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ASSESSING THE POTENTIAL OF AN UNDERUTILIZED CROP – A CASE STUDY USING BAMBARA GROUNDNUT

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SUMMARY

Using experience with bambara groundnut (*Vigna subterranea*), this paper examines how local knowledge, genetic evaluation, research in fields, glasshouses and laboratories, and crop simulation modelling might be linked within a methodological framework to assess rapidly the potential of any underutilized crop. The approach described is retrospective in that each activity was not clearly defined and structured at the outset. However, the experience gained may help to establish a methodology by which growers, researchers and international agencies can integrate their knowledge and understanding of any particular underutilized crop and apply similar principles to accelerate the acquisition of knowledge on other underutilized species. The use of a methodological framework provides a basis for activities that maximize knowledge, minimize duplication of effort, identify priority areas for further research and dissemination, and derive general principles for application across underutilized crops in general. It also allows policy makers and planners to make comparative decisions on the nutritional, economic and research importance of different underutilized and more-favoured species. In particular, the incorporation of a generic crop simulation model within the methodological framework may assist growers, extension agencies and scientists to refine general recommendations for any particular crop to local conditions. Also, the incorporation of information gathered from the field, laboratory or market can be used to update rapidly the predictive capacity of the model for each crop.

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INTRODUCTION

Although there are over 350 000 plant species, fewer than 20 'major' crop species provide for most human food needs. Within the rest of the plant kingdom there remain many hundreds of underutilized food crops 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 fertilizers and with little guidance on improved practices. Because the production and improvement of most underutilized crops have been ignored or actively discouraged by agricultural scientists, breeders and funding agencies, any attempts to improve their germplasm or management rely on local knowledge and initiative. It is axiomatic that underutilized crops are also under-researched crops. Those efforts that have been made to evaluate such species have usually been piecemeal, and rarely have results been published in the international literature. There are few examples of a multidisciplinary research effort on an underutilized crop and no methodological framework that can be applied across a range of underutilized species.

Bambara groundnut (*Vigna subterranea*) provides a rare example of an international research effort on an underutilized crop. At various times since 1988, scientists at institutions in the United Kingdom, the Netherlands, Germany and Italy have joined forces with researchers, growers, traders and consumers in Botswana, Tanzania, Sierra Leone, Swaziland, Namibia and Zimbabwe to work on this indigenous African legume. Together, their efforts now provide a comprehensive assessment of the genetics, eco-physiology, agronomy, nutritional biochemistry, agro-processing and marketing potential of bambara groundnut. Whilst all of these activities were not always collaborative or systematically structured, the experience provides the basis for using a similar approach to evaluate, rapidly, many other under-researched species. The authors describe here how a methodological framework might be developed, using bambara groundnut as a case study.

In most developing countries, the time and funds available for research are limited. It is appropriate to ask, therefore, whether precious financial and human resources should be dedicated to research on any underutilized species about which little evidence has been systematically gathered or published. It may be that many of these species have already been investigated but they have failed to compare with the nutritional or economic qualities of the major species that have supplanted them. This may even be the case in those regions where the underutilized crops have their centres of diversity or are cultivated.

Perhaps the first questions to ask about any underutilized food crop are:

1. Why is it underutilized?
2. Does it have any nutritional or food-processing value?
3. Is there any economic demand for its products?
4. What is its agro-ecological potential?

5. Can its geographical potential be mapped?
6. What is the genetic diversity of its germplasm?
7. How can its existing germplasm be improved?
8. Can experience gained on this crop be extended to other underutilized crops?

WHY IS THE CROP UNDERUTILIZED?

Bambara groundnut is an indigenous grain legume grown mainly by female subsistence farmers in drier parts of sub-Saharan Africa. Its seeds can be eaten fresh (when semi-ripe), as a pulse (when dry and mature) or they can be ground into flour (Linnemann and Azam-Ali, 1993). The English common name derives from the Bambara tribe that now lives mainly in Mali. Its centre of origin, however, is thought to be from the Jos plateau and Yola regions of northern Nigeria through to Garua in Cameroon and, possibly, as far as the Central African Republic (Hepper, 1963). For many centuries the crop has been cultivated in tropical Africa, south of the Sahara. Slaves took it to Surinam and it has been found also in small quantities in South and Central America, India, Indonesia, Malaysia, the Philippines, Sri Lanka and parts of northern Australia (Linnemann and Azam-Ali, 1993).

Despite its long history, bambara groundnut is still cultivated from *landraces* rather than *varieties* bred specifically for particular agro-ecological conditions or production systems. Even now, the breeding system of bambara groundnut is not well understood and no one has yet produced a true variety of the crop. Nevertheless, over many centuries farmers have accumulated a wealth of relevant knowledge and have cultivated an array of landraces that have become well adapted to the vagaries of local climates and soils. Local expertise and germplasm of bambara groundnut have rarely been exchanged between different growing regions in Africa, however, and knowledge systems have not been recorded or widely disseminated, either informally or through the scientific literature.

Until recently, bambara groundnut, like many indigenous African crops, has been virtually ignored by international agricultural scientists and funding agencies. This is at least in part because of its status as a 'poor man's crop' grown for subsistence rather than cash. To the authors' knowledge, the first description of bambara groundnut in the international literature appeared early last century (Zagorodsky, 1911) but it was not until 1969 that a detailed analysis of the growth habit and reproductive behaviour of the crop was published (Doku, 1969). Since then, there have been sporadic efforts to encourage interest and research activities on the crop (for a historical review of the crop see Linnemann and Azam-Ali, 1993). Much of the published literature on the crop has been specific to particular countries or has addressed only single aspects such as the nutritional value of the seeds (Poulter and Caygill, 1980) or visual descriptors of the germplasm (IBPGR/IITA/GTZ, 1987).

The limited evidence demonstrated that the crop has a number of advantages over more favoured species in terms of its tolerance to adverse environmental conditions. It can tolerate low-fertility soils and low rainfall and is the preferred food crop of many indigenous people. The seeds often command a high market price, with demand far outweighing supply in many areas (Coudert, 1984). In much of Africa, bambara groundnut is the third most important legume after groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) (Sellschop, 1962). In relation to crop rotations, experiments by Mukurumbira (1985) indicated that bambara groundnut has a greater residual nitrogen effect than has groundnut, maize or fallow. It was concluded that, in these rainfed systems, there was no nitrogen requirement for maize when it succeeded bambara groundnut in the rotation.

Reasons why the crop has remained underutilized may be associated with the perception that it has limited economic potential outside its areas of cultivation. For example, groundnut, a crop first introduced into West Africa from Brazil by the Portuguese (Smartt and Simmonds, 1995), may well have replaced the local bambara groundnut because seeds of the former contain significant amounts of lipid and can be grown as an oilseed crop. In this way, a cash crop with export potential for the colonial powers replaced a food crop for the subsistence of the local population.

DOES THE CROP HAVE ANY NUTRITIONAL OR FOOD-PROCESSING VALUE?

Initial work at the University of Nottingham (Brough and Azam-Ali, 1992; Brough *et al.*, 1993) demonstrated that bambara groundnut is a rich source of protein (16–25%) and confirmed previous evidence (Poulter and Caygill, 1980) that it has potential for food processing and increased utilization. The protein percentage was found to be superior to that reported for cowpea, groundnut and pigeon pea (*Cajanus cajan*) (Brough and Azam-Ali, 1992). Although the protein in bambara groundnut seeds is deficient in methionine and cysteine (a common feature in legumes) it achieves the FAO requirements for all other essential and non-essential amino acids (Aykroyd and Doughty, 1982). Brough and Azam-Ali (1992) also reported starch content in bambara groundnut seeds of 43% and a lipid fraction of 7.9%. They concluded that, in terms of lipids, bambara groundnut seeds compare favourably with cowpea (1.0–1.6%) and pigeon pea (1.2–1.5%) but are inferior to groundnut (45.3–47.7%). The gross energy value of bambara groundnut seeds is greater than that of pigeon pea, cowpea and lentil (*Lens culinaris*).

Bambara groundnut seeds can be used to produce a vegetable milk that is comparable with soya milk, and the ground seeds can compete with or replace other conventional flours in a range of processed products (Poulter and Caygill, 1980; Brough *et al.*, 1993). Brough *et al.*, (1993) compared bambara groundnut milk with milks prepared from cowpea, pigeon pea and soyabean (*Glycine max*). Sensory analysis showed that all were acceptable, with bambara groundnut ranked first in the preference trial. However, standard protein functionality tests (Brough *et al.*, 1993) showed bambara groundnut, like most other legumes, to be inferior to the standard used (egg albumen and soya isolate). Similarly, as with most legumes, bambara groundnut seeds were found to contain both tannins (142 g BSA precipitated kg^{-1} dry matter) and trypsin inhibitors (12.99 g kg^{-1} dry matter) (Brough and Azam-Ali, 1992). In principle, this trypsin inhibitory activity and presence of tannins in the seed coat may reduce the availability of dietary protein in diets containing raw bambara groundnut seeds. In practice, however, it is unlikely that this should be a problem since, usually, the seeds are boiled and dehulled prior to consumption.

Bambara groundnut seeds are used also as feed for pigs and poultry and the haulm as fodder (Doku and Karikari, 1971).

IS THERE ANY ECONOMIC DEMAND FOR THE CROP'S PRODUCTS?

Having established its nutritional and food-processing potentials, the next step was to assess whether products made from its seeds fetched a price that justified the infrastructure required for transport and distribution, and met the demands of local or international markets.

Marketing survey in Zimbabwe and Swaziland.

Since the crop is grown on a small scale across much of sub-Saharan Africa, it would be impractical to assess the market demand for the crop across all of its areas of cultivation. Instead, in 1999 a preliminary project, funded by the Crop Post-Harvest Programme (CPHP) of the UK Department for International Development (DFID), was established to investigate the factors that affect the processing and increased utilization of bambara groundnut in two sub-Saharan countries, Zimbabwe and Swaziland. In this way, an initial baseline analysis of the marketing potential of the crop was obtained for a country with a relatively developed infrastructure (Zimbabwe) compared with a smaller, less developed economy (Swaziland). Further details of this study appear in Hampson *et al.* (2000). Its main findings are summarized here.

Approach. The purpose of the project was to investigate factors affecting the processing and increased utilization of bambara groundnut in Zimbabwe and Swaziland. A market survey designed to evaluate the continuum from production through to marketing of the crop was instrumental in identifying and recommending potential areas for further development and research.

Initially a desk-based study was undertaken in the UK. Published and unpublished, or 'grey' literature, on bambara groundnut in Africa was reviewed, specifically in relation to Zimbabwe and Swaziland. BAMNET (an international network of scientists and institutions interested in bambara groundnut) was contacted and a project outline was posted on the BAMNET Web page (http://www.dainet.de/genres/bambara/).

In both countries, the survey method relied on individual and semi-structured group interviews that used informants selected with assistance from local agri-

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cultural extension officers. In Zimbabwe, the survey concentrated on Natural Regions IV and V (the driest parts of Zimbabwe) as this is where most bambara groundnut is grown. However, fresh markets, supermarkets and stores were visited in all urban areas, including Harare, Bulawayo, Mutare, Masvingo, Chinhoyi, Chitungwiza, Birchenough Bridge, as well as smaller rural markets. In Harare, supermarkets in low and high-density areas were visited. In Swaziland, local undergraduate students were employed to assist in the consumer survey part of the study. Fresh markets, shops and supermarkets were visited in all areas of the country.

Analysis. In both countries, the survey was split into categories that included as respondents, farmers, traders (informal and formal), consumers, wholesalers, government institutions, non-governmental organizations, educational and research institutions. There were 101 respondents in Zimbabwe and 150 in Swaziland. The information collected was qualitative, although some was translated into percentages. Checklists tailored according to respondents were used to guide the interviews. These checklists were used to group and code qualitative information into matrices which were then analysed using the qualitative software analysis programme QSR NUD*IST 4 – Non-numerical Unstructured Data Indexing Searching and Theory-building (Qualitative Solutions and Research Pty. Ltd, Australia, distributed by Sage Publications Software).

For both Zimbabwe and Swaziland, the analysis showed that the domestic market in fresh bambara groundnut is characterized by the informal nature of its production with very few stages between farmer and consumer. It was judged that Zimbabwe produces enough for its domestic market and that market potential for the dried bambara groundnut, as seed or food, is good, particularly for export within the region. The latest production figures compiled from the government's Central Statistics Office for 1997 show a countrywide production estimate of $15\,138 \times 10^3$ kg, with $10\,161 \times 10^3$ kg from the communal lands and the rest from resettlement areas (3219×10^3 kg), small scale commercial farms (1694×10^3 kg) and a minimal contribution from large scale commercial farms (64×10^3 kg). The demand for the fresh crop in Swaziland was also estimated to be high but production is lower and more localized. This country is not yet self-sufficient in bambara groundnut production. The majority of the dried crop sold as seed or food within Swaziland is imported from South Africa, and a small amount comes from Zimbabwe.

Farmers in both countries consume the majority of their harvested crop and sell any excess, some informally, in the locality or over borders. Wholesalers and supermarkets report slow trade due to competition from street vendors of the fresh and dried crop (dried seed for planting). Consumer demand is judged to be high and, therefore, opportunities for increasing production and utilization exist.

No small-scale processing of bambara groundnut was found in either country. One company in Harare, though, is canning the product for a small domestic market. The crop is mostly consumed as a snack prepared from the fresh product.

Though the dried bean is popular, very few recipes are known for the product in this form due to the long cooking time required and the concomitant high demand for the associated resources of water and fuel.

Conclusions. Factors limiting the increased utilization of bambara groundnut included a lack of awareness of best agronomic practices, lack of recipes, ignorance of its nutritional value, its limited potential as a cash crop, availability of seeds and access to markets. In addition, the 'hard-to-cook' issue; gender implications (as the crop is cultivated mainly by women), lack of government support for marketing, urbanization of the population and lack of funding were all perceived as constraints. From the review by Hampson *et al.* (2000) the following recommendations were made for both Zimbabwe and Swaziland:

1. That small-scale farmers should be included in future agronomic trials.
2. Recipes and agro-processing options should be developed to reduce cooking time.
3. An extension package for small-scale farmers should be developed and implemented.
4. There should be marketing and promotion of final products by retailers.
5. Market links and support mechanisms should be established to promote the crop.
6. The possibility of export markets (Fair Trade or niche markets) should be explored.

Despite these constraints, its popularity amongst the peri-urban population means that the seed commands a higher market price than do comparable species, such as cowpea and groundnut, particularly during the brief period when it is sold fresh. It is also highly sought after in countries and regions outside the main production areas, with demand outweighing supply in many areas. Currently, Zimbabwe exports annually about 3000 t of the seed to South Africa and Botswana at a premium of US\$325 t^{-1} (D. Greenberg, pers. comm.).

In Swaziland, it was concluded that production of the crop has declined due to a combination of rainfall patterns, land availability and lack of suitable technologies specific to the crop. However, 98% of farmers interviewed in a recent survey regard bambara groundnut as a profitable food crop and are keen to increase its productivity (Sesay *et al.*, 1999).

The project identified the following constraints to the increased utilization and processing of bambara groundnut:

1. Technology – the limited availability of suitable processing technologies.
2. Hard to cook – the dried seed requires significant energy for processing.
3. Supply – most seed is produced specifically for household consumption with little left for processing and sale.
4. Demand – to date, there is a limited demand for processed products.

It is important at this stage to mention that the constraints and limitations encountered during the market assessment of bambara groundnut are no different from those identified historically with the development and expansion of most crops. However, unlike bambara groundnut, comparable species such as cowpea, pigeon pea, groundnut and lentil have all benefited from promotion and advocacy by the network of international research centres, governments and international donors.

WHAT IS THE AGRO-ECOLOGICAL POTENTIAL OF THE CROP?

Preliminary work at Nottingham and Wageningen

Since 1988, the University of Nottingham Tropical Crops Research Unit (TCRU) has conducted detailed research studies on bambara groundnut. The decision to initiate these activities was in response to requests from a number of institutions in Africa. An essential feature of the Nottingham studies is that measurements on crops growing in five purpose-built, controlled-environment glasshouses at Nottingham should complement field experiments at sites in the tropics. The TCRU glasshouse system uses a central computer to control environmental factors, such as air temperature and humidity, for crops growing with their roots in undisturbed soil. Thus, the effect of a single variable can be monitored and quantified at the crop level so that the specific factors that limit crop productivity can be identified under closely controlled conditions.

In 1988 and 1989, stands of bambara groundnut and groundnut were compared in the TCRU glasshouse system. In both years, air temperature was maintained at a mean value of 28 °C and basal levels of NPK fertilizer were applied to the seedbed prior to sowing. Results from a range of soil water treatments confirmed much circumstantial evidence that bambara groundnut is more drought tolerant than groundnut and can produce a yield of pods in environments where groundnut may fail completely (Linnemann and Azam-Ali, 1993).

In 1990, experiments in the TCRU glasshouses and at the University of Wageningen in the Netherlands (Linnemann, 1994) showed that, although flowering in many bambara groundnut landraces is unaffected by daylength, the filling of pods (seed growth) appears to require daylengths of 12 h or less. The mechanism underlying this process is still unknown. It has important practical implications, however, and may explain the variability of bambara groundnut yields across Africa where crops generally are sown in response to the onset of rains rather than at a specific daylength. At Wageningen, studies on eight landraces of bambara groundnut from Nigeria demonstrated that all were day neutral for flowering (Linnemann, 1994). Onset of seed filling, however, differed with photoperiodic differences. A 14 h photoperiod delayed the seed filling in six of the landraces and inhibited it altogether in the other two. This was caused by a check on the growth of ovaries that had been fertilized successfully. Ovaries produced under conditions of a 14 h photoperiod, developed into fully grown pods after transference to a 12 h photoperiod.

In experimental conditions at Nottingham, where water and nitrogen were not limiting and daylength was maintained at 12 h, a bambara groundnut *landrace* from Zimbabwe achieved pod yields of over 3000 kg ha^{-1}. This value was greater than that achieved from a groundnut *variety* from India that had been grown under the same experimental conditions. It was also many times greater than typical yields of bambara groundnut achieved in the field.

The first EU bambara groundnut project

The projects described above established interest in the crop from both producers and consumers, and demonstrated that experimental yields substantially exceed those usually achieved in the field. The next major activity was to establish the agronomic potential and environmental constraints to the productivity of bambara groundnut in its current areas of cultivation, and how these might be overcome by an understanding of physiological mechanisms and agronomic management. This would require an assessment of its agro-ecological potential across a representative transect of its geographical distribution.

In 1991, the complementary research at Nottingham and Wageningen, and links established with a number of African institutions, resulted in the European Union (EU) awarding a major contract for a research programme on bambara groundnut. The project design involved a multidisciplinary approach to assess rapidly the potential of bambara groundnut for different environments in Africa. The initial controlled-environment research at Nottingham and Wageningen had already identified the growth and yield of bambara groundnut in terms of its responses to intercepted radiation, accumulated temperature and water use. Using this knowledge, it was envisaged that a programme of field and controlled-environment experiments and a crop simulation model could be combined to evaluate the factors believed to control bambara groundnut productivity in field environments.

Approach. Between 1992 and 1996, this project assessed the agronomic potential and agro-ecological requirements of bambara groundnut in Tanzania, Botswana and Sierra Leone. Results from field experiments carried out at Sokoine University of Agriculture, Tanzania, Botswana College of Agriculture and Njala University College, Sierra Leone were integrated with controlled-environment studies at Nottingham and Wageningen.

It was agreed at an early stage, that a crop simulation model of bambara groundnut was the most effective means of integrating the research efforts of the various partners. The intention was that this model would use well-established principles of resource capture to identify growth and development in relation to the availability and use of the three principal physical resources of water, radiation and temperature. At the outset, it was specified that the model for bambara groundnut (BAMnut) should be based on the PARCH (Predicting Arable Resource Capture in Hostile environments) series of models under development at the University of Nottingham and elsewhere. The exact means and extent to which

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the model would incorporate landrace characteristics from each of the African locations was not specified, however.

The five objectives of the EU bambara groundnut project were to:

1. Identify suitable agro-ecological regions and seasons for the cultivation of bambara groundnut in Tanzania, Botswana and Sierra Leone.
2. Produce a validated model of bambara groundnut to predict the total biomass and pod yield of different genotypes in contrasting soils and atmospheric environments.
3. Identify the physiological attributes associated with the capacity to produce yields under semi-arid conditions.
4. Recommend suitable management practices to stabilize the yields of bambara groundnut under rainfed conditions.
5. Outline a method for applying a similar approach to assess rapidly the potential of other underutilized species in tropical environments.

For the field experiments, sites were selected at each African partner institution. Additional sites were also used to assess the performance of landraces within each local cropping system. In Botswana and Tanzania, experiments were carried out in all four years between 1992 and 1995. Because of civil conflict in Sierra Leone, studies were confined to 1992 and 1993. At various times and locations, and for different landraces, experiments investigated the effects of sowing date, soil water, planting density, soil micro-topography, earthing up, fertilizer and sowing depth. A common protocol was adopted for the design and execution of the field experiments and the collection and collation of crop measurements.

Facilities available at the European partner institutions were used on various landraces to investigate the effects on plant behaviour of constant and changing photoperiod, soil water, seed size, temperature, seed priming and phosphate nutrition. In addition, the growth and yield of landraces from each African partner country were compared in terms of their capture and conversion of solar radiation and soil water.

Modelling. A bambara groundnut version of the PARCH model was developed using 'Modelmaker' software Version 2 (SB Technology Ltd, UK) which enables components to be linked via a flow diagram to assist in visual interpretation. Meteorological data are read from files containing irrigation or rainfall, maximum and minimum temperature, atmospheric saturation deficit, pan evaporation and solar radiation. On each day, light and water are 'intercepted' and 'converted' into dry matter. An index of crop stress is derived from the ratio of light-limited to water-limited growth. In this way, the amount of dry matter produced each day is calculated on the basis of the interception of radiation and uptake of water, with the lower of these calculations determining actual productivity. The model then partitions daily assimilation between plant organs depending on developmental stage and the level of stress. The rate of development to flowering, and then to podding, depends on daylength and temperature.

Analysis. Experimental evidence from the field and controlled environments indicated that bambara groundnut is capable of attaining significantly greater seed yields than those typically achieved by farmers. In controlled environments, pod yields of more than 3500 kg ha^{-1} were achieved under conditions of non-limiting soil water, confirming results of initial studies at Nottingham. Under rainfed conditions in Tanzania, where the sowing date was synchronized with the daylength requirement for pod filling, field crops achieved yields in excess of 3000 kg ha^{-1}. Preliminary model predictions for Tanzania indicated that pod yields in excess of 4500 kg ha^{-1} are possible in appropriate agro-ecological regions and with suitable agronomic management. However, model validation was limited by the shortage of field comparisons to identify the overall strengths and weaknesses of the predictive capacity of the model. Where they were attempted, model validations were hampered more by a shortage of adequate environmental data (for example, sufficiently localized records of daily solar radiation are not widely available across Africa) than by physiological knowledge. Nevertheless, model predictions would undoubtedly have also benefited from better field-based estimates of conversion coefficients for water and light, growth of roots and shoots and canopy surface areas. In addition, the model took no account of damage caused by pests and diseases that had a significant influence on crop performance at a number of locations. Similarly, although the model was highly sensitive to the initial soil water content, it could not account for any effects of transient waterlogging.

Experiments in the field and in controlled environments showed that sowing date is strongly implicated as a principal determinant of final pod yield in bambara groundnut. Critical photoperiods for podding were identified for different landraces in controlled environments and these were confirmed under field conditions. For example, in a field experiment in Tanzania, pod yield declined from >3000 kg ha^{-1} to zero when sowing date was delayed by 60 days (Collinson *et al*., 2000).

The complex behaviour of bambara groundnut landraces in relation to daylength may help to explain large inter- and intra-annual variations in pod yields previously observed within and between seasons across locations in Africa. During the project, intensive controlled-environment studies identified landraces that are (i) slightly sensitive to daylength for flowering and strongly sensitive for podding, (ii) those that are insensitive for flowering and sensitive for podding and (iii) those where a combination of temperature, photoperiod and minimum development rate best describe the influence on reproductive development. In some cases, transferring plants from 14- to 11-h photoperiods at various dates accelerated the rate of podding when compared with plants maintained under continuous short photoperiods. In the landraces used in this study, critical periods for podding ranged from 10.6 h d^{-1} at 26 °C to 14.1 h d^{-1} at 21 °C. Base temperatures for flowering ranged from 5.8 °C to 9.9 °C (EU STD3 Final Report, 1997).

Information on mineral nutrient requirement and nutrient use efficiencies of bambara groundnut is limited. The critical phosphate level (expressed as the level at which the relative growth rate is 80% of normal growth) decreased during the growing season, for example from 61 mmol kg^{-1} (0.18%) at 28 days after sowing (DAS) to 26 mmol kg^{-1} (0.08%) at 119 DAS for the landrace studied (EU STD3 Final Report, 1997).

The conversion coefficient for intercepted radiation across various landraces maintained in the TCRU glasshouses, ranged between about 0.8 and 1.1 g MJ^{-1}. The comparable range in the dry matter:water-use ratio was 1.8 to 3 g kg^{-1} (Collinson *et al.*, 2002). This variation was largely accounted for by measurements of the actual leaf to air vapour pressure difference and, when these were taken into account, the resultant 'transpiration equivalents' (see Azam-Ali *et al.*, 1994) varied between 4.2 and 4.6 g kPa kg^{-1}. Under irrigation, pod yields varied between 2200 and 3500 kg ha^{-1}. Yields under conditions of severe water stress were extremely small or negligible. Drought increased the relative allocation of dry matter to roots (Nyamudeza, 1989).

The mechanisms that enable bambara groundnut to produce at least some seed yield during severe drought conditions have been reported (Collinson *et al.*, 1996; Collinson *et al.*, 1997). Their studies identified morphological and physiological attributes that were critical, such as high root:shoot biomass ratio, small leaf area, osmotic adjustment and effective stomatal regulation of water loss. These attributes provide a useful approach for understanding the principles behind drought tolerance, and might be used as morphological or physiological markers to investigate differences between diverse landraces of bambara groundnut.

The poor establishment of bambara groundnut prompted more detailed investigations of germination and early growth. Experiments indicated that sowing depths of between 70 and 120 mm, under rainfed conditions, and seed soaking for 24 h, increased the percentage and rate of seedling emergence respectively (EU STD3 Final Report, 1997; Massawe *et al.*, 1999). Results from planting density and earthing-up experiments at different locations were inconclusive, and it was assumed that these factors depend on both landrace and location.

Conclusions. This project provided supporting evidence that bambara groundnut is a crop with considerable potential deserving of further investigation. Indeed, an ancillary experiment in Botswana (Wigglesworth, 1997), on local landraces grown with supplementary irrigation, identified pod yields in excess of 500 g $plant^{-1}$ (that is the equivalent of a 5000 kg ha^{-1} yield at a planting density of 1 m^{-2}). From the evidence assembled during this project, it can be concluded that by closely matching crop production to the availability of resources expected during the growing season even higher annual yields than this, with less variation between seasons, could be achieved without significant improvement in the existing germplasm.

Irrespective of all other environmental factors, it appears that sowing date plays a pivotal role in the actual and potential yields of current bambara groundnut landraces. This has enormous implications for the future development of the crop. Where rainfall and temperature are adequate, sowing date sets the maximum duration for pod production. Thus, unlike in many other tropical species, sowing date and genotype need to be considered at each site for pod induction, irrespective of whether the crop has successfully produced flowers. In particular, it is clear that the period of pod induction is genotype dependent irrespective of other factors, such as seasonal rainfall.

An interesting corollary of the project, and the initial work at Nottingham and Wageningen, was that it required controlled-environment research to identify the daylength requirement for pod filling in bambara groundnut. This characteristic had never been identified in field studies despite the wide range of environments and seasons across which different bambara groundnut landraces have been grown in Africa for centuries, and the reported variability in yields obtained from year to year at the same locations. In fact, it is largely this annual variability in yield that has deterred prospective sponsors from investing research funds on bambara groundnut. Although the physiological approach used in this project was vindicated as a basis for investigating a crop of unknown potential, there are important conclusions to be drawn from this collaboration that involved a wide range of institutions with limited previous experience of working together. The first lesson is the need for all collaborators to have agreed an experimental philosophy, measurement protocols and common data-processing formats at the outset. Second, there must be access to long-term meteorological and soils data for each location. Finally, procedures must be put in place that can ensure the swift and successful exchange of germplasm between collaborating institutions. Most crucially, the project was limited in its significance by a lack of interaction and exchange of information between collaborating scientists, farmers and consumers in each African partner country, and the lack of local knowledge incorporated in the experimental programme.

Nevertheless, a number of publications have resulted from this project (Collinson *et al.*, 1996, 1997, 1998, 1999, 2000; Brink, 1997, 1998, 1999, Brink *et al.*, 2000; Massawe *et al.*, 1999; Karikari, 1996, Karikari *et al.*, 1999, Ramolemana, 1999). Perhaps the most useful of these is the proceedings of the first international symposium on bambara groundnut which brought together project scientists from each partner institution and scientists working on the crop in other countries (Anonymous, 1997).

CAN THE CROP'S GEOGRAPHICAL POTENTIAL BE MAPPED?

Despite its sporadic appearance in other regions, it is Africa that is both the centre of origin and current production centre for bambara groundnut. However, as with any crop, there are locations outside its current distribution that may offer conditions at least as conducive to its growth and yield as those that are currently cultivated. Bambara groundnut has not benefited from a systematic effort to disperse it either through migration, colonialism or research. The problem remains, therefore, as to how new potentially suitable areas for the cultivation of any underutilized crop can be identified without advocating a major multi-locational programme of field experiments. In addition, how can any information that is gathered at various locations be collated to provide a more generalized picture of the potential distribution of a crop?

The FAO mapping project.

In 1999, the Food and Agriculture Organization (FAO) of the United Nations collaborated with the TCRU group at Nottingham to map, for the first time, locations that have potential for the production of bambara groundnut across the world (Azam-Ali *et al.*, 2001). To achieve this, project scientists linked a weather generator and a revised version of the BAMnut model that had already been developed through the first EU project into a Geographical Information System (GIS).

The objectives established during this project were to:

1. Evaluate, with respect to bambara groundnut, the productive potential of Africa.
2. Define regions not previously associated with the cultivation of bambara groundnut, but where the combination of environmental factors indicates a potential for productive growth without recourse to costly inputs, such as irrigation.

Approach. This study examined how well sites across the globe satisfy potential biomass requirements for bambara groundnut and their likely pod yield thresholds. There were two major analytical procedures in this study:

1. Integration of a weather generator into a GIS for the creation of daily weather data.
2. Integration of BAMnut into a GIS.

Data on the most important factors that affect crop yields are the model inputs. BAMnut converts these inputs into a number of outputs including maps and statistics of crop yields. A schematic diagram summarizing the methodological framework developed in this study is shown in Fig. 1.

BAMnut – A simulation model for bambara groundnut. The original version of BAMnut was modified during the FAO collaboration. A major objective for developing BAMnut was to provide a means of integrating the preliminary understanding of the dynamics of crop growth as influenced by soil water and other environmental variables. This approach allowed the agro-ecological potential and resource requirements of the crop to be established. Because BAMnut is a process-based model that uses physiological principles to describe the capture and use of environmental resources (see Fig. 2), it could be incorporated rapidly within the FAO mapping exercise to predict crop productivity for regions beyond those

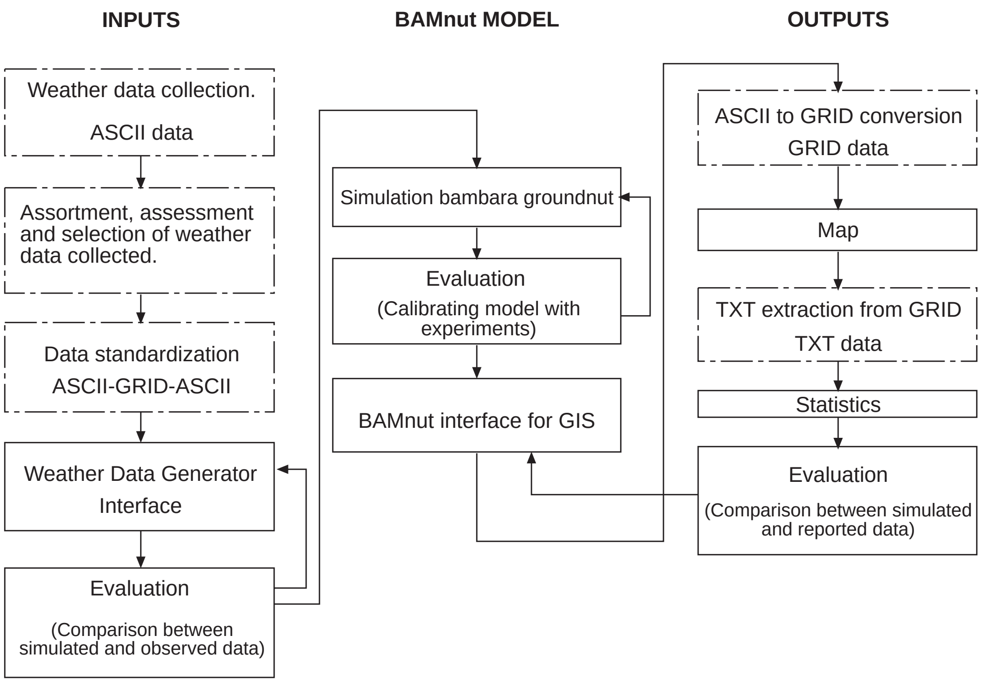

Fig. 1. Schematic diagram describing the procedures involved in estimating and mapping the potential production of bambara groundnut. Note: Dashed boxes refer to GIS activities while solid boxes refer to the modelling activities.

used in the development of the model. These predictions included areas where the crop has never been cultivated.

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

Weather data – Inputs to BAMnut model. The observed climate data from the University of East Anglia Climate Research Unit (CRU), available through the Intergovernmental Panel on Climate Change (IPCC) Data Distribution (http://ipcc-ddc.cru.uea.ac.uk/cru_data/examine/have_index.html), provided the main inputs to the weather generator. These included mean monthly climate data for global land areas, excluding Antarctica, for the period 1961–1990. The mean (1961–1990) daily values of seven weather variables were selected as inputs for the model: rainfall (mm), radiation (W m^{-2}), wet day frequency (d), maximum temperature (°C), minimum temperature (°C), vapour pressure (kPa) and wind

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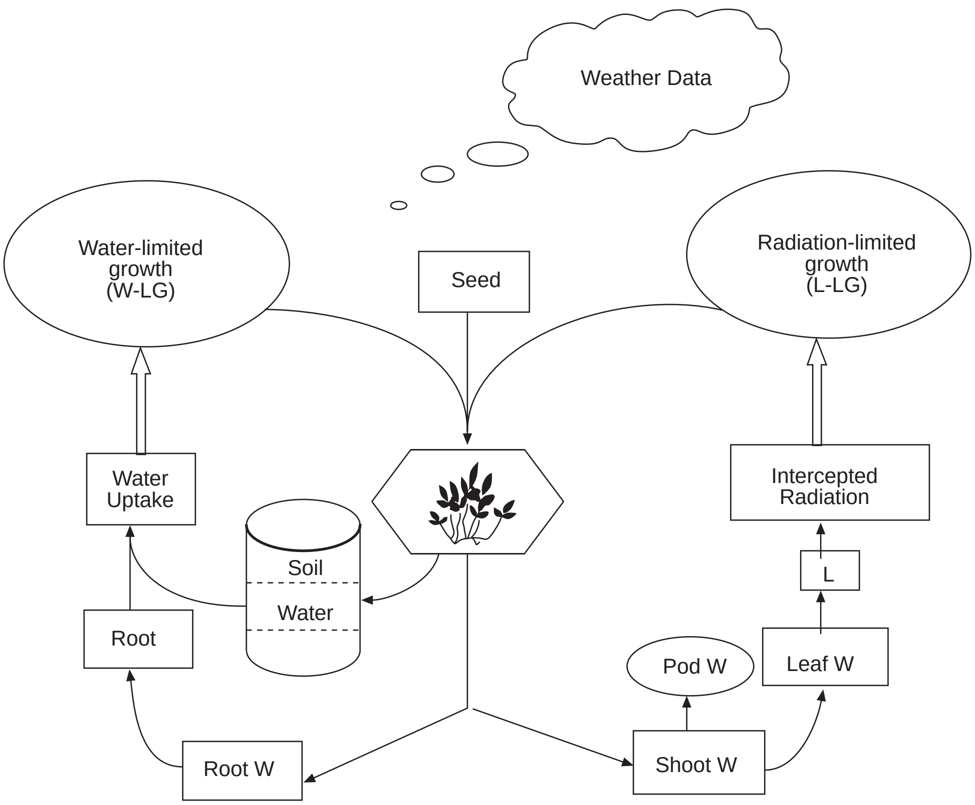

Fig. 2. Relational diagram of the BAMnut model. The water balance for growth under water-limited conditions is represented in the left part of this figure. The right part of the figure represents potential growth of shoots and pods. L is the leaf area index. LeafW, PodW, RootW and ShootW represent the respective dry weights of crop components. L-Lg = light-limited growth.

speed (m s^{-1}). The outputs from the model were, in turn, used as inputs into the GIS to develop the required maps and statistics.

Analysis. The outputs of the model for both biomass and pod yield were classified into four representative ranges of suitability as shown in Table 1. Although these categories were arbitrary, they helped to simplify the analyses and provided a basis for comparisons between regions. The levels, defined as very suitable (VS), suitable (S), moderately suitable (MS) and unsuitable (US), were 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} corresponded to reported pod yields of up to 3870 kg ha^{-1} in Zimbabwe (Johnson, 1968). Similarly, the MS category corresponded to typical farmers' yields of 650–850 kg ha^{-1} in Africa as reported by Stanton *et al.*, (1966). Regions producing pod yields below 300 kg ha^{-1} were defined as unsuitable (category US) for bambara groundnut cultivation. Crop failure was not included as it obviously had the definition of no yield.

Table 1. Classification of suitability ranges for predicted total biomass and pod yield of bambara groundnut.

	Very Suitable (VS)	Suitable (S)	Moderately Suitable (MS)	Unsuitable (US)
Biomass (kg ha^{-1})	>8500	4500–8500	1500–4500	1–1500
Pod Yield (kg ha^{-1})	>3000	1000–3000	300–1000	1–300

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

Figures 3 and 4, respectively, show the predicted biomass and pod yield of bambara groundnut across the world. The different suitability ranges defined in Table 1 indicate the geographical distributions of each classification in Figure 3 and 4. These show that there is potential for bambara groundnut production in many parts of the world beyond its current distribution, including America, Australia, Europe and Asia as well as Africa. In fact, locations within the Mediterranean region show the highest predicted biomass, often exceeding 8500 kg ha^{-1}.

PLUS COLOUR PLATES

Conclusions. This study used only data that are comparable across the world. The approach limited the number of important factors that could have been used in the evaluation (for example 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. In relation to underutilized 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. Thus, this preliminary assessment allows planners to select promising locations, countries or regions that justify more detailed studies, bring local factors into the analysis and take advantage of data of higher resolutions.

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

The analysis of the spatial productivity of bambara groundnut demonstrates how a weather data generator and a dynamic crop simulation model can be linked usefully in a GIS on a global scale, allowing exploration of a number of possible interactions that would be expensive and time consuming to establish in the field. 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 underutilized species – this approach allows the production of a reasonable assessment of likely productivity with minimal field data. Second, this approach allows assessment of the potential consequences for all crops of future climatic variability and changes in agricultural production.

Despite its limitations, the model linked with GIS technology allows scrutiny of the world potential for bambara groundnut over relatively small unit areas and provides a means to ask:

1. Where is the best potential for cultivation of bambara groundnut on a world scale?
2. What is the likely yield threshold for different regions?
3. Over how much surface area of land are potential yields achievable?

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 can be enhanced continuously whenever more data are available. Updating of weather and crop data would enable revision and refinement of the simulation approaches built into them. In particular, the limited datasets available in the development of the BAMnut model are of most concern, especially for application across the world. However, it should be noted that, as information and expertise on bambara groundnut expands, the user will be able to input landrace-specific information to provide estimates of likely productivity and best management practices for the cultivation of local genotypes at particular locations. The development of a wider 'generic' methodology would provide comparative estimates of productivity for diverse underutilized (and major) species at any location.

Future applications. Widespread access by end-users and policy-makers to the methodology and outputs presented here could allow future developments to be demand-led. In particular, comparison of the simulated yields of underutilized crops with existing yield maps for major crops enables decision-makers to prioritize crop and cropping systems in terms of farmers' needs and national benefits.

Finally, although the approach described here is a first attempt to map the potential areas for cultivation of one underutilized food legume across the globe, it has wider implications in terms of food security and poverty elimination. Rather than consuming single specific crops, people eat a range of agricultural products that provide nutritional compounds including proteins, carbohydrates and lipids. Thus, one development of the mapping strategy would be to produce 'nutritional maps' whereby the relative food values of different species were assessed against production patterns for individual countries or regions. In this way, policy-makers could utilize 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.

WHAT IS THE GENETIC DIVERSITY OF THE CROP'S GERMPLASM?

Bambara groundnut has not been improved through co-ordinated breeding programmes and, therefore, different genotypes of this crop still exist as landraces. Various researchers (see Zeven, 1998 and references therein) have described the meaning of a landrace. The description by Zeven (1998) defines a landrace as 'a variety with a high capacity to tolerate biotic and abiotic stress, resulting in high yield stability and an intermediate yield level under a low input agricultural system'. From the definitions given by other researchers, landraces can be described as a mixture of genotypes with highly diverse populations both between and within them. On the other hand, the International Code for Nomenclature for Cultivated Plants (ICNCP) defines a cultivar as 'a taxon that had been selected for a particular attribute or combination of attributes, and that is clearly distinct, uniform and stable in its characteristics and that, when propagated by appropriate means, retains those characteristics' (Trehane, 1995). Zeven (1998) argued that although only limited human selection is carried out to maintain a landrace, it may be distinct from other landraces. Repeated cultivation under subsistence agriculture, however, often results in a different appearance of the landrace over time. This is clearly the case with bambara groundnut landraces where growers either save their own seed for the next season or buy various seed lots from the market. The subsequent mixing of seeds (of similar or different testa colour) results in a completely different population to that originally sown and the variability of growing conditions again changes the composition of the progeny of a sown population. Landraces differ from cultivars in many ways but the main distinction is that they are not uniform and stable in their characteristics from season to season for the reasons given above.

Diversity and yield stability.

The main reason for yield stability in landraces is the diverse nature of the population of seeds sown. Hence, individuals within a landrace may be different from each other and more or less adapted to varying conditions within a particular environment. As a consequence, landraces are well buffered or homeostatic across a range of environments: a concept discussed by Simmonds and Smartt (1999) with regard to heterogeneous populations. Because of intensive breeding, individuals within a cultivar are virtually identical and to a great extent perform similarly under a given set of conditions. The population, therefore, performs better only when the conditions are favourable (usually under high input agricultural systems) and will not produce the same yield if the conditions are changed. The homogenous nature of cultivars means no particular individuals within the population will outperform others when conditions change at any location or the seeds are grown at a new site.

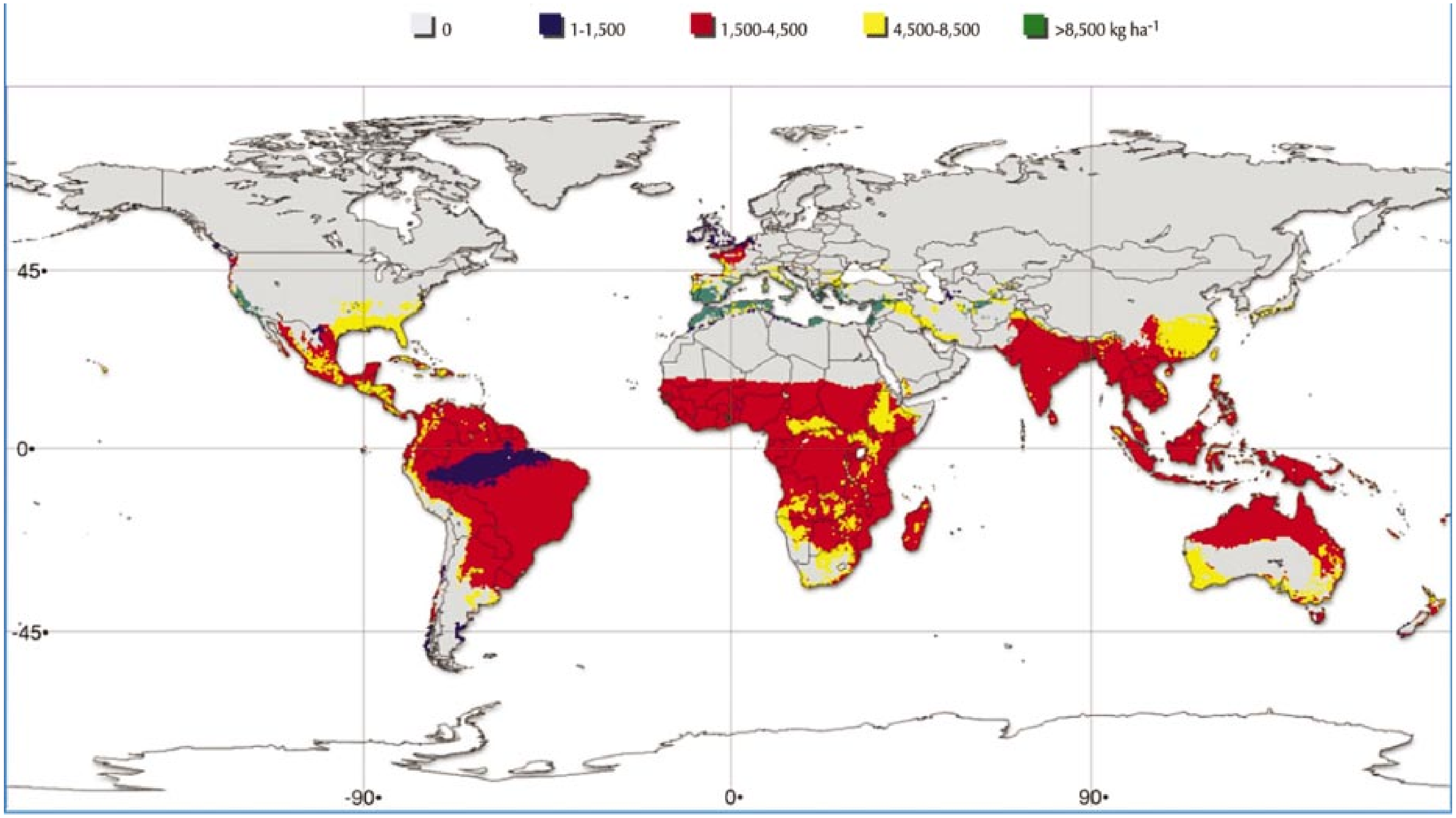

Fig. 3. Predicted biomass of bambara groundnut (kg ha^{-1}) across the world.

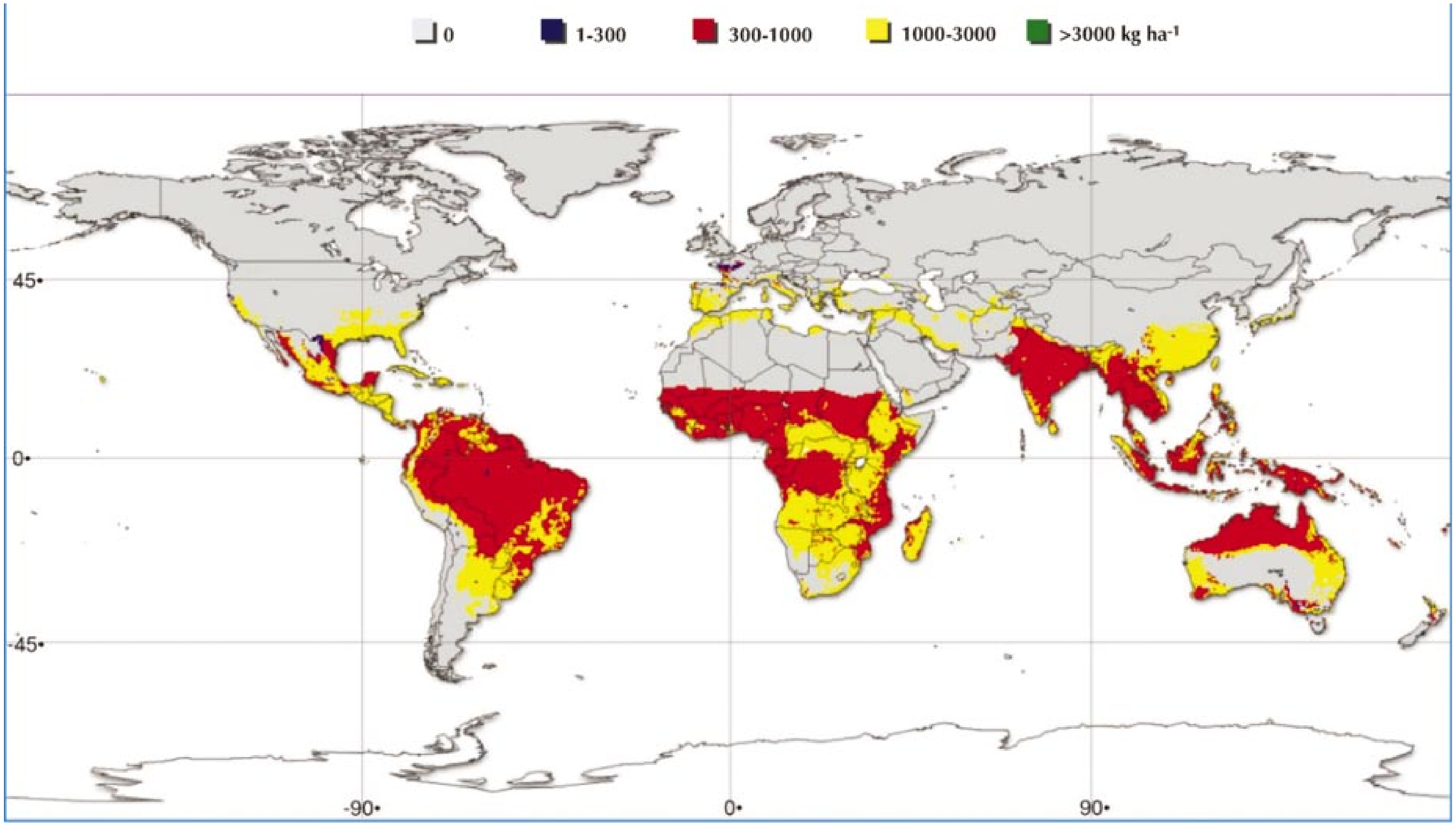

Fig. 4. Predicted pod yield of bamara groundnut (kg ha^{-1}) across the world.

From the above it can be seen that landraces are grown mainly for their yield stability and, therefore, minimization of risk, rather than their high yield capacity. This is due largely to the fact that, whatever the varying biotic or abiotic conditions for each plant, one or more individuals within the landrace population will yield satisfactorily (Zeven, 1998). Research to improve bambara groundnut should consider, therefore, that because growing conditions in semi-arid regions can be hostile, yield stability may be as important an objective as yield potential in the production of new cultivars. Whether one species can achieve both high- and stable-yielding cultivars at the same time is debatable. The lesson is, however, that an approach that emphasizes diversity and yield stability along with the goal of increased productivity is more sensitive to the complexities of local or traditional agricultures, and is culturally compatible since it actually builds upon traditional farming knowledge combined with elements of modern agricultural science.

Physiological and molecular characterization of landraces

Knowledge of genetic diversity is useful in any breeding programme as it facilitates efficient sampling and utilization of germplasm resources. The breeder can use genetic variation information to make informed decisions regarding the choice of parents to use in a breeding programme. In plant species, characteristics that define morphological and physiological traits through to genetic markers are used to evaluate genetic diversity.

Approach. Between 1997 and 2000, experiments were conducted at Nottingham to evaluate genetic diversity in bambara groundnut landraces using morphological and molecular markers. In the following sections, the use of two types of markers is explored, and the analysis of the results obtained from these studies is presented.

Morphological and physiological markers. The use of morphological and agronomic traits is a classical way of assessing genetic variation. For many species, especially under-researched crops such as bambara groundnut, it is still the only approach available to breeders and agronomists. One of bambara groundnut's attractive features is that, probably due to its wide geographic dispersion in Africa, there appears to be a wide range of genetic variability, which increases the scope for selection. This is most obviously manifested as variation in seed size, testa colour and pattern; leaf, flower and pod numbers; traits conferring drought tolerance (Begemann, 1988; Collinson *et al.*, 1996; Collinson *et al.*, 1997; Squire *et al.*, 1997); and photoperiod requirements for pod filling (Linnemann, 1994).

These traits have been used successfully in crop improvement programmes. They may not be significantly distinct, however, and usually require growing the plants to full maturity prior to identification. Moreover, the morphological characters are unstable due to environmental influences. Advances in molecular biology have led to the development of a wide range of techniques that allow the analysis of an individual's genome (complete set of genes of an organism). They permit a faster and clearer understanding of species and their genetic diversity, the mechanisms by which that variation is generated in nature, and the significance of that variation in the adaptation of plants to their environment. Molecular techniques allow the development of methods for rapid screening of germplasm for specific traits, including, for example, drought, pest and disease resistances. Genetic markers are used in molecular genetics to study the relationship between genotype and phenotype and, hence, to group individuals into a limited number of entities based on their degree of similarity.

Genetic markers. These are fragments or sequences of DNA or protein that can be detected readily and whose inheritance can be monitored (Ford-Lloyd and Painting, 1996; Newbury and Ford-Lloyd, 1999). The pattern of these fragments may differ from one cultivar, landrace or species to another and may be used to detect specific DNA sequences that uniquely identify the plant or individual. In most cases, DNA or protein segments that are used as markers have no known function(s) within the plant. In some cases, however, the presence of a particular fragment (marker) may be linked or associated to genes that are responsible for specific characteristics of the individual (Newbury and Ford-Lloyd, 1999). Genetic markers are very useful in providing information about the individual from which they are derived, and it is this value that genetic- diversity studies have used in analyses of genetic relationships between and within species. Researchers working on major crop species have used these techniques in genetic diversity studies (Tao *et al.*, 1993; Sharma *et al.*, 1995; He and Prakash, 1997), identification of genetic loci associated with the expression of agronomic traits, and in marker-assisted selection (Lee *et al.*, 1996; Mian *et al.*, 1996; Nguyen *et al.*, 1997). Clearly, such experience provides an opportunity to apply similar techniques in bambara groundnut.

The present studies have used AFLP (Amplified Fragment Length Polymorphism) and RAPD (Random Amplified Polymorphic DNA) markers to evaluate genetic diversity in selected landraces of bambara groundnut. Further details appear in Massawe *et al.*, (1998); Massawe (2000); and Massawe *et al.*, (2000).

Analysis. This investigation explored both phenotypic and molecular variations in bambara groundnut landraces. Measurements of individual plants to establish the degree of variability in vegetative and reproductive traits between and within landraces revealed that there is no strong relationship between vegetative and reproductive development in bambara groundnut landraces such that, although most plants capture resources and produce a substantial biomass, just a few plants flower and produce seed yield. Phenotypically, there is variability both between and within bambara groundnut landraces but the degree of variation did not suggest any possible association between their morphological characters and the collection sites.

Phenotypic correlations were used to establish pairs of traits that influence each other, and results showed that there exists a possibility of changing two or more traits to achieve high seed yield. For example, pod number and seed dry weight per plant were positively correlated suggesting that selection for high seed yield

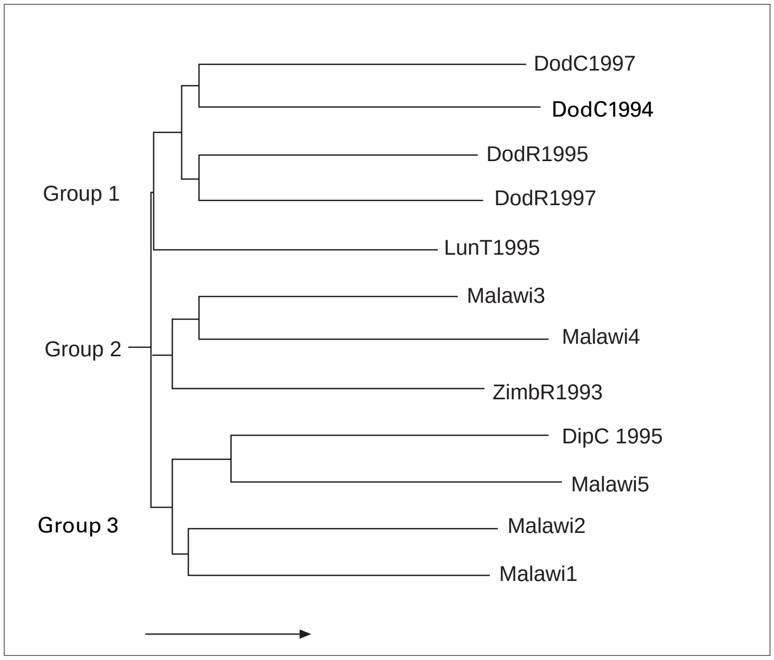

Fig. 5. Genetic relations, as determined by Random Amplified Polymorphic DNA (RAPD) technique, among 12 bambara groundnut landraces based on genetic distance estimates (1-Jaccard's similarity coefficient). The neighbour-joining cluster tree (dendrogram) is based on 16 primers. The arrow shows the direction of decreasing genetic diversity.

would be achieved through a large number of pods per plant while, at the same time, achieving large seed size. Relations between total above-ground dry matter and pod dry matter indicated that, depending on the landrace and environment, required a minimum vegetative dry weight of between 6.0 and 8.0 g plant^{-1} landraces before assimilates were partitioned to pods. Above these values, the proportion of aboveground dry matter partitioned to pods was between 0.27 and 0.48 for landraces used in this study.

RAPD and AFLP markers revealed high levels of polymorphism among landraces. Analysis of Molecular Variance (AMOVA) was used on RAPD data to partition variation into between- and within-landrace components. Results indicated that there is variation both between and within landraces although the latter was lower than the former. Using RAPD and AFLP markers, genetic relations observed among bambara groundnut landraces from different regions in Africa (Fig. 5 and 6) were related to their place of collection rather than to their phenotypic affinities. AFLP results suggest the possibility of developing location- or landrace-specific markers for identification purposes and there is potential for association of AFLP markers and agronomic traits.

Comparative advantages and disadvantages of the potential use of phenotypic and molecular variation data have been discussed (Bachmann, 1994). In par-

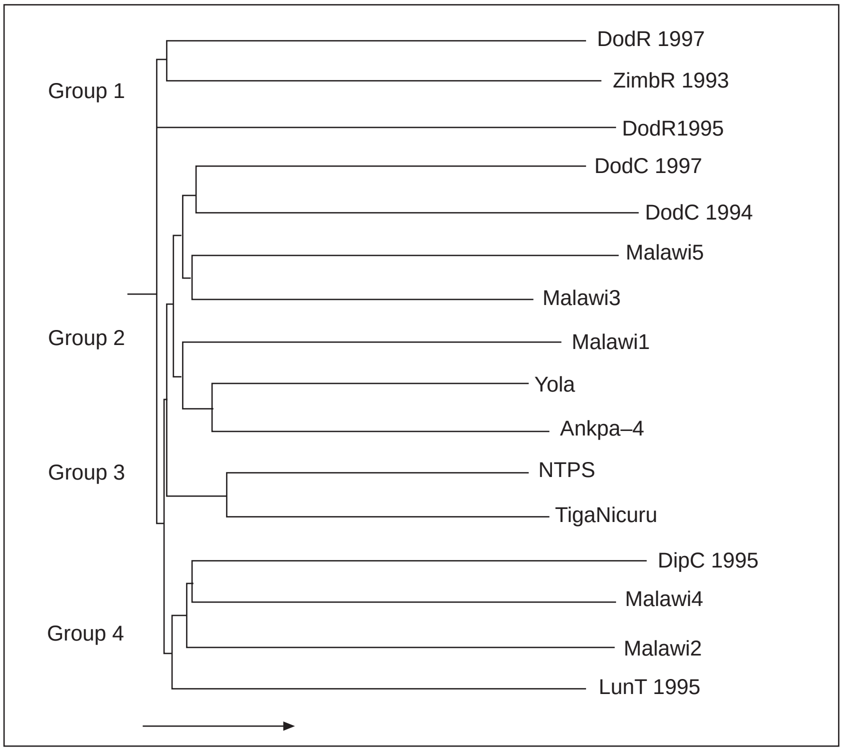

Fig. 6. Genetic relations, as determined by Amplified Fragment Length Polymorphism (AFLP) technique, among 16 bambara groundnut landraces based on genetic distance estimates (1-Jaccard's similarity coefficient). The neighbour-joining cluster tree (dendrogram) is based on seven primer pair combinations. The arrow shows the direction of decreasing genetic diversity.

ticular, there are potential problems when attempting to relate phenotypic variation to underlying genotypic variation (McRoberts *et al.*, 1999). In most studies, considerable phenotypic variation has been reported, even in species such as groundnut with a narrow genetic base, while the use of molecular markers shows low genetic variation among genotypes in this species (He and Prakash, 1997; Singh *et al.*, 1998). One reason for this may be that phenotypic plasticity evolves independently from genetic diversity. The potential of molecular variation data is evident especially when dealing with heterogeneous populations, such as crops composed of landraces (for example bambara groundnut), where reliable genetic diversity data are essential.

Conclusions. Practical experience gained here highlights the major problem of finding sufficient seed material of crops such as bambara groundnut for experimental purposes. The problem arises because there is no seed industry, and farmers either save seeds from the previous season or buy them from the market. Scientists too usually buy seeds from the market, or from individual growers, and every time experiments are conducted different seed material is used. Often there is only cursory evidence for the maternal history of a so-called 'landrace'. For example, these authors found that seeds bought in Gaborone market in Botswana were sold by individual entrepreneurs who had travelled from Zimbabwe specifically for this purpose. If this practice is commonplace across Africa, the distribution of particular seed populations, the subsequent mixing of seeds from different locations and the effects of local environment on phenotypic performance mean that the labelling of seed lots as landraces with a specific local identity has enormous implications for research and extension. To provide some basis for landrace authenticity, the authors are in the process of identifying specific ones from different locations in Africa using molecular techniques. Seeds of these landraces will be multiplied under known conditions and a common seed lot will be used for future experiments across a number of seasons and locations.

It is clear from the authors' investigations both in the field and in controlled environments that the non-uniform nature of landraces means that experimental methods developed on and for uniform plant populations such as cultivars may be inadequate. For example, it is difficult to establish the link between vegetative and reproductive development in bambara groundnut because not all vigorous vegetatively growing plants flower and yield seed; some of the visually healthy plants did not flower. Rather than use a physiological approach based on canopy-level and bulked values of traits as applied to uniform crop stands to establish yield potential under different environmental resources, this study used an individual-based approach similar to that described in Squire *et al.* (1997). It is proposed, therefore, that for a physiological understanding of a diverse number of landraces from different geographic regions, assessment of resource capture and seed yield should be done at an individual plant level. There are a number of implications of working with landraces that have messages for the field agronomist. The most important of these is probably the question of how one should deal with biologically variable germplasm within physically and biologically variable environments. The convention of seeking to describe the average of the population or treatment, or the use of statistical methods designed for crop varieties in relatively uniform plots, must be reconsidered.

The studies described here and those carried out elsewhere using both phenotypic analysis and molecular markers (Anonymous, 1997; Collinson *et al.*, 1997; Pasquet *et al.*, 1999; Massawe, 2000; Massawe *et al.*, 2000) suggest that there is great genetic diversity in bambara groundnut germplasm with potential value in non-conventional breeding programmes. Landraces have a long history of successful adaptation to low-input agriculture (their survival is despite rather than because of plant breeders, agricultural scientists and extension agencies). Under these hostile conditions a considerable amount of genetic diversity has been maintained. In breeding cultivars of bambara groundnut for difficult environments and poor farmers, selection must be conducted within the target environment and under the agronomic conditions of the local farmers.

In bambara groundnut improvement programmes, the potential gain from a more uniform population in benign environments needs to be balanced against the proven advantages of non-uniformity in growth and development, and sequential harvesting in marginal environments. Nevertheless, under rainfed conditions where rainfall is unpredictable, and where a more even distribution of food and income is desired, a non-uniform population will have a number of implications on the agronomic management of the crop. Cultural practices, such as weeding, cannot easily be co-ordinated and all plants cannot use environmental resources optimally because some individuals will be either too early or too late to capture and exploit these efficiently. Bambara groundnut breeding objectives must, therefore, be well defined on the basis of available evidence for the high-yielding potential of individual plants, as well as the yield stability provided by 'composite' landraces. In this regard the contribution of the studies reported here plays a major role. There are many parameters that will form the basis for future research on this crop and these require physiological and molecular analyses as well as farmer's preferences.

The presence of a high level of genetic diversity between and within landraces suggests that, in addition to the need for continuous collection and both *ex situ* and *in situ* conservation, there is a possibility of using this large reservoir of genetic diversity for plant improvement. Pure lines (superior for yield and other characters) will be developed from landraces through single plant selection. These will be confirmed after testing their stability in different environments and seasons. The identification of uniform populations of plants allows the subsequent development of 'ideal blends' composed of a number of pure lines properly characterized for a set of agronomic traits. Developments in molecular genetics offer new opportunities for trait-marker analysis, where certain phenotypic or morphological features can be associated or correlated with plant performance. (See McRoberts *et al.* (1999) for a recent account of how molecular markers can be associated with eco-physiological traits of interest.)

HOW CAN THE CROP'S EXISTING GERMPLASM BE IMPROVED?

All the efforts described so far have attempted to evaluate various aspects of the nutritional, agro-ecological, genetic and marketing potential of existing bambara groundnut landraces. The choice of particular landraces for specific activities, for example nutritional composition, was inevitably governed by the availability of local germplasm and by the perceptions of the various scientists and participants involved in each activity. By definition, little was already known about the crop, and the sequence of research activities, therefore, depended to a large extent on the availability of financial support and the specialist interests of participants at each institution rather than an overarching strategy from the outset. Nevertheless, by 1999, the collective history of research on bambara groundnut had generated sufficient critical mass and scientific evidence to justify a project to evaluate how the genetic potential of the existing germplasm might be maximized by appropriate crop management or improved by crop breeding.

The second EU bambara groundnut project

In 2000, the EU Framework 5 programme funded a new multidisciplinary project on bambara groundnut, with partners in Africa and Europe. This project harnesses expertise in molecular biology, physiology, agronomy, modelling and agricultural extension and combines farmers' and scientific knowledge within a common framework of analysis. Over three years, the project will provide the basis of a crop improvement programme that combines both conventional and novel methods of genetic evaluation and improvement. Crucially, a pre-requisite of the project is that it is based on the perceptions and preferences of the growers themselves, and only uses scientific technologies to achieve objectives set by bambara groundnut farmers in each partner country. In this way, it is envisaged that the development of any bambara groundnut material, achieved either through the multiplication of existing landraces or the breeding of varieties, will be based on a conceptual 'ideotype' identified by communities of farmers in each country rather than exclusively by scientists.

Specifically, the project objectives for bambara groundnut are to:

1. Identify 'ideotypes' for local conditions in Botswana, Namibia and Swaziland using a farmers' survey.
2. Characterize the genetic and agronomic performance of landraces from Botswana, Namibia and Swaziland in field, controlled and on-farm environments.
3. Evaluate genetic diversity in existing germplasm using simple, readily transferable molecular strategies.
4. Produce a robust model to match suitable ideotypes to contrasting environments and end users.
5. Establish an operational method of crossbreeding for intraspecific hybridization.
6. Develop a strategic breeding programme based on morphological and molecular considerations.
7. Provide a blueprint of how the methodology established for bambara groundnut can be applied to other underutilized crops.

Approach. Since the start of the project, each African partner institution has initiated an extensive survey of local bambara groundnut farmers. These survey data on farmers' and consumers' preferences for ideal bambara groundnut genotypes will be combined with results from genetic, physiological and agronomic studies of bambara groundnut conducted by the various project partners. A bambara groundnut simulation model will incorporate this information to define 'ideotypes' that are best suited to diverse growing environments and end-users. During the project, this approach will be used to establish a priority list of achievable objectives and desirable traits to guide the planning of a breeding programme. Field studies will be complemented by detailed physiological experiments in controlled environments to elucidate the specific responses of different bambara groundnut landraces and individual plants to quantified variations in soil water, solar radiation and temperature.

The breeding system in bambara groundnut is not well understood. Therefore, the project will develop techniques to facilitate crossbreeding in bambara groundnut alongside methods that match the suitability of existing landraces to particular growing conditions. The plan here is to have parallel strategies whereby suitable plant material might be obtained either through hybridization or the multiplication of landraces that fit particular ideotypes.

Rather than relying exclusively on visible characters, the genetic diversity in bambara groundnut landraces will be examined using molecular techniques as a first step towards identification of suitably diverse parents for use in a breeding programme. Molecular approaches will be explored for the possibility of marker-assisted selection where specific markers are associated with important agronomic traits.

Details of the various activities that will be completed between 2000 and 2003 are summarized below.

Farmers' survey. Each African partner institution is conducting participatory research with local growers to collect information on farmers' knowledge, perceptions and preferences for bambara groundnut. The aim is to identify specific attributes and preferences that would enhance the productivity and demand for bambara groundnut in each locality. Both growers and consumers will not derive benefit from production advances if there is a mismatch between production and post-harvest technologies.

Participatory tools to be used at various stages of the survey typically include semi-structured interviews, mapping, seasonal calendars, rankings and prioritization exercises. A phased survey process is being used wherein small group sessions to collect general information will be followed up by workshops, focus-group discussions, and other methods, to collect more detailed information. Depending on local circumstances, this can be done at the farmer, village or local group level and for growers and non-growers of the crop. These activities will continue throughout the timeframe of the project.

Information from each location will be collated and managed using the QSR NUD*IST 4 software that was used in the marketing survey of Zimbabwe and Swaziland. (Additional funding from CPHP/DFID has been secured to support this aspect of the project). This approach will help identify features that are common to all growing regions and where specific requirements exist at any particular location. The analysis will give quantitative outputs in the form of ranking desirable traits to define a minimum number of achievable objectives for breeders and agronomists. This information, together with genetic and agronomic data, will form the basis for a list of objectives to establish a bambara groundnut breeding programme.

Characterization and evaluation of the landraces. Genetic, agronomic and morphological traits of selected bambara groundnut landraces will be evaluated in field, glasshouse and on-farm environments. At each location, genotype-environment interactions will be estimated to assess the range of adaptation of landraces to various agro-ecosystems. On-farm field trials will provide participatory information from farmers to define breeding goals based on local environments and farmers' preferences.

Each African partner will supply seeds from local landraces. The landraces will be planted in at least two locations in each African partner country to study the performance of the landraces across different environments. An agreed experimental design and management strategy will be maintained over all three seasons. Information on weather, soil, pests and diseases will be recorded for each site. Besides yield and other agronomic traits, the IITA descriptor lists (IBPGR, 1987) will be used for a comprehensive morphological characterization of landraces. To supplement field trial results, the TCRU glasshouse suite at Nottingham will be used to distinguish between the environmental and genetic causes of variation. Based on data from the first experiments, one landrace will be selected from each partner country. Besides exhibiting desirable agronomic traits, each 'ideotype' landrace will best match farmers' needs as defined in the farmers' survey for the particular location from which it is sourced. From the second growing season onwards, these three landraces will be distributed and planted at local farm sites. The performance of landraces under the conditions of indigenous management practices will facilitate feedback from smallholder farmers, and form a basis for defining appropriate breeding goals. At each location (or country), additional field trials will be performed to include local management practices.

Molecular analysis of germplasm. The core collection from the germplasm held at IITA will be defined. The genetic characterization of this core collection and the selected landraces will be done using molecular marker technologies such as AFLP and RFLP. Germplasm clusters related to promising landraces will be established based on genetic similarities. Each member of the core collection will represent a group of accessions, thus allowing the activation of the total genepool. This will allow the pre-selection of germplasm accessions to be evaluated in local breeding programmes.

Based on passport and characterization data of approximately 1400 accessions of the IITA germplasm, genetic distances will be calculated and a cluster analysis will be performed. Ninety-six accessions with high intra-group- and low inter-group similarities will be defined. From each group, one accession will be selected to contribute to a core collection. The resultant set of accessions is aimed to match the original set in mean, minimum and maximum values of all evaluated traits, thereby representing the full genetic diversity of the genepool. Within-group means of important traits will be calculated to identify clusters with promising features.

Besides the core collection, the selected landraces will be included in molecular genetic characterization. Based on data obtained in cluster analysis, accessions with maximum genetic distance will be selected to screen markers for polymorphic banding patterns. Development of RFLP probes will be based primarily on screening of heterologous probes from related species (cowpea and soyabean). This will allow effective use of resources and may reveal a link with existing molecular maps due to synteny in the genus *Vigna*. Primers for the AFLP technique will be screened on selected accessions for yield of polymorphic fragments. All accessions of the core collection and the selected landraces will be genetically characterized with the developed molecular markers. The genetic data will be used to calculate genetic distances between and within the core collection and landraces. This will allow comparison of groupings based on molecular rather than morphological data. Furthermore, the well-characterized landraces will be linked to the core collection using genetic similarity information. Identification of groups of germplasm with superior field performance will be identified to exploit the available germplasm for breeding purposes.

Molecular technology transfer. The project will establish simple and feasible marker technology that can be used in laboratories with basic equipment for genetic characterization of bambara groundnut. Also, young scientists from Africa will be trained to help build, in partner countries, a molecular technology base that can also be exploited for other underutilized crops. To achieve this, a RAPDs kit will be developed. This will include a standardized protocol (established in close collaboration with selected African partners) for reproducible RAPD marker analysis for bambara groundnut, primers based on specific sequences obtained from AFLP analysis, and a manual that describes the methodology and its use in bambara groundnut and other underutilized crops. Possible problems and their solutions will be presented in a troubleshooting format. Besides well-described methods, the kit will contain reagents for genomic DNA isolation, standard genomic DNA of selected genotypes, selected RAPD primers and buffers. In the process of developing the RAPDs kit, young scientists from partner countries will be invited to participate in the development process, and full training will be provided. The kit will be tested and modified for use in genetic characterization of landraces local to their home country. This information will be made available to partner institutions and other countries and will form the basis for a similar approach in other underutilized crops.

Modelling. Results of the survey of farmers, and experimental and molecular information will be incorporated into a database that can be used for selection criteria and crop simulation modelling. Either BAMnut will be adapted to produce ideotypes for existing and desirable genotypes, or a new model will be established specifically for this purpose. It may well be that model development will include a much greater reliance on graphical imaging to provide a more interactive and user-friendly system for non-modellers. At each stage of the process, local growers will be involved in evaluating and developing the database and model in response to results from field observations, glasshouse experiments and model predictions. Survey, field, glasshouse and on-farm data on bambara groundnut will be combined within the model to develop a bambara groundnut ideotype for each participating region.

The model will be used to:

1. Predict the likely performance of each theoretical ideotype across a range of growing environments and end users.
2. Assess the suitability of existing landraces that match the ideotypic characteristics for each environment.
3. Define breeding objectives for suitable crosses to be produced through intra-specific hybridization.

In addition, the model will be used to predict the performance of landraces in diverse agro-ecological regions. In this way, appropriate management practices and potential yields of bambara groundnut will be defined and recommendations extended across a range of growing environments and soil types.

Hybridization. In inbreeding species like bambara groundnut, the number of combinations of traits is limited to the number of available lines. The advances by simple selection are limited and the genetic potential of the species cannot be fully exploited. A new combination of favourable traits is essential for development of improved cultivars. This can be achieved only by artificial hybridization of selected parental lines. Pure breeding lines will be developed to serve as potential parents in future hybridization programmes. The degree of outcrossing in bambara groundnut will be investigated.

The failure to achieve crossbreeding to date is assumed to be caused either by undue timing of pollination or mechanical damage to the flowers during emasculation and pollination. Attempts to hybridize will first focus on these two problems. Glasshouse trials will be conducted to find a cultivation method that permits easy access to the flowers for emasculation and pollination. Spreading genotypes that permit easy access to the flower buds due to longer internodes will be used to optimize emasculation procedures that can be transferred to bunchy genotypes. Trials on timing of pollination and emasculation will be performed and pod abscission rates recorded. An ideal schedule for emasculation and pollination will be established.

Field trials will be performed with different emasculation and pollination methods. The status of putative hybrid seeds will be confirmed with molecular marker technology. From the core collection and selected landraces, pure lines will be developed by the Single Seed Descent method. Three selfing generations are considered sufficient to reach an acceptable level of homozygosity, since natural outcrossing rarely occurs. The first generation of selfing will be conducted in glasshouses. This also permits easy access to leaf material for molecular marker characterization. The percentage of natural cross-pollination will be evaluated by

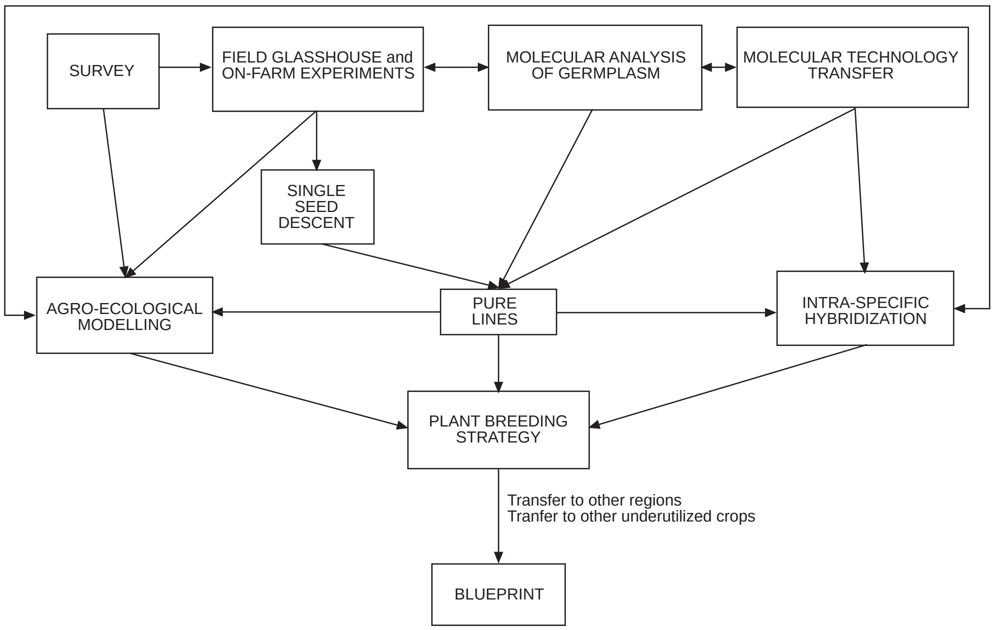

Fig. 7. Relational diagram of the second EU bambara groundnut project.

mixed cultivation of pure parental lines with easily scorable dominant marker traits.

Conclusions. This is an ambitious project that is designed to build on previous experience in environmental physiology, agronomy and modelling, and develop new strategies that encompass fundamental molecular biology and the perceptions and preferences of bambara groundnut farmers. Its success will depend on how field experiments and farmers' evidence can drive laboratory-based molecular techniques and crop simulation modelling. However, because the project provides a number of choices, the failure of one approach does not invalidate the applicability of another. For example, there is no guarantee that a method of hybridization will be established within the timeframe of the project. The selection, multiplication and single-seed descent method for producing enough desirable genotypes means, however, that either the 'hybridization route' or the 'multiplication route' may lead to the defining of the most suitable available germplasm to match the conceptual ideotypes defined by farmers.

The project will also develop generic molecular and crop modelling expertise within the African partner countries. Therefore, irrespective of how much the project assists in the development and improvement of bambara groundnut, it provides a local technology base for the appraisal of other underutilized species.

An overview of the various activities and linkages within the second EU bambara groundnut project is shown in Fig. 7.

CAN THIS EXPERIENCE BE USED ON OTHER UNDERUTILIZED CROPS?

During this research experience with bambara groundnut, informal and formal links have been established with workers and institutions exploring other underutilized species. This lends itself to the question 'can we use our collective experience to establish a general methodological framework to establish the potential of any underutilized crop? The possible structure of a wider methodology is explored here, and activities that may be necessary for such a programme to be initiated are identified. In particular, consideration is given to the question of how a central 'project team' might link with individuals and institutions working on particular crops.

Establishing a methodological framework for underutilized crops.

Any general framework needs to be robust enough to integrate information from growers, on-station reports, local surveys and published literature on any underutilized crop. By combining existing information within a common format, a methodological framework should be able to provide growers and researchers with the most up-to-date information available on their species. For each location, it should be able also to provide comparative information on other underutilized crops and, where appropriate, on major species.

Approach. The GIS-based version of the BAMnut model already developed and tested for bambara groundnut provides an ideal basis on which to establish a methodological framework for underutilized crops. Once established, this framework could incorporate existing information and expertise on each underutilized species and use a generic model to predict potential yields and distributions of each species.

Selection of exactly which species to include within a generic methodology will depend on the advocacy and co-operation of individuals and institutions involved in research or production of particular species. The intention here is not to produce a definitive list of eligible crops but to establish an approach that is responsive to the needs and interests of the end-user. A common feature for each species will be the incorporation of crop information within a generic, robust and user-friendly model that can assess and map the likely productivity and potential distribution of each crop. In this way, the model will contribute to a methodology that combines published and indigenous knowledge of marketing, processing, agronomy and physiology, with soils, climate and germplasm information, to identify the salient attributes of each crop in terms of growth, development and yield. These marked properties include:

1. Appropriate management practices to optimize yield.
2. Nutritional, biochemical, processing, feed and economic value of crop products.
3. Information on people and institutions involved with research on each crop.

Based on existing information and mechanistic predictions, the model will define:

1. Present distributions and yields of each crop.
2. Agro-ecological potential and distribution based on soil and climate knowledge.
3. Environmental and physiological limits to distribution, yield stability and yield increases.
4. Priorities for research and development activities to overcome constraints.
5. Comparative performance of other underutilized and major crops at any location.

Activities.

General list of species. To establish a methodological framework, it is necessary first to identify those species that are most appropriate for assessment. It would be unrealistic to list all the underutilized crops worthy of research attention. However, there is much sense in rationalizing the many hundreds of potentially useful species into a list of those food crops that have the greatest development potential and regional importance. One way to achieve this would be to produce a candidate list of species after consulting international, national and individual institutions involved in research on particular underutilized crops. This initial survey would also need to establish criteria, such as access to germplasm collections, geographical distributions and the possibility of establishing research networks, to produce a list of, say, 25 neglected crops that are most likely to benefit from research attention. Once established, this list would allow collation of available literature, identification of genetic resources and contact with scientists working on each of the listed species.

Preliminary methodological framework. Before proposing a major effort on any particular crop, a preliminary version of the methodological framework and generic model should be developed using existing expertise and knowledge. Such an exercise will establish basic requirements in terms of crop, climate and soil information and criteria for potential collaborators. Examples of different crop types (for example cereals, legumes, fruits and nuts) will establish the basis of a generic framework and preliminary versions of the model.

Detailed methodological framework. At the end of the preliminary phase, an international workshop will allow participants to discuss and agree a list of priority crops for thorough investigation within the detailed methodological framework. It is envisaged that this list will lead to a number of co-operative agreements between individual institutions or consortia and the project team. For each listed crop, a specific version within the generic model will be produced through collaboration between interested parties. The expansion of knowledge on each crop will contribute towards the overall programme. A mapping and prediction system for all the listed underutilized crops will be completed so that these species

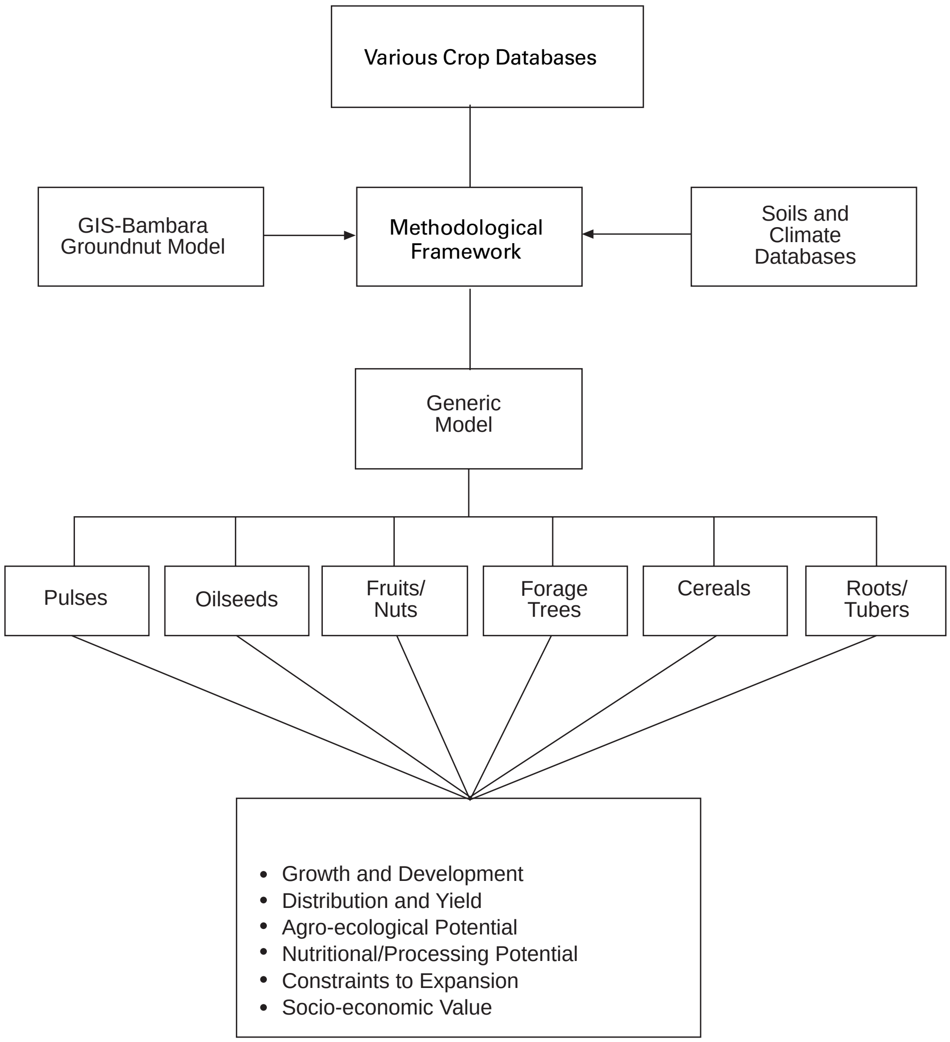

Fig. 8. Possible structure of Methodological Framework for Underutilized Crops.

can be included within the global FAO crop mapping system already established for bambara groundnut.

An overall plan of the methodological framework is shown in Fig. 8.

Conclusions. At this stage, the concept of a methodological framework is purely hypothetical. Envisaged activities and modifications to the structure and number of participants all depend on obtaining funding. The details of any final programme may be significantly different from that outlined above. It is clear, however, that any progress on particular underutilized crops, and the advocacy of an increase in agricultural biodiversity, require an integration of activities between practitioners and researchers. Piecemeal, *ad hoc* and duplicative research on different crops is unlikely to obtain support and ill-serves those who seek an improvement in the genetics and agronomy of underutilized species – the growers themselves.

DISCUSSION AND CONCLUSIONS

One of the main problems for agricultural research throughout the world is to predict the performance of crops and management practices for locations other than those used for the original experimental investigations. For this, there is a need to define the temporal and spatial variability of environmental conditions within a region, and to identify the biophysical constraints to crop production and resource management. Such an agro-ecological characterization linked with multi-locational and repetitive field trials allows scientists to set research priorities, target breeding programmes and research alternative soil and crop management practices. Agronomic experimentation is the standard method for evaluation of crop productivity in response to weather, soil, and management options.

Even for major crops, agronomic experiments are often limited by the availability of resources and are conducted usually for a limited number of sites and seasons. For most underutilized crops, an extensive multi-locational programme of experiments is simply unrealistic and any field research that is initiated is rarely combined with farmers' knowledge. It may seem surprising that the use of highly technical methods is advocated for crops of unknown potential and with an unproven track record. Together, however, the use of computer tools such as crop simulation and socio-economic models, GIS techniques and weather generators, the development of molecular techniques and detailed physiological studies, provide an innovative and cost-effective strategy to complement local knowledge of underutilized species. At the very least a preliminary mapping exercise, as demonstrated above for bambara groundnut, allows the assessment of which crops are most likely to justify further research, where that research should be located for maximum returns and in which disciplines effort should be concentrated.

The development of a broader methodological framework that includes a predictive model for each underutilized crop provides a comprehensive means of evaluating and characterizing any species and management activity at any location and providing an objective comparison between potential crops at each location. Finally, from the authors' experience, it is clear that, as with all plant sciences, the greatest progress in agricultural biodiversity will be made through a multidisciplinary and multinational approach. As with all crop science, any narrow perspective based only on molecular reductionism, qualitative social sciences or empirical field trials is unlikely to be successful!

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