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Project Title
Environmental adaptability of tropical and sub-tropical legume species as hillside cover crops

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Executive Summary

The more widespread introduction of legumes into hillside farming systems has considerable potential for improving the sustainability of rural livelihoods by reducing loss of soil and nutrients through erosion and by encouraging better soil fertility management and weed control when employed in a wide variety of ways such as cover crops, green manures, surface mulches and trash lines. However, the adaptation of specific legume genotypes to environment is often quite narrow and therefore, in the highly diverse environments found typically in hillside agriculture, the correct choice of legume species (and the further choice of accession within a species) for a specific location is frequently a difficult decision to make for both agronomists and farmers. Likewise, the transfer of technology involving specific crop species from one location, or one sowing date, to the next is fraught with uncertainty for extension personnel and NGOs. As a result, research designed to make recommendations to extensionists and farmers of potentially adapted exotic legume genotypes for introduction into their farming systems is a tremendously inefficient and expensive process. To ensure success requires several years of multi-location, multi-sowing date trials with a very large number of candidate legumes. To overcome this problem the project has developed, and validated with independent field observations, a simple model which accounts for the photothermal influences on crop phenology across a broad range of tropical and sub-tropical legume species and genotypes. It predicts whether or not, for a given sowing date and environment, a specific genotype can flower and then reach pod maturity in the time available in the existing cropping calendar. As the model coefficients describe unique genetic characteristics for each genotype, it can be used to make predictions of phenology, for that and related genotypes, at any location or elevation in the tropics or sub-tropics given knowledge of the temperature regime and latitude of the site. It is thus a very powerful and flexible tool capable of rapidly improving the success rate of location-specific agronomic research. Moreover, it can then be used to scale up such research findings to watershed scale and beyond or assess the risk of crop failure in a range of environmental conditions. The predictions from the model are already being independently tested by NGOs (CARE International and Rhizobiologia) and NARS in Uganda, Bolivia and Nepal (NARC) and it has further attracted the interest of a number of International Agricultural Research Centres (CIAT, ICRAF, ICIMOD, IITA, ICARDA) who will assist with its promulgation and dissemination globally. The potential for far-reaching eventual impact of this technology on research to improve sustainable rural livelihoods is substantial.

Background

The project was planned to contribute to the generic applicability of cover crop technologies for the control of soil erosion and the enhancement of soil fertility in hillside environments. The project was to determine the degree of environmental adaptability of a range of tropical and sub-tropical species of proven performance as cover crops such as are grown in Honduras or used as forages in west Asia to consider their potential suitability for introduction into new target hillside environments in Nepal, Bolivia and Uganda given the likelihood of their phenological responses to photoperiod and temperature being highly variable.

Soil and soil fertility losses from steep hillslopes, clear-felled forest land and recently established terraces have been shown to be reduced substantially by maintaining as continuous a vegetative cover as possible throughout the year. One agronomic intervention towards this objective, previously shown to be of value in central America, has been the introduction and effective management of legume cover crops (Sims *et al.*, 1994). Species potentially well adapted to this role in tropical environments include *Canavalia ensiformis, Mucuna pruriens, Dolichos lablab, Phaseolus coccineus, Phaseolus vulgaris, Cajanus cajan* and many others. However, given the fact that tropical hillside farming systems are very diverse in terms of sowing dates, degree of slope, intermittent dry season length, livestock feed demand and in intensity of agronomic management, reliable information is required on the responses of these legumes to those environmental influences on crop phenology which affects crop duration and so cultivar adaption. Tropical legumes are known to be typically very sensitive to both small changes in photoperiod and sub- and supra-optimal temperatures. So, if robust generic recommendations for sustainable cover crop technology are to be disseminated and made relevant to other candidate countries based on experience in environments such as Honduras, obtaining additional basic information on their responses to photothermal effects on phenology across a range of environments is crucial. Photothermal phenological responses in these forage or dual-purpose legumes were relatively less-well quantified and understood than for tropical food legumes and it was not possible to predict their phenological behaviour in specific circumstances from existing knowledge. Furthermore, the sub-tropical environments in Nepal, Bolivia and Uganda/Kenya at elevations >750m were likely to require an additional range of species with greater ability to withstand cool weather and possibly occasional frost. In these circumstances, it was important that species such as *Vicia spp.* were also assessed.

Evidence of demand for the research was accumulated from previous DFID-funded projects. In these, cover crop technologies had been proven to be of value in promoting soil conservation and maintenance of fertility with specific species on steep hillsides in Honduras and elsewhere (ODA scheme R4843). However, the generic applicability of the recommendations of these projects was unknown, in particular, the likelihood of the species used having the adaptability and flexibility for functional employment in new target environments such as in Bolivia, Nepal and Uganda. Soil erosion problems and loss of soil fertility were known to be perennially chronic issues in these and almost all other hillside environments.

Project Purpose

The project addressed NRSP HPS Purpose 2. Improved methods to maintain and enhance soil fertility and improve availability of food and feed developed and promoted through appropriate use of systems based approaches. It has addressed a constraint to development by creating a generic model capable of identifying suitably adapted legume species for introduction as food, forage or green-manure crops for any area in the tropics in order to improve the likely efficiency of location-specific agronomic work with the intention of improving soil fertility and making subsistence cropping rotations more sustainable.

Research Activities

Planned inputs were all achieved with one additional input, this being the second controlled environment experiment examining the variability in photothermally induced phenological responsiveness amongst existing *Mucuna* spp. germplasm. See Activity 4 and Appendix I.

1) A systematic and thorough literature search to review and publish information describing the photothermal adaptability of target cover crop legume species was conducted. This included a wide range of journal articles, books and grey literature available from sources such as International Agricultural Research Centres (IITA, WARDA, CIMMYT, ICIMOD, ICRAF etc.) and NGOs such as CIDDICO --- The International Clearing House for Cover Crop Information. Further details are in Appendix A.

2) The acquisition and computerisation of long-term meteorological records (daily values of rainfall, and maximum and minimum temperature) for key locations in Bolivia, Nepal and Uganda was undertaken. This included a range of stations between 1000 and 4000m in Cochabamba, Bolivia; El Zamorano in Honduras; Kabale town and Namulonge in Uganda; and Hattiban, Lumle and Pakhribas in Nepal. Further details are in Appendices F, K, L and M.

3) A series of appraisal missions to major World institutions concerned with cover crop technology for hillside environments was undertaken. This included literature collection, field observation of on-going experimentation and discussion with active scientific participants at CIDICCO (Honduras), CIAT (Colombia), ICIMOD (Nepal), and ICRAF (Kenya) and associated NGOs to identify potential uses for cover/green manure/forage legumes in the target countries and likely problems faced by farmers in their use. Further details are in Appendix B.

4) A pair of complex experiments were performed to assess phenological development in 24 diverse legume genotypes grown in a wide range of day and night temperatures with different daylengths in highly specialised glasshouse facilities with full temperature and daylength control. Such facilities are only rarely available world-wide at the required scale to grow cover legumes and are key physical attributes of the Plant Environment Laboratory at The University of Reading. The skills to conduct these experiments, and to interpret their output, are also an almost unique resource vested in the staff at the Plant Environment Laboratory. These skills are largely derived from the successful execution of a substantial history of DFID-funded plant physiological investigations. Further details are in Appendices E, F and I.

5) Estimation of the genotypic photothermal constants from the equation predicting first flowering in annual crops (Summerfield *et al.*, 1991, Watkinson *et al.*, 1994) was made. This was achieved for almost all genotypes investigated with minor exceptions. These exceptions included *Pueraria phaseoloides*, which only flowered in the warmest and shortest day environment tested thus totally preventing constant estimation. However, it nevertheless allowed detection of the acute photoperiodic sensitivity of this species which was previously unknown. Further details are in Appendices F, I and N.

6) Photothermographs which were able to predict the likelihood of the target species completing reproduction successfully in wide ranges of field environments (Roberts *et al.*, 1996) were constructed. This activity highlighted the internal consistency of the experimental findings and thus the high quality of the experimental work executed. Further details are in Appendices C, D, F, G, H, I and N.

7) The predictive phenological models (Watkinson *et al.*, 1994) were run to predict safe first flowering and first pod maturity "windows" for the full range of germplasm examined, thus to make recommendations of suitable genotypes for field testing at target locations and with regard to the specific niches in the cropping calendars of the target locations in Nepal, Bolivia and Uganda that were most apposite. Initial small scale field trials were also conducted through local collaborators, specifically, to validate the robustness of the model predictions. Additional data were also collected from published experimental results involving comparable genotypes from Pakistan, Cyprus and Nepal and these were used either to amend the photothermal constants where prediction beyond the temperature range of environments employed in the glasshouse experimentation proved to be unreliable, as for *Vicia sativa* (Cyprus local), or to provide additional supporting validation data for the robustness of the model output. Further details are in Appendices F, K, L, M and N.

8) A final Project Dissemination Workshop was held and the proceedings are being published in two special editions of the scientific journal *Mountain Research and Development* to transfer the model methodology and management techniques, and to highlight potentially suitable species for further testing in Nepal, Uganda and Bolivia, to a broader group of IARCS, NARS and NGO field scientists and staff from tropical and sub-tropical environments.

Outputs

a) A thorough review of world literature on the photothermal adaptability of target forage and dual purpose legumes for use as cover crops. Achieved, see Appendix A.

J.D.H. Keatinge, Qi Aiming, T.R. Wheeler, R.H. Ellis, P.Q. Craufurd and R.J. Summerfield (1996). Photothermal effects on the phenology of annual legume crops with potential for use as cover crops and green manures in tropical and sub-tropical hillside environments. *Field Crop Abstracts* 49, 1119-1130.

Soil erosion and loss of inherent soil fertility are major problems throughout the tropics and sub-tropics. The greater use of cover and/or green manure annual legume crops is one way by which these problems might be redressed. However, to determine which of the many potentially useful species and genotypes to employ in the mosaic of niche environments as are commonly found on cultivated hillsides is a major problem. In order to improve the efficiency of matching genotype to environment, a precise knowledge is required of the phenology of diverse genotypes and of the environmental factors which control the timing of major events in the crop life cycle. Photoperiod and temperature are the two major environmental factors which influence crop phenological development in annual crops. Their influences on the timing *of reproductive events in annual legumes is reviewed for 13 major genera, or associated groups of genera, which are commonly employed either principally or secondarily as green manure or cover crops. These genera have been selected to span the full range of adaptation to climatic conditions from warm, wet tropical to cool, dry temperate which encompass the range of hillside agricultural environments found in the tropics and sub-tropics at all elevations <4000m.*

It is strikingly evident from this review that there is substantial diversity in the phenological responses to photothermal factors between and within most genera and species of legumes of potential use as multi-purpose green manure and cover crops. This finding implies that there is exciting potential to match appropriate legumes to specific spatial and temporal niche environments on hillsides throughout the range of climatic conditions experienced in the tropics and sub-tropics. Such a potential change in present cropping systems could be of substantial benefit in rendering hillside soils less vulnerable to both inherent loss of fertility and to physical erosion. Such interventions, then, could be a critical factor in ensuring the sustained output of agricultural products which is presently an urgent priority in many remote hillside locations. The research efficiency and practical impact by which this task can be achieved will be considerably hastened and improved by a much clearer understanding of the photothermal controls of major phenological events such as the timing and plasticity of first flowering, first podding and seed maturity. Determination of the likely magnitude of the photothermal coefficients controlling phenology in a representative range of legume species appears to be the logical first step in this challenging process.

b) A quantitative model of the effects of photoperiod and temperature on successive phenological stages in diverse genotypes of selected tropical and sub-tropical forage legumes. Achieved, see Appendices E, F I and N.

J.D.H. Keatinge, Qi Aiming, T.R. Wheeler, R.H. Ellis and R.J. Summerfield, 1998. Quantifying the effects of temperature and photoperiod on phenology to guide selection of annual legume cover crops for hillside farming systems. *Field Crops Research* 57, 139-152.

The effects of temperature and photoperiod on times from sowing to flowering and maturity in a range of multi-purpose leguminous cover crop species were investigated in controlled environments in order to quantify the photothermal coefficients which determine their potential environmental adaptation. Six genotypes representing six tropical or sub-tropical species were grown in 12 environments comprising all combinations of mean diurnal temperatures of 17°, 22° and 27°C and photoperiods of 11.5, 12.5, 13.5 and 14.5h d^{-1}*. Another six genotypes representing five temperate species were grown in 9 environments comprising all combinations of 17°, 22°, and 27°C and photoperiods of 12.5, 13.5 and 14.5h* d^{-1}*. For all tropical and sub-tropical species, the warmest temperature combined with the shortest photoperiod hastened flowering and fruit maturity. However, except for Lupinus mutabilis which was photoperiod-insensitive, all temperate species both flowered and matured sooner at the warmest temperatures combined with the longest photoperiod. These photothermal responses in phenological development were amenable to modelling. Times to flowering were satisfactorily described using a general triple plane rate model. Rates of progress from first flowering to first mature pod were also satisfactorily modelled using temperature alone as the independent variable. These photothermal and thermal relations have identified considerable inter-specific differences in phenological responses to environment.*

For the six short day species, it is evident that considerable care needs to be taken if crops, which are grown successfully at very low latitudes and elevations, are to successfully reproduce in environments with longer photoperiods and/or cooler temperatures, Pueraria phaseoloides in photoperiods >11.5h d^{-1} *or temperatures <27°C being the most sensitive example. Failure to reproduce, of course, may be advantageous in some situations such as in weed control for plantation agriculture; but for most small-scale hill farmers, the ability to retain seed at the end of the season is regarded as a necessary pre-condition for the acceptance of a new technological innovation such as the use of cover crops. There is some similarity in response to photothermal conditions between Canavalia ensiformis, Mucuna pruriens and Dolichos Lablab, all flowering in the most inductive regimes in 60-70 d. However, for all three species time to flowering would become inordinately long at higher latitudes and elevations which would severely compromise their likelihood of eventual reproduction --- as indeed has been the experience in recent trials at Godawari and Lumle in Nepal. Even under inductive conditions the time* *from sowing to fully matured pods is normally about 170 d in C. ensiformis which would accord with our findings of the earliest mature pod occurring at day 139 after sowing in an 11.5 h* d^{-1} *photoperiod. Mucuna pruriens and D. Lablab would seem to have some preferential advantage in time to pod maturity over C. ensiformis as they reached first pod maturity at 106 and 95 d, respectively. However, both C. juncea and S. hamata flower 20-25 d earlier than the other SDP species tested and thus might have a further value filling a niche in a short "fallow" interval between other crops, particularly at vulnerable times of the year for soil resources such as immediately preceding the onset of the rainy season.*

For the long day plants it would appear that the responses of the two V. faba genotypes, T. resupinatum and V. sativa are fairly conventional. They are influenced by photothermal factors across the full range of photoperiods and temperatures tested with first flowering occurring 28 to 38 d after sowing. Vicia sativa is the most sensitive in terms of delay in first flowering to non-inductive conditions. In terms of biomass production T. resupinatum seems to be widely adapted, making good growth, across a broad range of environments and as such might be a species whose inherent versatility could be valuable for exploitation in "mosaic type" hillside environments. Such a characteristic seems to be even more striking in V. dasycarpa which grew and reproduced well in all environments. Overall it seems to be relatively insensitive to both photoperiod and temperature in terms of all its reproductive behaviour (both flowering and podding). This reflects its apparent adaptability over a wide range of sites with very contrasting latitudes and altitudes. Coupled with its outstanding cold tolerant abilities and impressive forage yield potential these characteristics imply that V. dasycarpa has considerable scope for use as a cover species in hillside environments. These qualities have contributed to the recent release of the accession tested in this experiment (ICARDA #683) as a variety (Kuhak 96) for the highland areas of Pakistan. Lupinus mutabilis, which is widely grown over a wide latitudinal range in the Andes, appears to be insensitive to photoperiod and is thus for all practical purposes day neutral. In contrast, it has a clear response to temperature, characterised by an optimum at around 22 °C and which is reflected in the substantial abortion of flowers recorded in the warmest regime (27 °C). Therefore, any attempt to transfer this species to tropical lowlands would be extremely risky. Nevertheless, potential use across a wide latitudinal range in the highlands appears to be a robust and very productive practice. Output from the models can now be investigated to reveal the relative suitabilities of these diverse species as potential cover crops across hillside environments throughout the tropics and sub-tropics.

Qi Aiming, T.R. Wheeler, J.D.H. Keatinge, R.H. Ellis, R.J. Summerfield and P.Q. Craufurd (1999). Modelling the effects of temperature on the rates of seedling emergence and leaf appearance in legume cover crops. *Experimental Agriculture* (in press for 1999)

Selecting the most appropriate legume cover crop for a particular farming system is made difficult because no one legume species is likely to fulfil all the requirements of an "ideal" cover crop. Moreover, the most appropriate cover crop species will vary depending on the characteristics of the target environment. Quantitative models which describe the growth and development of different cover crops will aid the selection of genotypes that are adapted to the target environment. Two processes important to the establishment of ground cover are seedling emergence rate and leaf appearance rate in different photothermal environments.

The effects of temperature on the rates of seedling emergence and leaf appearance are in accordance with the thermal time approach. Linear relationships between these rates and sub-optimal temperatures have often been reported previously in many other crops for the rate of seedling emergence and for the rate of leaf appearance. The absence of photoperiodic effects on the rate of leaf appearance in all species examined here was also observed in cowpea (Vigna unguiculata (L.) Walp.) and is assumed implicitly in crop simulation models given that leaf production can be successfully modelled by a thermal time approach.

Quantifying the effects of temperature on the rates of seedling emergence and leaf appearance could be simplified because (with the notable exception of V. dasycarpa) within each photoperiod response group there was a common T_b*. The estimates of* T_b *for seedling emergence rate were 9°C for the short-day species, and 1°C for long-day species (except V. dasycarpa). For the rate of leaf appearance these values were 10°C for short-day species and -2°C for long-day species (except V. dasycarpa). Thus, future modelling of seedling emergence and leaf appearance of legume cover crops in target environments could start by adopting these respective common values of* T_b*.*

Keatinge et al. 1998 (Appendix F) reported a range of T_b *values from 8.5 to 9.5°C for the rate of progress from sowing towards flowering for the six short-day species investigated here.. The absence of a significant temperature effect within the range imposed here on the rate of seedling emergence for V. dasycarpa was also detected for the rate of progress towards flowering and from flowering towards maturity (Keatinge et al., 1998; Appendix F), and clearly distinguishes V. dasycarpa from the other cover crops investigated.*

Rapid development of ground cover may aid conservation of soil water and protect the soil from erosion. These simple thermal time models can now be employed to identify whether or not a given legume species is potentially adapted to a particular cropping environment in terms of rapid establishment of ground cover using a minimum data set of the daily records of minimum and maximum temperatures. The practical consequence is that the long-day legume species would be more suitable for temperate conditions as found at the more extreme latitudes or at higher elevations in the tropics and sub-tropics in order to achieve more rapid seedling emergence and earlier soil cover. Relatively cool supra-optimal temperatures for V. sativa, V. dasycarpa and L. mutabilis confirm that these species would not be the most suitable for lowland tropical environments, but may have considerable potential in the tropical highlands (>1000m).

The considerable interspecific variation in rates of seedling emergence and leaf appearance, and individual leaf sizes, permits the multi-purpose use of these legume cover crops to be assessed for different environments. For example, legume species with relatively large leaves and rapid leaf production would be more suitable for suppressing weeds and producing a large biomass in a short season. Mucuna pruriens and D. lablab grown in tropical environments may belong to this division of legume species. The widespread use of M. pruriens for control of Imperata cylindrica by farmers in Benin and central America exemplifies this conclusion. However, the highly competitive nature of such cover crop species can also be hazardous in inter- or relay- cropping situations. The simple leaf appearance models described might also be used for the prediction of 'safe' delayed sowing times for leguminous cover crops grown in relay with cereals such as maize or millet.

Qi Aiming, R.H. Ellis, J.D.H. Keatinge, T.R. Wheeler, S. A. Tarawali and R.J. Summerfield (1999). Differences in the effects of temperature and photoperiod on progress to flowering among diverse *Mucuna* spp. *Journal of Agronomy and Crop Science* (in press for 1999).

The use of Mucuna spp. in cover crop and green manure technologies is proving to be successful in the tropics and sub-tropics following intensive efforts in technology transfer to farmers by NGOs (Non Governmental Organisations). This includes the transfer of seed of Mucuna spp. for which the range of adaptation and the effect of environment on crop phenology is poorly understood. A selection of Mucuna spp. germplasm was evaluated over a range of contrasting photothermal conditions in controlled-environment glasshouses. Dates of emergence and first flowering were recorded. Where possible, triple-plane rate of development models were fitted to the first flowering data to quantify the relative sensitivity of each species to photoperiod and temperature. All accessions showed short-day responses but there were substantial differences in the sensitivity of rate of progress to first flowering to environment, particularly to photoperiod. This results in differences in maturity period between accessions which, with appropriate understanding, could be functionally exploited by NGOs and NARS. However, if ignored, it could result in the promotion and use of accessions ill adapted to the environment in which they are tested. In consequence there might be unnecessary resistance from farmers to the adoption of green manure and cover crops technologies which are vital to the design and maintenance of sustainable farming systems in low-income countries in the tropics.

It is clear from the substantial differences in photothermal sensitivity of flowering discovered here between Mucuna accessions that transfer of germplasm between locations considerably differing in latitude, or with radical changes in the seeding calendar, would be better undertaken within the context of an improved understanding of the photothermal implications for crop phenology. Failure to be aware of these differences may have critical consequences for NGOs and NARS seeking to extend cover crop technology with Mucuna spp. For example, some germplasm will flower and set seed successfully in longer photoperiods but others clearly will not. The range in relative maturity period (as indicated by flowering date) displayed between M. preta and M. aña (Zamorano Dwarf landrace) is both a potential *hazard and also a potential advantage depending on the precise objective in a specific farming system. If there is only a narrow window of opportunity for growing a cover crop, such as between the cropping of subsistence cereals, then clearly Zamorano dwarf's earliness could guarantee the satisfactory completion of the crop's growth within the cropping cycle. Whereas, if the objective was weed suppression for the longest possible period, such as under plantation crops or to maximise biological productivity for green manuring, an exceptionally late flowering species even in short days such as M. preta might well be preferable. Flowering responses to temperature must also be considered. Even though differences between germplasm in the thermal plane were negligible it is evident that species such as M. deeringiana, M. jaspadea and M. veracruz-stepan may be further delayed in flowering if average air temperatures are >32 °C. As such environments might be found closer to the tropics rather than the equator (owing to reduced cloud cover in drier seasons) the coupling of longer photoperiods with warmer temperatures might seriously influence phenology in such accessions.*

The findings of this research give clear indications to IARCS, NARS and NGOs that although Mucuna spp. are short-day plants, it would be unwise to adopt a cavalier attitude to their popular dissemination across key photothermal boundaries. Such actions might well provoke a negative farmer backlash to the very successful introductions that have occurred to date in Benin, Honduras and elsewhere. This may have been one of the factors in the poor uptake by farmers of green manure technology experienced in Rwanda. It is not necessary for such problems to occur as there is clearly a wide range in germplasm maturity which can be exploited sensibly. Nevertheless, it requires a clear understanding by NARS and NGOs that the photothermal boundaries of the recommendation domain of any one accession are defined and thus limited. This recognition must underpin the informed decisions of NGOs as they continue their dissemination of this family of species for use in cover crop and green manure technologies in the design of sustainable cropping systems in the tropics and subtropics.

Qi Aiming, J.D.H. Keatinge, T.R. Wheeler, I. Papastylianou, M. Subedi, P.B. Shah, F. Musitwa, E. Cespedes, C. Bening, R.H. Ellis and R.J. Summerfield (2000). Field evaluation of photothermal models for predicting the date of flowering and maturity in cover legumes using photothermal models. Journal of Agricultural Science (in press).

Lack of information about the specific environmental adaptation of cover crop species remains a serious constraint in the efficient design of agronomic experiments examining options for more suitable and more sustainable management of hillside farming systems in the tropics. Predictive models of crop phenology exist but the robustness of their generic applicability remains largely unproven. Evidence was therefore gathered here to determine the predictive ability of phenological models driven by temperature and photoperiod across a diverse range of cover crop genotypes and tropical hillside environments. Seeds of eleven legume species of cover and/or green manure crops collected from different hillside locations world-wide were sown in two groups of nurseries (tropical short-day plants in early summer and sub-tropical long-day plants in early winter) at a range of locations in the tropics, viz: Kabale and Namulonge in Uganda, Godavari and Lumle in Nepal, Cochabamba in Bolivia, Zamorano in Honduras, and Valenca in Brazil. Dates of sowing, first flowering and first pod maturity were taken and daily rainfall and temperature data were recorded at each site. Similar observations for the same genotypes were available from independent experiments conducted at Islamabad, Pakistan, Hattiban, Nepal and at three locations in Cyprus. Model predictions were compared to field observations. The proportion of variation accounted for in the period from sowing to first pod maturity was 88% and 89% for the short-day and the long-day groups of genotypes, respectively. Likewise, the average difference from sowing to pod maturity between the model predictions and the field observations was 6.3% and 7.9% for the combined short-day species and the combined long-day species, respectively.

Taking into account the limited availability of independent data for assessing the validity of the photothermal models evaluated here, it seems reasonable to conclude with average differences between observed and expected values of less than 10% that the model predictions should be sufficiently robust for their intended uses: These are envisaged as being as a crude screen for ill-adapted germplasm prior to agronomy trials at specific locations and for making a first quantitative estimate of the altitudinal and latitudinal dimensions of the recommendation domain associated with the results of location-specific agronomy trials in hillside areas.

When the models are combined to examine the full period from sowing to first pod maturity, they meet the simplistic quality criterion of an average difference between observed and expected values of less than a 10% error with the actual error being between 6 and 8%. Given that there has been very substantial work defining the models from sowing to first flowering and very little for the latter period, further efforts to define the relation between first flowering and pod maturity might well improve the predictive capability of the models accordingly. It is also possible that an improvement in the extent and quality of field observations of the date of first pod maturity (nominally without environmental stresses) might prove the models to be more robust than presently suggested by the small data set available. Yet, while acknowledging current weaknesses and room for improvement, it is still very possible to use the model to make clear and sensible predictions for selecting well-adapted cover legumes for agronomy trials in a wide range of different farming systems (Appendices K, L and M). Such trials are now in progress in Bolivia, Uganda and Nepal.

c) A review identifying the potential and actual use of cover/green manure/forage legumes for different purposes in a range of target environments and the likely problems faced by farmers in their use. This will include interrogation of the model output considering interventions by which such problems with cover crops can be overcome and by which their full potential can be realized. Achieved, see Appendices B, D, G, J, K, L and M. For model output see d).

J.D.H. Keatinge, T.R. Wheeler, P.B. Shah, M. Subedi, F. Musitwa, E. Cespedes, Aiming Qi, R.H. Ellis and R.J. Summerfield, 1997. Potential For and Constraints To the Production of Multi-purpose Cover Crop Legumes in Hillside Environments in Key Department for International development (DFID) Target Countries. DFID Project R 6447 Appraisal Report pp.46.

Opportunities for the use of cover crop legumes to improve soil fertility and simultaneously to reduce the risk of soil erosion on hillsides have been examined for farming systems in the key DFID target and networking countries of Nepal, Honduras, Bolivia and Uganda. It is clear that opportunities are substantial depending on the fitting of such crops into niches within existing cropping calendars. Constraints to the adoption of cover crop technology based on competition for land, labour and capital resources remain to be overcome. A key element in solving this problem is the selection of an appropriately adapted legume species and genotype. Use of the generic adaptation model being developed in DFID project R6447 should materially reduce the risks associated in this choice. The potential for improving the sustainability and economic viability of farming systems on hillsides by incorporating cover legumes into crop rotations seems to be large and yet the risks associated with attempting to sustain those existing cropping patterns in the face of declining soil fertility may be considerable. Research is needed to ensure that such interventions, designed to improve soil fertility, can be adopted by hillside farming communities as quickly and painlessly as possible before natural resources become irreversibly depleted.

There are substantial opportunities for the introduction of cover legumes into hillside farming systems in key DFID countries. Use of these crops could be one of a range of potential interventions designed to result in more sustainable farming systems through a reduction in soil erosion and an improvement of soil fertility. However, systematic research is required to overcome the likely biological and socio-economic constraints to adoption to be encountered in farming systems dominated by small-scale, resource-poor farmers. These have been encapsulated by Fischler (1997) under the following headings:

•Land --- will farmers be prepared to occupy land for a full season without immediate return, and can the loss of a season be compensated for by a subsequent increase in crop yields in the longer term? Identifying niches within cropping calendars where this constraint is least severe and in which the growth of a legume crop is biologically possible remains a key scientific issue. Likewise, what are the precise, shorter and longer-term rotational benefits resulting from an improved farming system involving cover legumes? What would be the implications of ***not*** *changing such systems if continued declines in soil fertility are inevitable?*

•Labour ---- will farmers be willing to invest in the additional labour required for growing, incorporating or mulching a cover crop unless it is compensated for by reduced time required for weeding or cultivation of subsequent crops? Such questions can only be resolved within the context of the farming system as a whole and over a time-frame longer than one year. The longer- term improvement in soil structure and thus ease of cultivation noted in Honduras by farmers intercropping maize and Mucuna illustrates this point.

•Inputs --- will farmers consider incorporating cover legumes in their systems if input requirements cannot be met within existing farm resources? Seed supply or capital to purchase seed is the likely principal non-human input. Seed of such species is rarely available. Thus efficient home seed production is a fundamental requirement as a prelude to adoption, as noted in Honduras.

•Variability --- will farmers who are largely risk averse be prepared to accept a technological intervention that is often erratic in behaviour in highly variable environments?

For each of these four main constraints, and particularly in the latter two cases, the selection of an appropriate, well adapted genotype is critical to the adoption of technologies involving cover legumes. A generic adaptation model is now required to maximise the likelihood that the cover legume species selected for any given niche environment has an appropriate phenology and is potentially capable of producing mature pods and seeds in whatever cropping window prevails.

d) Recommendations for suitable management techniques for testing by the NARS in specifically defined hillside environments in Nepal, Bolivia and Uganda, and globally by CIAT, ICRAF, ICARDA and ICIMOD. Achieved, see Appendices K, L, and M. In addition, the research process has involved the active collaboration of at least 16 scientists operating across ten countries (Nepal, Bolivia, Uganda, Brazil, Syria, Pakistan, Cyprus, Honduras, Nigeria and the United Kingdom and the resultant knowledge has been disseminated directly to the greater hillsides global network of 130+ concerned scientists.

J.D.H. Keatinge, Qi Aiming, T.R. Wheeler, M. Subedi, P.B. Shah, R.H. Ellis and R.J. Summerfield (1999). Selecting annual legume species with potential as autumn-sown green manures in the low-input farming systems of Nepal. *Mountain Research and Development* (in press for 1999).

Models which predict the duration between sowing and reproductive maturity have been used to examine the suitability of cover legumes for use in the farming systems of the mid-hills Region of Nepal. The locations of the principal National Agricultural Research Council hill research institutes at Hattiban, Lumle and Pakhribas, which are broadly representative of the wide range of environments found in the mid-hills, were selected for detailed examination. In addition, for each of these sites the temperature regimes of a typical span of elevations (600m -2400m) were constructed to examine the likely range of environmental variability associated with cropping in the mid-hills Region. Using appropriate sowing dates for winter and spring-sown crops, temperature and photoperiod data were used in models developed to predict rates of development and so the feasibility of six legume cover species reaching crop maturity prior to the sowing period for the principal summer cereal crops.

Rice, maize or millet grown under summer monsoonal conditions are the principal subsistence crops of the Nepali mid-hills and it is highly improbable that farmers would be prepared to consider any encroachment on their principal growing season by multi-purpose leguminous cover and green manure crops. Therefore, to maximise the likelihood of the inclusion of such species into a cropping system, it is necessary for them to mature well before the potential sowing or transplanting date (rice seedlings) of the summer crops. How might this "safe window of opportunity" for crop maturity be defined when clearly it must predate the formal start of the monsoon period? The probability of rain on any given day at the three locations is presented. From these data and the range of dates for rice nursery and direct sowing of summer crops reported close to the three target locations, it is feasible to suggest that the time for sowing summer crops coincides with the dates from when the probability of rain increases from 50 to 75% (Appendix K, Figure 9). However, there is likely to be not insignificant variability in these dates even within the mid-hills ecological zone of Nepal. For example, for Lumle this would imply the period from

28 April to 5 June, for Hattiban ca. 5 June to 11 July and for Pakhribas ca. 15 May to 17 June. Therefore, given the dates of first pod maturity for the various legume species the importance of early sowing and elevation are dominant in the choice of a suitably-adapted species. At Hattiban (the coolest location in winter) below 1000m all species tested are able to reach maturity before the first rainfall probability threshold irrespective of sowing date. In contrast, above 2000m only Vicia faba (Bolivia) and possibly Vicia dasycarpa with the earliest sowing date are capable of reaching maturity before the first threshold. At the intermediary elevation of 1500m Vicia faba (both Bolivia and Nepal), Lupinus mutabilis and Vicia dasycarpa all reach maturity prior to the threshold irrespective of sowing date whereas the other species do not. However, all species would achieve maturity prior to the second threshold if that was deemed acceptable.

At Lumle, which is the wetter and somewhat warmer in winter site, the relatively earlier 50% rainfall threshold has a substantial negative effect on the likely adaptability of legume species. Even below 1000m Trifolium resupinatum (late sown) and Vicia sativa (both early and late sown) cannot reach maturity by the first threshold date but all species and sowing dates can reach maturity before the second threshold. Around 1500m, it is clear that V. faba (Bolivia) and Vicia dasycarpa (early and late sowings) and V. faba (Nepal) and Lupinus mutabilis (early sowings only) can achieve maturity in time but not other species. Above 2000m, just V. faba (Bolivia, early sowing only) and Vicia dasycarpa (early and late sowings) mature sufficiently early.

The larger range of sowing dates that are compared for Pakhribas underscore the importance of sowing as early as possible if early maturity and a greater potential choice of legume species is desirable. The contrast between sowing in late October with that of the end of December implies that early sowing might permit use of Lupinus mutabilis, Trifolium resupinatum or Vicia sativa below 1800 m but these species would be inappropriate with the later sowing date with the exception of locations below 1000m. In the maize and relayed finger millet system (Eleusine coracana) commonly practised in the Pakhribas area, maize sowing may even be somewhat earlier than the date of 50% rainfall probability which only re-emphasises the need for the earliest sowing possible with some of the longer duration legumes.

Generally at higher elevations (>1000m but <2000m), the choice of species must be largely restricted to those capable of early maturity. Of these, the exotic species V. faba (Bolivia), Vicia dasycarpa and early sown Lupinus mutabilis seem to have potential for testing in comparison to the Nepalese V. faba landrace. Using the model, it has been possible to discriminate inexpensively between environments and species and is thus a good way to rapidly screen large numbers of potential cover legumes. This would be useful particularly at locations where, either little agronomic testing of legume species has been carried out, or where exotic species are being proposed for inclusion in multiple time-of-planting x location trials. In addition, if institutions have large recommendation domains with diverse environments (as ARS Lumle, NARC Kathmandu and ARS Pakhribas all have), then the model would be useful for extending applicability of results from on-station trials at specific agro-ecological research sites or for the assessment of the relative risk of not achieving maturity in those years with atypical weather conditions. The model therefore might assist in the development of simple extension messages across a clearly defined environmental recommendation domain.

J.D.H. Keatinge, Qi Aiming, T.R. Wheeler, F. Musitwa, N.A.P. Franks, the late D. Kuribuza, R.H. Ellis and R.J. Summerfield (1999). Selecting potential annual–sown legumes for trash lines, green manures or short-fallow replacement in low-input systems in the East African Highlands: The example of S.W. Uganda. *Mountain Research and Development* (in press for 1999).

Models are presented which can be used to examine the suitability of annual cover legumes, in terms of their maturity period, for their potential for incorporation into the hillside farming systems of the highland regions of sub-Saharan Africa. Sites in south-western Uganda, covering a range in elevations from 1600-2500m and having a bimodal rainfall distribution, were used as an exemplar. In such locations, it was evident that several of the short day "tropical" species tested were ill-adapted and would be unlikely to reach pod maturity within the time available in either of the available growing seasons, particularly at higher elevations. More temperate species, particularly Vicia spp., were better adapted but delays in sowing and increasing elevation severely restricted the *potential choice of an appropriate species. The flexibility of the models as potential tools for scaling-up location-specific agronomic research trials is discussed*

Legume crops must either fit into the current cropping system with minimum loss of subsistence food crops or need to be used to exploit opportunities in the cropping calendar when land was "resting " (which could be at any time) or where demands on land are less pressing (such as on upper slopes where land may be abandoned for some time). This is certainly a key issue in S.W. Uganda. All such opportunities reinforce the importance of being able to provide farmers with a wide range of well-adapted, optional legume crops which they can select according to their specific needs and use according to their own land and labor resources. While many adapted legumes are likely to be able to produce substantial biomass in available periods in the cropping calendar (often as short as 3-4 months) it is evident that the period required for them to produce seed may be substantially longer. The relative importance of the necessity for seed production versus the likely constraints of the growing season and direct competition for land from subsistence crops is as yet unquantified but surveys to examine these and other agronomic management issues are presently underway by CARE in the Kabale-Kisoro areas. This is complicated by the fact that farmers might wish to export any biomass with a high N content to act as fertility-enhancing mulches in their banana plantations at lower elevations. Also, it is certainly the case in some situations, where cover and weed control are the principal motivations for growing a cover crop, that seed production may not be desired. The models employed are sufficiently flexible to be capable of suggesting possible species with this attribute.

It has been estimated that up to 16% of the land in Kabale is under short term fallow (3-6 months) but this is largely a practice which they suggest can only be afforded by larger land owners. Earlier trials by CARE International support the observation that short day species such as those within the genera Mucuna and Canavalia are ill-adapted above 1500m and growth cannot be expected to be sufficiently vigorous to be a realistic option. Likewise, Crotalaria spp. would also be inappropriate above 1500m and that there is a need for field trials to identify alternative legume species, particularly for higher altitude areas where there are fewer known options. Having given due consideration to model output and immediate seed availability, such field work by CARE International is now in progress in S.W. Uganda incorporating, in the first instance Vicia villosa ssb. dasycarpa acc. 683, Vicia sativa and Lupinus mutabilis.

The models examined are useful tools to pre-screen a wide range of legume genotypes to eliminate unsuitable germplasm from further field testing. In addition, once field testing at one or more locations has been completed, the models can be used to scale up the results to the full range of sowing dates, elevations and locations of interest thus defining the boundaries of an appropriate recommendation domain. Likewise, they may be used to consider the variability in a historical data set at any one location to determine, for example, the number of years in ten in which a species could achieve maturity in sufficient time to allow the sowing of the next food crop when the onset of the start of the rainy season is later than normal. From the use of such models therefore, agronomic research should be made more cost effective and any subsequent general recommendations, in association with farmer preferance/acceptance trials, are likely to be more robust. Finally, when coupled with international data bases (e.g. IITA's LEXSYS,) or geographic information systems, these models might also be suitable mechanisms for extending results from the test environment to a macro-regional level such as throughout the target regions of the African Highlands Initiative or more globally to the Andean (Appendix M) or the Himalaya-Hindu Kush regions (Appendix K).

T.R. Wheeler, Qi Aiming, J.D.H. Keatinge, R.H. Ellis and R.J. Summerfield (1999). The selection of legume cover crops for Bolivian Hillside Environments. *Mountain Research and Development* (in press for 1999).

The mid-elevation hillsides of the Cochabamba region of Bolivia between 2500 and 4000m are characterised by a multitude of microclimates for crop production. Poor productivity of food crops in the Cochabamba region has been principally associated with declining soil fertility. The time that land is left in natural fallow has declined steadily as the need for more land for crop production rises. There is, therefore, an opportunity for using legume cover crops in this region to improve the restoration of soil fertility during the natural fallow period. Our objective was to identify potential legume cover crops which can germinate, flower and set seed within the possible growing season *constrained by temperature, photoperiod and rainfall patterns. A photothermal model which described the response of the rate of development of 12 diverse legume cover crops to temperature and photoperiod was calibrated for each cover crop and simulations were run using the climate records for three hillside sites near to Cochabamba: La Tamborada (2600m), Zapata Rancho (3220m), and Toralapa (3490m). Six of the more temperate cover crops investigated could mature and provide seed from any sowing date at 2600m, and from most sowings at 3220m. However, cover crops adapted to 3490m were more scarce.*

It is evident that the photothermal model of the rate of development of cover crop species can be used to investigate whether these cover crops are adapted to the different micro-environments found on hillsides of the Cochabamba Department, Bolivia. This provides further support for this method of selecting cover crop species which has also been found useful in the hillsides of Uganda (Appendix L) and Nepal (Appendix K). As a result of the current study, a number of legume species with potential for use as cover crops can be recommended for use in field trials in this region of Bolivia. At elevations near to 3500m only V. villosa ssp. dasycarpa and V. faba from Bolivia are potentially adapted. These two species plus L. mutabilis and V. faba from Nepal are potential cover crops for use at near to 3000m, and T. resupinatum and V. sativa are additional species with potential at the lowest elevations in the Cochabamba hillsides of about 2500 - 3000m.

Contribution of Outputs

The outputs have contributed substantially towards the achievement of the Programme Purpose by ensuring that IARCS, NARS and NGOs have a simple generic mechanism which allows them to make a choice of potentially-adapted legume species considerably more efficiently for hillside environments, in terms of operational resources and labour, than the previous use of large-scale of multi-locational, multiple date of sowing trials. It will also allow estimation much more comprehensively of the dimensions of the potential recommendation domain for a species identified in any field trial as having potential suitability. This has already lead to increased testing and dissemination of cover crop technologies and germplasm in key DFID countries, and more broadly in S. Asia, Latin America and Sub-Saharan Africa. This includes use of model recommendations by CARE in Uganda, by Rhizobiologia and other NGOs in Bolivia and planned use in Nepal at a range of NARC Agricultural Research Stations. For these three target countries NARS scientists have had access to the model and its output through direct mailing of key publications and by their attendance at the Hillsides Systems Conference at Silsoe in January 1999. Interest in the methods has also been indicated by IITA, CIAT, ICRAF, ICIMOD, ICARDA and the specific members of the hillsides scientist network which all will act as dynamic promotion pathways at a global level. Use of such technologies in hillside environments will reduce the potential for soil erosion and nutrient loss, will contribute to the sustainability of the cropping systems by improving soil fertility, and will help sustain rural livelihoods by providing additional food and/or feed and income to disadvantaged farming communities.

Further research will be required to validate the effectiveness of the model's recommended genotypes for specific cropping systems through participatory agronomic trials to formulate effective options for farmer management of these exotic species, their residual effects on following subsistence cereal crops, and their likely acceptability into local farming systems. Concept notes for such work in Bolivia and in Nepal have already been approved by the NRSP PAC for development to full project proposals. Associated HARP concept notes are presently in preparation by local organisations in Nepal which are designed to add value to the NRSP project submission. It is expected that opportunities to bid for funds for further work in Uganda will become available later in 1999. CARE International are already funding a series of follow-on trials in the Kabale/Kisoro area of S.W. Uganda.

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Appendix A: J.D.H. Keatinge, Qi Aiming, T.R. Wheeler, R.H. Ellis, P.Q. Craufurd and R.J. Summerfield (1996). Photothermal effects on the phenology of annual legume crops with potential for use as cover crops and green manures in tropical and sub-tropical hillside environments. *Field Crop Abstracts* 49, 1119-1130.

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Appendix E: Qi Aiming, T.R. Wheeler, J.D.H. Keatinge, R.H. Ellis, R.J. Summerfield and P.Q. Craufurd (1999). Modelling the effects of temperature on the rates of seedling emergence and leaf appearance in legume cover crops. *Experimental Agriculture* (in press for 1999)

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Appendix I: Qi Aiming, R.H. Ellis, J.D.H. Keatinge, T.R. Wheeler, S. A. Tarawali and R.J. Summerfield (1999). Differences in the effects of temperature and photoperiod on progress to flowering among diverse *Mucuna* spp. *Journal of Agronomy and Crop Science* (in press for 1999).

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Appendix L: J.D.H. Keatinge, Qi Aiming, T.R. Wheeler, F. Musitwa, N.A.P. Franks, the late D. Kuribuza, R.H. Ellis and R.J. Summerfield (1999). Selecting potential annual –sown legumes for trash lines, green manures or short-fallow replacement in low-input systems in the East African Highlands: The example of S.W. Uganda. *Mountain Research and Development* (in press for 1999).

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Final Inventory of Project

No capital items procured.

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