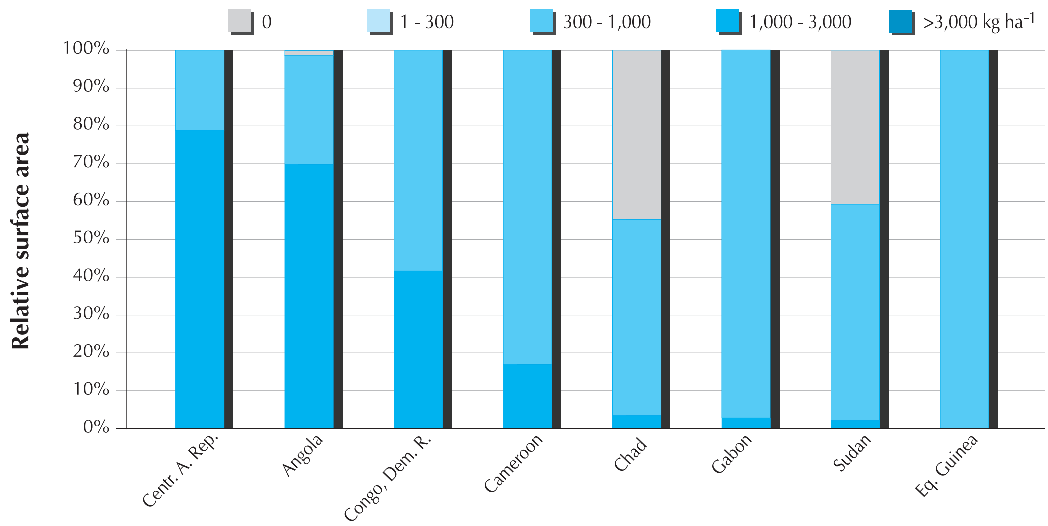


Figure 13.4 - Relative surface area with potential pod yield for bambara groundnut SOUTH AFRICA

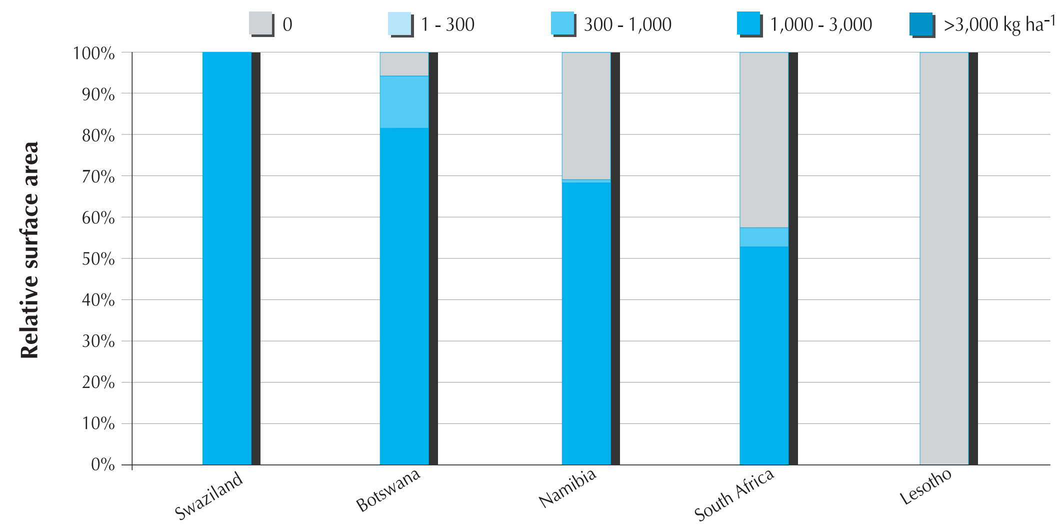


Figure 13.5 - Relative surface area with potential pod yield for bambara groundnut EAST AFRICA

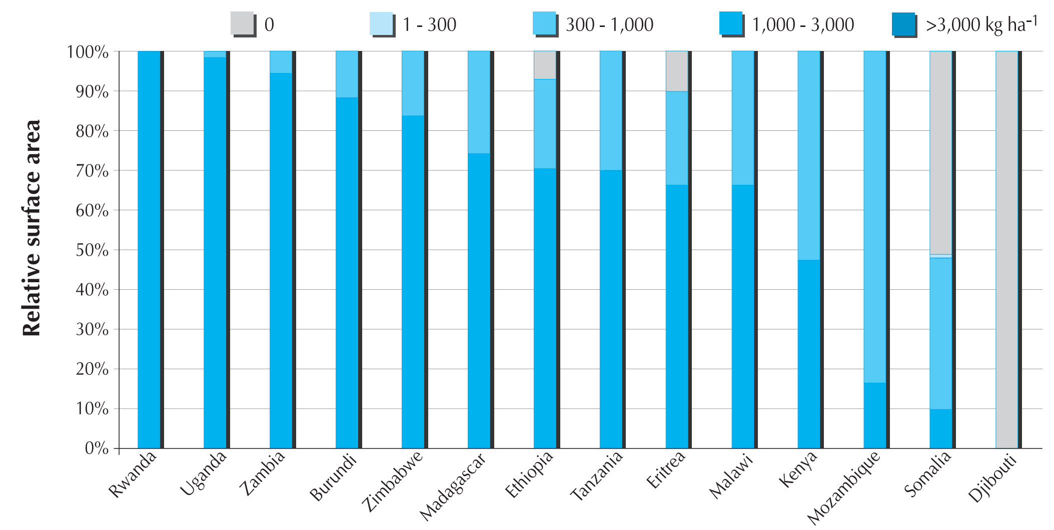


Figure 13.6 - Relative surface area with potential pod yield for bambara groundnut WEST AFRICA

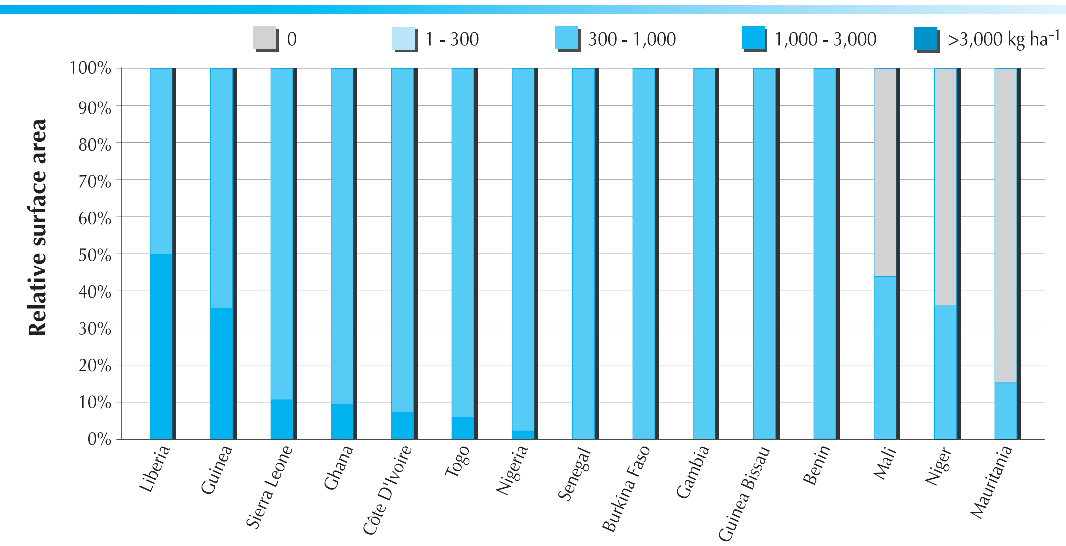


Figure 13.7 - Relative surface area with potential pod yield for bambara groundnut AMERICA

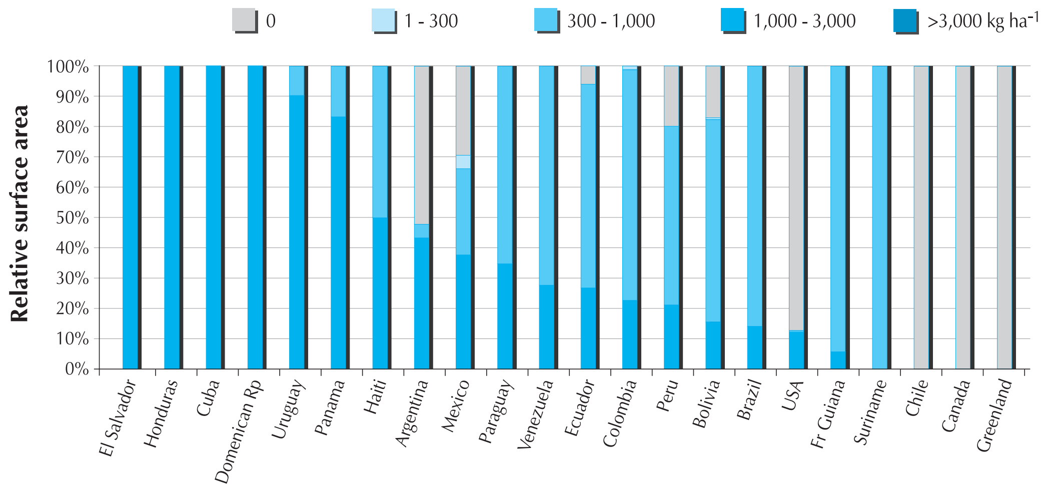


Figure 13.8 - Relative surface area with potential pod yield for bambara groundnut ASIA

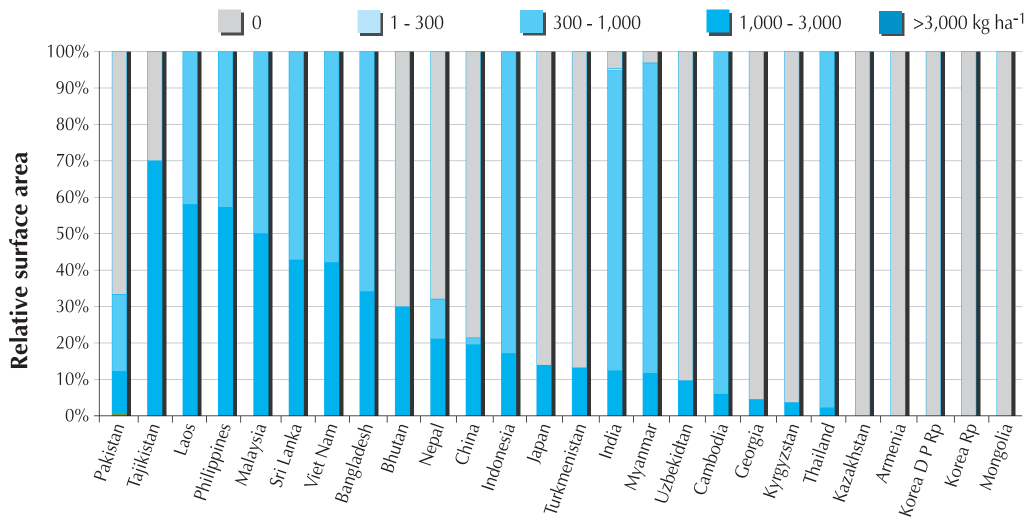


Figure 13.9 - Relative surface area with potential pod yield for bambara groundnut NEAR EAST

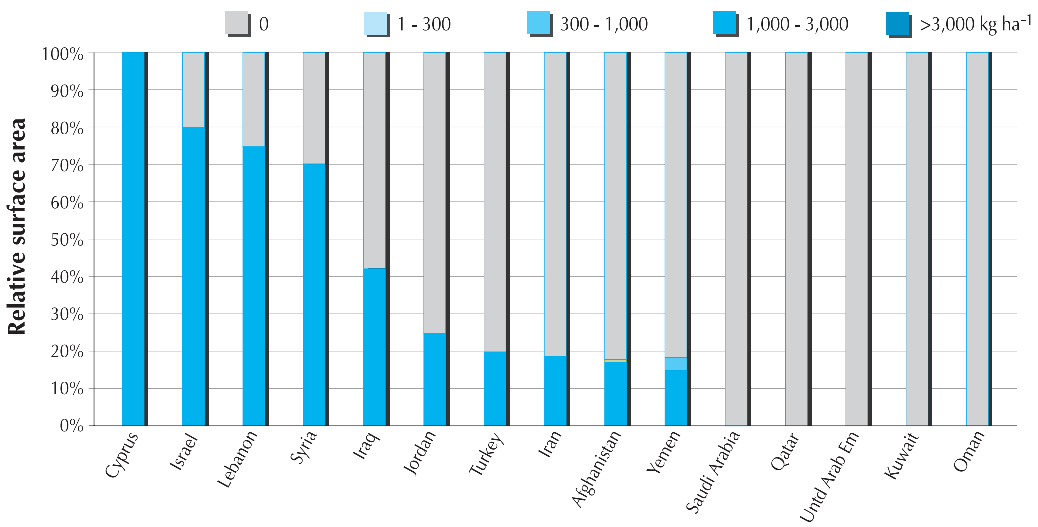


Figure 13.10 - Relative surface area with potential pod yield for bambara groundnut EUROPE

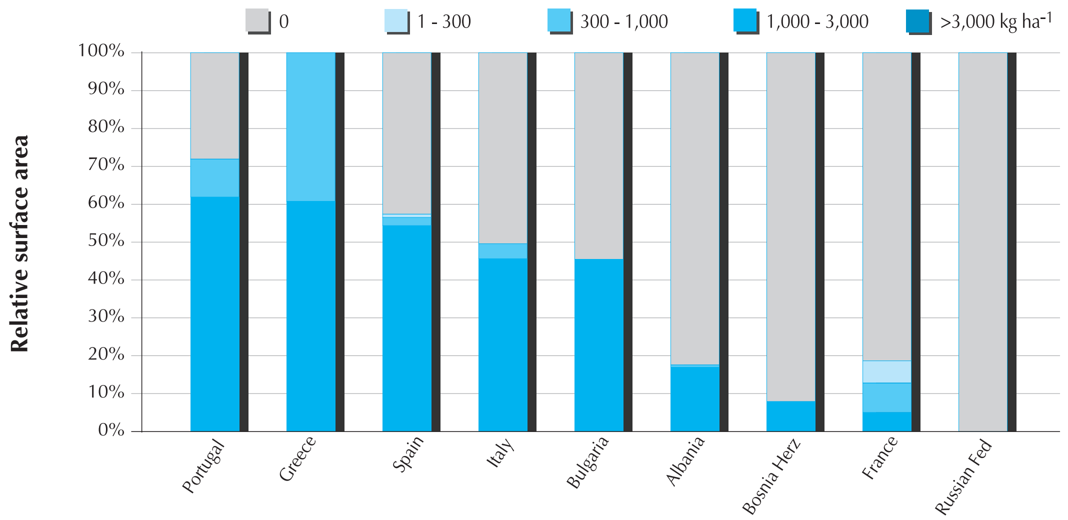
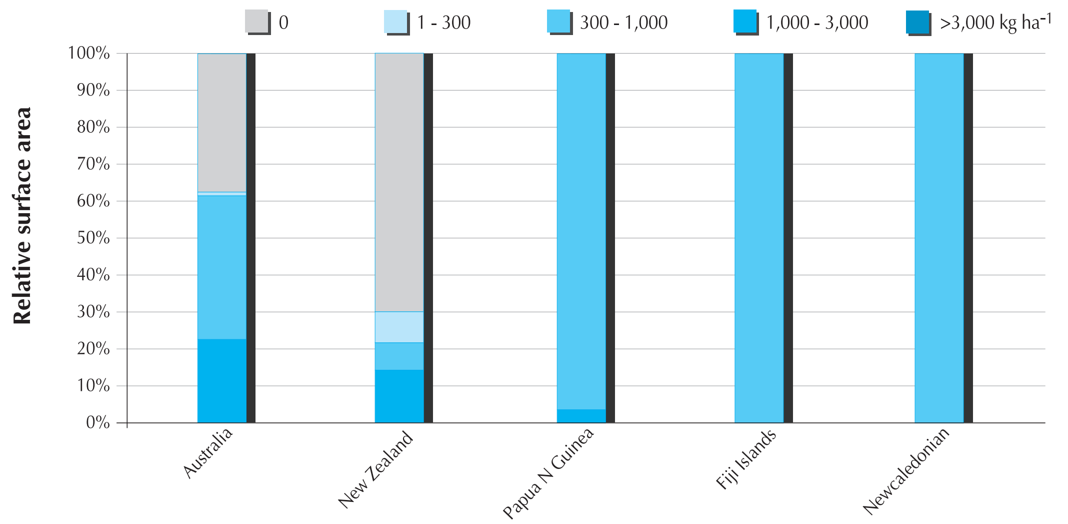


Figure 13.11 - Relative surface area with potential pod yield for bambara groundnut AUSTRALIA & OCEANIA



This limitation is likely to restrict the period of the year when maximum crop yields can be achieved and its influence becomes more significant at locations with greater annual variation in daylength, i.e. those progressively further from the equator.

In practice this limitation can be overcome by inputting the daylength requirements for any particular landrace in relation to productivity at any specific latitude.

From the above analysis it is difficult to identify a uniform ecophysiological niche for bambara groundnut. However, based on model predictions, a combination of uniform distribution of rainfall during the growing season linked with relatively cool temperatures in terms of tropical species that extend the growing season appear to result in the highest potential pod yields.

EVALUATION

As mentioned earlier, the spatial patterns of simulated yield can improve production estimates and highlight areas that are most vulnerable to drought (Carbone *et al.*, 1996). However the main limitations in such

TABLE 3
Comparison between predicted and reported pod yield values (kg ha^{-1})

Area	Predicted				Reported	
	min	max	mean	SD	range	author
Africa	134	2765	1277	544	500	Heller *et al* (1997)
					300-800	Begemann (1988)
					650-850	Stanton *et al* (1966)
Tanzania	612	1557	1082	216	650-850	Rachie (1979)
Zimbabwe	843	1567	1199	175	3870 max.	Johnson (1968)

analyses are not only the limited availability of climate and soils data, which preclude the use of the more sophisticated simulation models, but also the lack of observed or reported crop yields. This problem is common to all underutilised crops where a common system of yield reporting and evaluation is lacking. It is therefore extremely difficult to verify predicted yields of underutilised crops against reliable figures for actual on-farm yields achieved at similar locations. Moreover, predictions in this study are simply based on agro-ecological potential and ignore the effects of management. In some cases the actual yields are based on farmers fields (unreliable and unreplicated) and in others on experiments with management inputs. Thus, at this stage, it was not possible to construct a comprehensive comparison between predicted and reported figures.

Based on the above and on the scarcity of data available, **Table 3** shows a simple comparison between predicted and reported pod yield values.

Conclusions

INTERPRETATION OF BAMBARA GROUNDNUT POTENTIAL PRODUCTION

This study only used data that are comparable across the world. This approach limited the number of important factors that could have been used in the evaluation (e.g. soil data), but it enabled comparisons to be made between countries based on consistent climate data. More importantly, this methodology enables crop experimentation and improvement to be planned and executed by evaluating the similarities and needs within and between countries and regions. To this end, the primary objectives of this study have been achieved. The methodology provides both an assessment of the productive potential of regions such as Africa, where the crop is widely grown but where quantitative evidence is scant, incomplete or inaccessible, and defines new regions not previously associated with bambara groundnut but where environmental factors indicate a potential for productive growth.

Much of the Mediterranean basin appears to provide the ideal agro-ecological environment for bambara groundnut with predicted biomass exceeding that in regions of sub-Saharan Africa that have been associated with the crop for centuries. Nevertheless, there remains considerable scope within its current distribution to increase bambara groundnut productivity by a clearer understanding of how factors such as the seasonal distribution of rainfall, daylength and range of temperatures influence the allocation of assimilates to pod yield. Ultimately, it is the expansion of production and consumption patterns for crops such as bambara groundnut both within and beyond their current areas of cultivation that will determine whether they become significant crops for the world or disappear.

In relation to underutilised crops, one of the major concerns of sponsors is the possibility that effort is wasted on species of unknown potential in locations of unknown suitability. At this stage, our preliminary assessment allows planners to select promising locations, countries or regions that justify more detailed studies that bring local factors into the analysis and taking advantage of data of higher resolutions.

Primarily because of the world-scale used and the resolution and the assumptions employed, the estimates of bambara groundnut potential generated in this study are essentially indicative of bambara groundnut *potential*. Clearly, as with any crop, not all of the areas that has been identified as having potential can be allocated to bambara groundnut cultivation as some of these are already occupied by protected areas, inland water bodies, buildings and roads.

Our analysis of the spatial productivity of bambara groundnut demonstrates how a weather data generator and a dynamic crop simulation model can be usefully linked in a GIS on a global scale. This integration allows an examination of spatially complex, non-linear, interacting environmental variables and their combined influences on crop yield. Consideration of the spatial variability of model inputs has at least two potential benefits. First, where site-specific information on particular crops is lacking – as with most underutilised species – this approach allows us to produce a reasonable assessment of likely productivity with minimal field data. Second, for all crops this approach allows us to assess the potential consequences of future climatic variability and change on agricultural production.

The major drawback with such activities is the paucity of input data. Generally, the availability of digital soil data is more limited than meteorological data. To build digital soils data is an expensive and time-consuming process (Reed and Whistler, 1990). At this stage, we have not applied soils data mainly because of their inaccessibility and processing requirements. The inclusion of soil information to explain local variations in crop yields is an important future objective. Another major limitation is that the model takes no account of the effects of pests and diseases on the likely yields of bambara groundnut at any particular locations. This is a major limitation that needs to be considered in any future developments.

Our crop model is still some way short of a being a generic and comparative model for underutilised crops. This is mainly because there are insufficient datasets available for any other underutilised species. However, the basic modelling strategy developed for bambara groundnut can be rapidly adapted to any other underutilised (or major) crop if suitable collaborators can be identified. Ideally, co-operation between growers, experimenters and modellers interested in a representative range of species would provide sufficient critical mass to test and refine the approach that we have taken for a single species. The output from such collaboration could result in a user-friendly package to benefit all interested partners with minimum cost and maximum speed. In particular, such activities that generate reliable and widespread information on underutilised species could be of greatest benefit to developing countries, where most of these species originate and grow.

STUDY REFINEMENTS

The analytical system applied in this study consists of three main components; a weather data generator, a crop model, and GIS. The first two components can be continuously enhanced whenever more data are available. The updating of weather and crop data would enable us to review and refine the simulation approaches built into them. In particular, the limited datasets available in the development of the BAMnut model, especially for application across the world, are of most concern.

The strong effects of soil conditions, in particular water releases characteristics, on crop growth and development mean that better information on soil conditions as well as climate data and specific crop requirements is a priority for the future. It is also appropriate to identify those areas where soils are either highly productive or impoverished to establish likely yield limitations and potential yield ceilings within any specific agro-ecological environment. FAO's agro-ecological zoning (AEZ) methodology developed by FAO and the International Institute for Applied System Analysis (IIASA) already does this (www.fao.org/ag/agl/agll/aez.htm) and this methodology could usefully be applied in the future.

Many of the results presented in this study will help develop an interactive online information and mapping system for bambara groundnut that WAICENT has already begun to construct. The first phase of the Web site is finished and involved preparing and verifying the bambara groundnut collection by Begemann (www.dainet.de/genres/bambara/index.htm). For the second component a map for Africa was prepared showing 705 collection sites as points from which the user can click and retrieve data from Begemann's database. Then, five different thematic maps i.e. annual rainfall, climate, dominant soils, and topography for Africa were prepared that the user can select and view along with the collection sites. The next phase involves the map modelling exercise, so that the resulting maps from this study can be incorporated into the Web site. Furthermore, to make the GIS version of BAMnut constructed in this study accessible, it is intended to include this model in the Web site so that users will be able to create, online, different map outputs according to their chosen BAMnut model variables and, ultimately, for other underutilised crops.

The GIS version of BAMnut could be integrated into a Web-based Common Modelling Environment (CME) developed by Texas A & M University. The goal of the CME is to package a suite of models such as ASM, FLIPSIM, PHYGROW, EPIC, SWAT, APEX and NUTBALL into a unified environment that contains a matrix of mission-critical data files. These files would support policy-makers exploration of alternatives and emerging technology options. A detailed description of the CME is available at http://cnrit.tamu.edu/CME/. Collaborative work with the CNRIT team that is developing the CME has been established and preparations for adapting and testing the GIS version of BAMnut are currently underway.

As information and expertise on bambara groundnut expands, the user will be able to input *landrace*-specific information that will provide estimates of likely productivity and best management practices for the cultivation of local bambara groundnut genotypes at particular locations. The development of a wider 'generic' methodology will provide comparative estimates of productivity for contrasting underutilised (and major) species at any location.

FUTURE APPLICATIONS

Evaluation of the BAMnut model across the world and its subsequent development into a generic framework for other underutilised crops is an activity that requires an international effort. However, for all underutilised crops, any realistic effort to expand their cultivation and establish improved genotypes for specific environments must be based on identifying those regions that are most *likely* to match their physiological requirements. To maximise the use of research effort the mapping exercise described in this report should be an essential *pre-requisite* to field-based research or breeding efforts on crops such as bambara groundnut. Subsequent field studies can serve the dual purpose of accelerating progress on each particular crop with less risk of crop failure and an improvement in the accuracy of the global mapping technique.

The widespread access of the methodology and outputs presented here to end-users and policy-makers will allow future developments to be demand-led by those most interested in the use of this information. In particular, comparison of the simulated yields of underutilised crops with existing yield maps for major crops will enable decision-makers to prioritise crop and cropping systems in terms of farmers needs and national benefits.

Finally, the approach described in this report is a first attempt to map the potential areas of cultivation of one underutilised food legume across the globe. However, the approach has wider implications in terms of food security and poverty elimination. Rather than consuming specific crops, people eat a range of agricultural products that provide nutritional compounds including proteins, carbohydrates and lipids. Thus, a development of the mapping strategy described here is that it enables the production of 'nutritional maps' whereby the relative food values of different species could be assessed for individual countries or regions. In this way, policy-makers can utilise evidence of the likely yield and nutritional value of different species to design food security strategies based on the most appropriate crops to grow within each region.

Appendix

This appendix provides full and detailed description of the database and the methodology used in this study.

HARDWARE AND SOFTWARE

Hardware
Almost the entire GIS analyses were carried out using a Sun Spark Station 10.

The weather generator and BAMnut programs were run on a Pentium III DELL OptiPlex GX1 PC, 1.2 GB, 130,488 KB RAM 17 inch Video Super VGA.

Data transfers between the Sun Spark Station and the Pentium PC were carried out under Microsoft Windows NT.

Software
A Geographic Information System (ARC, Version 7.03, ESRI, Redlands, CA, USA) which has both raster and vector capabilities was used. This system is able to efficiently store geographical referenced database which includes both digital maps and their attribute files.

The weather generator and BAMnut were written in Visual Pascal. BAMnut should be run on at least a 486PC with 8MB of RAM with Windows 95 as the operating system.

WORLD WEATHER DATABASE

WORLD WEATHER DATA SELECTION AND EXTRACTION

Downloading
Location of climate data for downloads:
http://ipcc-ddc.cru.uea.ac.uk/cru_data/datadownload/observed/climatology_download.html

The following data were selected and downloaded; Maximum Temperature (ctmx6190.zip), Minimum Temperature (ctmn6190.zip), Precipitation (cpre6190.zip), Wet Days (cwet6190.zip), Vapour pressure (cvap6190.zip), Radiation (crad6190.zip), and Windspeed (cwnd6190.zip).

ASCII data format
An extract of the ASCII data file ctmx6190.dat contained in ctmx6190.zp is illustrated below:

grd_sz	xmin	ymin	xmax	ymax	n_cols	n_rows	n_months	missing
0.50	0.25	-89.75	359.75	89.75	720	360	12	-9999

-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999
-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999
-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999
-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999
-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999
-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999	-9999

Separating data by month

Each zipped file (e.g. ctmn6190.zip) contains 12 monthly ASCII files, so it was necessary to separate these files by month. Due to the very large size of each file (i.e. 259,200 records) the separation of these files was done using software. Once files were separated they were saved into individual files.

The header for each monthly ascii file

ncols	720
nrows	360
xllcorner	-180.0
yllcorner	-90.0
cellsize	0.5
NODATA_value	-9999.0

Correcting shift

The data downloaded presented a shift at zero latitude, so a shift adjustment had to be made to all the files and this was done automatically using Java software.

STANDARDISING THE DATABASE

Adjusting to Potential Evapotranspiration (PET) data from the International Institute for Applied Systems Analysis (IIASA)

The observed climate data from the University of East Anglia Climate Research Unit (CRU) data was found to be the most comprehensive and complete climate data available, however, while displaying this data using Java it was realised that a large number of islands not displayed in the CRU data visualisation page were present (i.e. http://ipcc-ddc.cru.uea.ac.uk/cru_data/visualisation/visual_index.html). To solve this problem, adjustments were made according to PET data from IIASA for the following two reasons; (a) PET data could be used as an input to the model of the present study because it was based on CRU data, and (b) the islands displayed in the PET data were identical to the CRU data visualisation page. The adjustments made are described below:

Converting text files from DOS to UNIX

The following example illustrates how one of the text files was converted from DOS to UNIX using Arc/Info software:

Grid: asciigrid ctmx6190_0.dat ctmx6190_0.txt

Where:
asciigrid = Arc/Info command
ctmx6190_0.dat = ASCII file for maximum temperature for the month of January in DOS format
ctmx6190_0.txt = ASCII file for maximum temperature for the month of January in UNIX format.

Converting data from ASCII to a GRID

The following example illustrates how one of the files was copied and converted into a grid using Arc/Info software:

Grid: asciigrid ctmx6190_0.txt ctmx6190_0

Where:
asciigrid = Arc/Info ASCII to grid conversion command
ctmx6190_0.txt = ASCII file for maximum temperature for the month of January
ctmx6190_0 resulting grid.

Base grid

A grid was used as a template to standardise grid extensions. The cell size and geographical project of PET for the month of January was chosen as the base grid. A description of the base grid is illustrated below:

The base grid

Description of GRID /sun1 disk4/faogis4/jippe/dem/petjan

Cell Size = 0.500	Data Type: Integer
Number of Rows = 360	Number of Values = 289
Number of Columns = 720	Attribute Data (bytes) = 8
Boundary	**Statistics**
Xmin = -180.000	Minimum Value = 0.000
Xmax = 180.000	Maximum Value = 288.000
Ymin = -90.000	Mean = 63.706
Ymax = 90.000	Standard Deviation = 70.197

Coordinate System Description

Projection GEOGRAPHIC

Units DD Spheriod CLARKE1866

Based on the number of rows and columns defined above, the base grid had a total of grid cells (i.e. 360 x 720 = 259,200). The number of pixels for the global 'land' areas alone was 62,482. Data originally stored in ASCII format or having a different resolution or projection were converted to the base grid. Example:

```
Grid: setwindow petjan
Grid: setmask petjan
Grid: setcell petjan
Grid: tmx6190_0 = ctmx6190_0
```

Where:

setwindow, setmask and setcell are Arc/Info commands
petjan = PET grid for the month of January
ctmx6190_0 = maximum temperature for the month of January
tmx6190_0 = output grid.

SUMMARY STATISTICS OF CLIMATE DATA USED AS INPUTS TO BAMNUT

Tables 4, 5, 6 and **7** show statistics of the mean monthly climate datasets for global land areas used in this study as inputs to the model BAMnut developed.

A comparison of climate values between the original CRU data and the adjusted CRU data (i.e. CRU data set to the exact PET format from IIASA) showed no significant differences amongst data, the largest difference was of 0.4 when comparing the mean value of minimum temperature for the month of January.

WORLD WEATHER GENERATOR

SETTINGS CREATED AS ENTRIES FOR THE DAILY DATA WEATHER GENERATOR

Table 8 shows the settings that were made for the weather generator. Each folder corresponds to one area of the world, the number of files created from each area and their size in Mb is also shown. Computer memory problems were encountered due to the vast amount of files that the generator had to create, so the information in **Table 8** is based on trial-and-error meaning that it is information that should be used to

TABLE 4

Statistics of mean monthly air temperature values for global land areas

Month	Maximum temperature (°C)				Minimum temperature (°C)			
	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD
January	-48.6	40.3	3.58	22.81	-56.0	26.5	-7.66	22.00
February	-44.3	39.2	5.00	22.33	-54.2	26.0	-6.65	21.79
March	-39.9	40.5	8.83	20.11	-56.3	25.9	-3.33	20.10
April	-32.9	41.9	13.80	16.79	-45.2	26.8	1.66	16.50
May	-18.6	43.3	18.40	13.39	-34.7	28.5	6.57	12.35
June	-7.8	44.7	21.97	10.70	-24.6	29.2	10.19	9.68
July	-5.1	45.6	23.68	9.39	-21.6	31.0	12.05	8.67
August	-7.0	44.8	22.76	9.93	-28.5	30.2	11.19	9.21
September	-15.4	42.3	19.53	12.14	-41.4	28.5	8.18	11.23
October	-26.7	39.3	14.42	15.93	-44.4	26.9	3.77	14.37
November	-38.5	40.1	8.57	19.85	-53.0	26.0	-2.29	18.76
December	-45.7	40.9	4.74	21.96	-53.6	26.4	-6.01	20.78

TABLE 5

Statistics of mean monthly precipitation and wet days values for global land areas

Month	Rainfall ($mm\ d^{-1}$)				Wet days (Days)			
	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD
January	0	21.9	1.71	2.42	0	30.5	10.51	7.15
February	0	19.5	1.74	2.48	0	27.8	9.36	6.14
March	0	19.1	1.75	2.39	0	30.6	9.72	6.19
April	0	19.8	1.75	2.22	0	29.8	8.99	5.39
May	0	21.4	1.80	2.22	0	29.8	9.38	5.44
June	0	37	2.12	2.57	0	29	9.70	5.64
July	0	40.1	2.35	2.69	0	30.9	10.34	5.82
August	0	39.2	2.31	2.57	0	30.9	10.42	5.83
September	0	38.7	2.05	2.28	0	28.8	9.97	5.68
October	0	32.7	1.80	2.08	0	27.8	10.25	6.13
November	0	26	1.76	2.15	0	28.9	10.37	6.58
December	0	20.8	1.71	2.31	0	29.8	10.62	7.03

TABLE 6

Statistics of mean monthly vapour pressure and radiation values for global land areas

Month	Vapour pressure (hPa)				Radiation ($W\ m^{-2}$)			
	MIN	MAX	MEAN	SD	MIN	MAX	MEAN	SD
January	0.1	31.1	7.77	8.96	0	294	89.49	77.79
February	0.1	32	8.01	9.06	0	268	104.78	72.34
March	0.1	31.5	8.61	8.90	16	262	129.33	58.09
April	0.1	32	9.53	8.60	59	286	159.31	41.47
May	0.1	34.6	10.86	8.05	33	307	181.00	42.11
June	0.1	35.8	12.62	7.40	22	335	190.09	48.61
July	0.1	35.6	14.14	7.16	25	332	186.70	46.79
August	0.1	34.2	13.83	7.39	42	308	166.79	47.95
September	0.1	35.4	12.08	7.83	18	268	140.56	60.07
October	0.1	32.3	10.16	8.2	0	282	114.61	72.79
November	0.1	31.8	8.72	8.55	0	290	95.04	79.18
December	0.1	31.5	7.96	8.77	0	301	85.78	79.78

TABLE 7
Statistics of mean monthly wind speed values for global land areas

Month	Wind speed ($m\ s^{-1}$)			
	MIN	MAX	MEAN	SD
January	0.1	14.3	3.16	1.52
February	0.2	14.3	3.19	1.46
March	-2.8	14.2	3.28	1.36
April	-6.1	14.1	3.38	1.34
May	-7.4	14.2	3.31	1.26
June	-7.2	24.4	3.21	1.29
July	-8.6	28.9	3.15	1.35
August	-7.4	29	3.13	1.39
September	-7.1	24.4	3.18	1.41
October	-4.7	19.8	3.26	1.47
November	-2.2	14.2	3.23	1.52
December	-1	14.3	3.15	1.49

TABLE 8
Settings for weather generator

	Top left		Bottom right		Technical notes	
Folder no.	**Lat.**	**Long.**	**Lat.**	**Long.**	**No. Files**	**Size Mb**
1	90	0	75	180	505	9.27
2	75	0	65	180	4410	84.2
3	65	0	60	180	3581	68.3
4	60	0	50	180	5706	9.26
5	50	0	40	180	5283	100
6	40	0	30	180	4453	85
7	30	0	20	180	4560	87.1
8	20	0	10	180	2968	56.5
9	10	0	0	180	2250	42.7
10	0	0	-10	180	1881	35.6
11	-10	0	-30	180	4210	80.3
12	-30	0	-60	180	1225	23
13	-60	0	-90	180	0	0
14	90	-180	85	0	0	0
15	85	-180	83	0	28	0.55
16	83	-180	75	-90	305	5.43
17	83	-90	75	0	0	0
18	75	-180	65	-90	1945	36.9
19	75	-90	65	0	0	0
20	65	-180	60	0	2100	39.8
21	60	-180	50	0	3054	58.2
22	50	-180	40	0	2599	49.4
23	40	-180	30	0	2125	40.3
24	30	-180	20	0	1302	24.5
25	20	-180	10	0	1173	22
26	10	-180	0	0	1292	24.3
27	0	-180	-10	0	1738	32.9
28	-10	-180	-30	0	2534	48.2
29	-30	-180	-60	0	1255	23.6
30	-60	-180	-90	0	0	0
					62,482	

recreate the data or is helpful in creating daily data for another year or even better for enhancing the generator used.

Output data format for one of the files created for the United Republic of Tanzania, only the first 10 days of the simulated year (1990) are shown:

@Date	SRAD	Tmax	Tmin	Rain	Evap	MNVP	Wind	ACO2
90001	6.2	25.3	17.1	4.9	-99.	-99.	-99.	340.0
90002	11.8	29	20.9	15	-99.	-99.	-99.	340.0
90003	10.8	29.6	19	6.1	-99.	-99.	-99.	340.0
90004	4.6	30.3	20.3	0.2	-99.	-99.	-99.	340.0
90005	1.6	29.4	23.6	8.4	-99.	-99.	-99.	340.0
90006	9	31.5	22.2	10	-99.	-99.	-99.	340.0
90007	16.5	28.5	21.2	3.5	-99.	-99.	-99.	340.0
90008	9.5	25.8	19.1	1.4	-99.	-99.	-99.	340.0
90009	14.1	23.3	17.5	5.3	-99.	-99.	-99.	340.0
90010	16.7	26.6	17.4	5.4	-99.	-99.	-99.	340.0

The weather generator takes approximately 160 hours to generate the required data, however, it can now serve as inputs to current and future versions of BAMnut, thus, there is no need to recreate daily data. The present GIS version of BAMnut takes 80 minutes to create the biomass and pod yield files, and it is expected that the Web version of BAMnut will the take about the same amount of time to generate the two files. However, the user will be able to work in other computer applications and leave the model running, and the Web model will have a report progress function, so that the user will not have to wait for model outputs.

STATISTICS OF OUTPUTS FROM BAMNUT

CONVERTING GRIDS TO AN EQUAL-AREA PROJECTION

The result grids were converted to an equal-area projection (Flat Polar Quartic) to calculate the areas covered by each class in each country of Africa.

```
Arc: project grid bio11feb_5 biomass_pq llpolq.prj
Arc: project grid pod11feb_5 podyield_pq llpolq.prj
```

To convert grids to Flat Polar Quartic projection the parameters specified in the file llpolq.prj illustrated below were used:

```
INPUT
PROJECTION GEOGRAPHIC
UNITS DD
PARAMETERS
OUTPUT
PROJECTION FLAT POLAR QUARTIC
UNITS METERS
PARAMETERS
00 00 00
end
```

ADJUSTING AND STANDARDISING THE PROJECTION

After the biomass and pod yield maps had been converted to a polar quartic projection, they presented a distortion in the projection when displayed. To solve this problem a polar quartic projection mask (named templpolq) was used:

Arc: describe templpolq

Description of Grid templpolq

Cell Size = 9250.000	Data Type: Integer
Number of Rows = 1827	Number of Values = 1
Number of Columns = 4057	Attribute Data (bytes) = 8
Boundary	**Statistics**
Xmin = -18761636.000	Minimum Value = 1.000
Xmax = 18765614.000	Maximum Value = 1.000
Ymin = -8445739.000	Mean = 1.000
Ymax = 8454011.000	Standard Deviation = 0.000

Coordinate System Description

Projection FLAT_POLAR_QUARTIC			
Units	METERS	Spheroid	SPHERE
Parameters:			
Longitude of projection centre	0	0	0.000

Procedures for projection adjustment using a mask:

Grid: setmask templpolq
Grid: biomass_pq2 = biomass_pq

Grid: setmask templpolq
Grid: podyield_pq2 = podyield_pq

Converting a world coverage to a grid

The coverage WFSCOV, which contains the country boundaries (i.e. areas) was converted to a GRID:

Arc: polygrid wfscov wfscov_grd cntcode

Where:
polygrid = GRID command
wfscov = coverage
wfscov_grd = output grid
cntcode, coverage item containing to country boundary names.
The cell size was set to an equal area projection cell size of 59311.282.

Combining grids

The GRID wfscov_grd was overlaid on the biomass and pod yield maps in order to produce the statistics by country.

Grid: biomass_stat = combine(wfscov_grd, biomass_pq2)
Grid: podyield_stat = combine(wfscov_grd, podyield_pq2)

Where:
biomass_stat and podyield_stat = output grids
combine = GRID command
wfscov_grd = world grid in flat polar quartic projection
biomass_pq2 and podyield_pq2 = biomass and pod yield grids in flat polar quartic projection.

Creating the text files using Arc/Info INFO

Biomass

ENTER COMMAND >SEL BIOMASS_STAT.VAT
ENTER COMMAND >OUTPUT ../BIOMASS_STAT.TXT
ENTER COMMAND >DISPLAY COUNT,',',WFSCOV_GRD,',',BIOMASS_PQ2 PRINT
ENTER COMMAND > Q STOP

Pod Yield

ENTER COMMAND >SEL PODYIELD_STAT.VAT
ENTER COMMAND >OUTPUT ../PODYIELD_STAT.TXT
ENTER COMMAND >DISPLAY COUNT,',',WFSCOV_GRD,',',PODYIELD_PQ2 PRINT
ENTER COMMAND > Q STOP

Converting text files from UNIX to DOS

The following example illustrates how one of the text files was converted from UNIX to DOS using Arc/Info software:

Grid: gridascii biomass_stat.txt biomass_stat.dat

Where:
gridascii = Arc/Info command
biomass_stat.txt = biomass file in UNIX
biomass_stat.dat = resulting biomass file in DOS format.

Manipulating text files in EXCEL

a. The text files were imported into EXCEL
b. To calculate the areas of each class occurring in the countries, the number of cells (COUNT) was multiplied by the square of the cell size in kilometres (59.30642 x 59.30642).
c. Percentage areas were calculated from each suitability class for each country.

For example: 59.30642 x 59.30642 = 3517.251

Suitability class	Count	Cell size	Count x cell size	Sum	Percentage
2	155	3517.251	545174	622553.5	87.57
2	22	3517.251	77379.53	622553.5	12.42

d. Results were plotted using histograms.

GRID OUTPUTS

The procedures used to create the map compositions for the maps presented in this study are illustrated below using the biomass grid as an example:

Standardising the grid to a common colour range

For purposes of analysis and/or illustration, the biomass grid had to be reclassified to a common colour range.

biomass_5 = reclass (biomass, bio11feb_5.rem)

Where:

biomass_5 = reclassified grid file

reclass = GRID function to reclassify (or change) integer values of the input cells using a remap table on a cell-by-cell basis within the analysis window

biomass = original water requirement grid

biomass_5.rem = remap table.

The remap table biomass_5.rem is shown below:

0 – 0 : 1
1-1,500: 2
1,500-4,500: 3
4,500-8,500: 4
>8,500 : 5

AML to plot the grid

The AML, biomass.aml illustrated below was used in ARCPLOT to generate a map composition for the biomass grid:

```
killmap biomass_mc
mape biomass
pagesize 11.7 8.3
map biomass_mc
linesymbol 5
box 0.1 0.1 11.6 8.2
mapposition cen cen
shadeset BAMnut.shd
gridnodatasymbol white
grids biomass
linecolor black
arcs/sun1disk1/faogistemp/ctry25m
textset font
textsymbol 1
textsize 0.18
keyarea 0.6 1 10.7 1.23
keybox 0.15 0.1
keyseparation .13 .14
keyshade biomass.leg
```

POSTSCRIPT FILES

The maps which are presented in this study were converted to eps (i.e. postscript format). The following example illustrates how the biomass grid (map) was converted into and eps file:

```
gissw2-faogis>> setenv CANVASCOLOR WHITE
                                Arcplot: &r biomass.aml
```

```
Arcplot: display 1040
Arcplot: biomass.gra
Arcplot: plot biomass_mc box 0.1 0.1 11.6 8.2
Arc: postscript biomass.gra biomass.eps
```

where:

setenv CANVASCOLOR WHITE = sets the background colour to white
&r biomas.aml = automates the map composition of the grid
display 1040 = command used to save the map composition
biomass.gra = graphics file
plot biomass_mc box 0.1 0.1 11.6 8.2 = map composition which was reduced to suit the size required for publication
postscript = ARC command used to create the postscript file.

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