A HARVESTCHOICE PRIMER ON

AGRICULTURAL POTENTIAL

(VERSION 1.0, MAY 2007)

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GLOSSARY

AEZ	Agroecological Zone
GIS	Geographic Information System
GPS	Global Positioning System
LGP	Length of Growing Period
NDVI	Normalized-difference Vegetation Index

1. Agricultural Potential

The conceptual perspective of agricultural *potential* is of the absolute advantage of a location in terms of its intrinsic biophysical capacity to support the production of economically useful plants and animals – regardless of whether or not that potential has been realized (adapted from FAO 1978 and Wood et al. 2005).

The growth of Europe's mercantile fleets during the 17-19th centuries was in some measure a testament to the notion that, from the perspective of plants, location matters. Fortunes were built on cargoes of spices, nuts, oils and other food and fibre crops, transported half way round the globe (Landes 1998, Diamond 1997). Even now, international buyers for supermarket chains start their search for new produce according to some broad geographic understanding of where mangoes, bananas, dates, coffee and other crops are being, or could be, produced competitively. And even at the local scale, farmers have long managed their farms so as to best match the needs of specific crops and production systems to the different biophysical attributes of individual plots and fields (Ruthenberg 1980).

The belief that there is strategic value in differentiating geographical areas best suited to the conduct of specific economic activities is not new, especially with regard to the conduct of agriculture (Ricardo 1951, FAO 1978, Ruthenberg 1980, Bunting 1987, Wood and Pardey 1998, Wood et al. 2000, Fischer et al. 2000).[1] Here we briefly review the state of knowledge with regard to the linkages between biophysical location attributes and economic opportunities for crop production. We examine these linkages from two perspectives of relevance to HarvestChoice, from crop growth theory, and from empirical studies based on applying such knowledge in ex ante policy and investment analysis, particularly with regard to the development of smallholder agriculture in the tropics.

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[1] One important finding of this body of work is how relatively limited, in a global context, are areas well suited to agriculture. Fischer et al. (2002) report that more than three-quarters of the global land surface is unsuitable for crop cultivation, suffering constraints of being too cold (13%), too dry (27%), or too steep (12%), or having poor soils (40%). Multiple constraints occur in some locations.

1.1 Functional linkages between biophysical attributes and agricultural potential

The fundamental process governing plant growth potential is photosynthesis, the synthesis of organic compounds from carbon dioxide and water by harnessing the light energy of the sun. The principal factors influencing the rate of photosynthesis are: light intensity (irradiance), CO_2 concentration, temperature, humidity, water availability, leaf morphology, leaf nitrogen (N), and the specific photosynthetic pathway associated with the plant (Hall and Rao 1999). There are two important photosynthetic pathways found in crops; C_3 (most crops, including rice, wheat, bananas, beans, cassava) and C_4 (principally, maize, millet, sorghum, and sugar cane). C_4 crops have a pathway and leaf anatomy that make them more efficient users of sunlight and water than C_3 crops (Evans 1993, Hall and Rao 1999). The reproductive performance of plants, and hence the potential yield of crops, is strongly linked to day-length (photoperiod) sensitivity. Both incoming radiation (measured at the surface of the earth's atmosphere) and day-length vary by location but are predictable for any latitude and time of year. Incoming radiation reaching the earth's surface, however, is affected by cloud cover conditions and the aspect of the site location. Notwithstanding the recent trends in global climate change, long-term mean and variance of temperature and rainfall patterns during the growing season tend to be relatively stable by location,[2] and are influenced by latitude, elevation, aspect, exposure, and distance from the coast (Jones 1979, Jackson 1989). From an agroclimatic perspective therefore locations are likely to differ in predictable ways with regard to the extent to which they can support photosynthesis and potential crop growth.

Nutrient cycling in undisturbed ecosystems tends to be in equilibrium, but this is very seldom the case in agroecosystems, particularly under conditions of subsistence agriculture in Africa. Furthermore, nutrient supply is complex with regard to both the range of and interaction amongst macro and micro nutrients and has high levels of spatial variability (Stoorvogel et al. 1993, Scoones 2001, Sanchez 2002).

Where relevant location attribute data exist, however, the foregoing discussion suggests that locations endowed with higher levels of irradiance, temperature, soil moisture

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[2] This is not to say that these attributes do not vary at a given location but, over time, the range of variability is often well established. There is growing evidence, however, that patterns of variability of rainfall and temperature are changing globally, as a consequence of global warming trends (IPCC 2001). HarvestChoice has yet to define its analytical scenarios for including the potential impacts of changing climate.

holding capacity, water supply and soil nitrogen will, other things being equal, be associated with greater plant growth potential. There seems a strong *a priori* case, therefore, that regional biophysical variables might provide substantial explanatory power in assessing the agricultural potential of any given location. But there are several potentially confounding issues; the geographic scale of analysis, differences in growth potential among and within crop types, threshold and non-linear crop growth responses, and often covariance and complex interactions amongst the biophysical variables. There is also the important distinction between vegetative growth and economic yield.

Geographic scale influences the relative importance of biophysical factors in accounting for variation in crop growth. At continental and sub-continental scales variation in day length, incoming radiation, thermal and wind patterns (determined primarily by latitude) can account for a significant amount of variation in crop growth potential. In tropical areas, rainfall and elevation patterns take on a greater role as we zoom in (increase scales) geographically; elevation strongly influencing temperature regimes. At the scale of individual landscapes and farms, rainfall variability superimposed on a much less dynamic but spatially more heterogeneous set of soil conditions, play a more dominant role in determining growth potential. Covariance in biophysical factors is strongly evident between elevation and temperature, but also amongst elevation, slope and soil properties (Strahler and Strahler 1979, Money 1988).

Plant growth exhibits many non-linear or threshold responses to biophysical conditions, and such responses differ amongst crops. Figure 1 shows the seed yield of beans at sites with different mean growing season temperatures (predominantly distinguished by elevation) in Colombia.[3] There are two important features of this figure of relevance to this discussion. The first is simply the shape exhibited by each curve, in which yields decline quite rapidly outside the range of established adaptability, an instance of the general non-linear relationship exhibited by crops in response to many biophysical "inputs" to production. The second is how, even within one crop type, different genotypes can respond quite differently to similar environmental conditions.[4] In the tropics in particular there are

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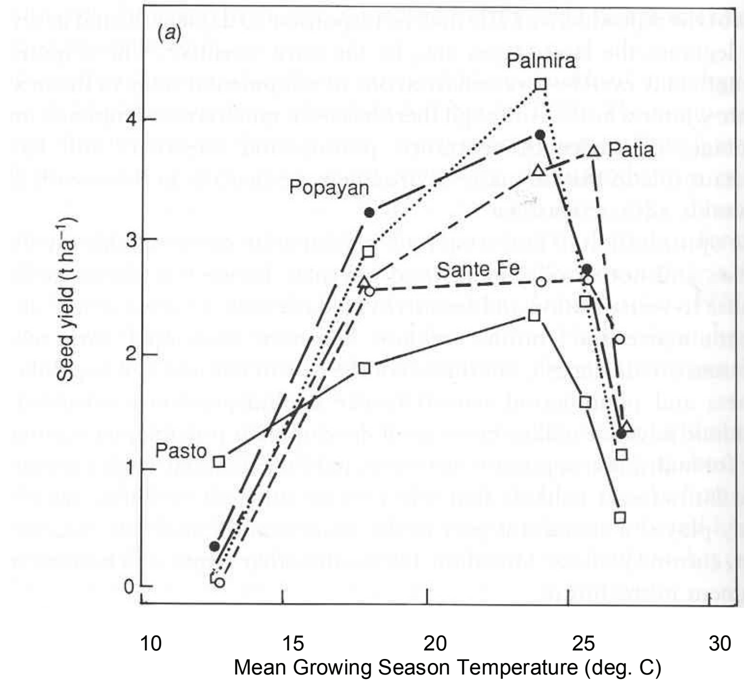
[3] This example is drawn from Evans (1993 pp 131-133)

[4] The intrinsic genetic properties of each crop determine, for example, those temperature ranges that minimize growth stress and that condition the time needed for each stage of crop development, e.g., time to flowering and maturity (Evans 1993). Extreme values of soil pH impose fatal stresses on plant growth, and excessively low

tradeoffs between the benefits of higher temperatures in accelerating plant growth and its costs in terms of heat stresses (Stone 2001). In comparison with temperate regions, crop productivity in tropical areas is also impacted negatively where high night-time temperatures impose significant (respiration) energy losses, and where the absence of frost provides no check on the life cycles of harmful pest and diseases (Bloom and Sachs 1998, Masters and Macmillan 2001, Sachs 2000)

Figure 1 Yield Response to Temperature: Beans in Colombia.



Source: From Evans (1993), adapted from Laing et al. (1983).

Through a process of selection, domestication and, for the past century in particular, science-based crop improvement, specific attention has been paid to altering the physiology of crops so as to enhance the yield of the most economically valuable crop components, e.g., seeds and tubers. For example, attempts have been made to improve drought resistance, and heat and salinity tolerance and, generally, to adapt crops to be either more widely adapted, or

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values of water or nutrient supply limit productivity, but precisely what “high” or “low” levels are critical to facilitating or limiting crop development vary considerably by species, genotype and ecotype and, in practice, by the range of crop management practices employed (FAO 1978, Fischer et al. 2000).

to perform better in specific agroecological niches (Smith 1998, Evenson and Gollin 2003a and 2003b). These efforts serve to weaken the association between crop *growth* potential *per se* and crop *yield* potential (Evans 1993)

All of these factors add complexity to the expectation of establishing simple and direct linkages between biophysical attributes of location and agricultural potential, and will shape the specification of appropriate measures of agricultural potential for evaluation purposes.

Progress in remote sensing techniques, however, has provided several means of directly monitoring *actual* vegetation production potential and performance including the Normalized-difference Vegetation Index (NDVI), an index calculated from reflectances measured in the visible and near infrared channels from satellite-based remote sensing. NDVI is related to the fraction of photosynthetically active radiation and provides a measure of the vigour of plant growth.

1.2 Agricultural potential concepts in strategic, ex ante development studies

As well as enhancing scientific endeavours to improve genetic potential and to increase resistance to biotic and abiotic constraints, knowledge of crop adaptability to specific biophysical conditions has underpinned a range of analytical methods for assessing potential agricultural productivity that, in turn, have supported a number of strategic agricultural development studies. The two main branches of analytical methods examined here are differentiated by their approach to assessing agricultural (crop production) potential. One approach has been to develop crop growth models that build on theoretical knowledge by attempting to mimic the processes of photosynthesis, light, water and nutrient use, biomass accumulation and partitioning (Loomis et al. 1979, James and Cutforth 1996, Sinclair and Seligman 1996), the other has been based on more stylized, empirical, rule-based approaches to crop "suitability" (FAO 1978, FAO 1996, Fischer et al. 2000).

Crop growth simulation models were originally developed for site specific application, but their use in regional applications is increasingly frequent, (e.g., Moulin et al. 1998, Yun 2002, Jones and Thornton 2003) notwithstanding problematic issues of parameterising such data-intensive models even at a site scale. Applying crop growth models in a regional context requires dealing adequately with simultaneous issues of spatial correlation of climate and heterogeneity of soils, and variability in planting dates, and with specifying an appropriate set of crop genetic properties. Despite the implementation challenges, however, the significant potential benefit of applying growth models lies in the intelligent integration of a large number of relevant variables from a plant growth perspective – thus bypassing or at least mitigating some significant problems of non-linear responses to and correlation amongst those variables if treated individually.

It is particularly difficult for crop simulation models to reproduce on-farm yields since they are ill-equipped to deal with agronomic, pest, disease and many other real-world constraints (other than by the application of arbitrary factors to mimic observed yield losses). Their strength lies in assessing different measures of potential yield, and for this reason such models are well placed to assess agricultural potential.[5] Crop modellers generally recognize and simulate one or more of three levels of yield potential: theoretically attainable yield, water constrained yield, and water and nutrient constrained yield (Aggarwal and de Vries 1989, Bouman et al. 1996, Affholder et al. 2004). Theoretically attainable yield at any location is derived from local CO_2, light, radiation and temperature resources assuming no other growth limitations. Water constrained yield simulation imposes actual local rainfall (and irrigation) conditions, resulting in a lower yield (the difference in yield with the theoretical maximum being a measure of the maximum possible benefits from overcoming local water constraints). Water and nutrient constrained simulation imposes the realities of the site-specific water and nutrient availability. The yield with the water constrained condition representing, in this case, the upper bound on potential yield gains from overcoming local nutrient constraints. One major strategic use of such crop simulation approaches to land use potential is that undertaken to assess four rural land use scenarios for the European Community (Netherlands Scientific Council 1992).

Perhaps the most widely known and utilized of the rule-based models are those derived from the concepts and methods developed for agricultural land evaluation and land use planning that grew out of earlier work on land "capability" assessment in the USA (Klingebiel and Montgomery 1961) but that emerged from collaboration between the

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[5] Albeit on a crop specific basis that might at times be too restrictive. For example, it is difficult and perhaps inappropriate to use such models to estimate the potential for "cereals" or "food staples", other than by undertaking simulations for representative, individual crops and integrating the results in some meaningful way.

International Institute of Land Reclamation and Improvement (IILRI), in the Netherlands and the FAO in Rome in the 1970s (FAO 1976, Beek 1978, FAO 1978). In part, this work was given impetus by the completion of the first comprehensive soil map of the world (FAO-UNESCO 1974), a major achievement of applied soil science in the latter half of the past century. Armed with complete and consistent information on physiography, climate and soils of the developing world, a new set of scientific questions could be addressed, including the extent to which the world's land resources could support adequate food production for future populations of the developing world (Buringh et al. 1975, FAO 1978, Higgins et al. 1981). The land evaluation approach was predicated on the notion that land (characterized as a complex of biophysical attributes described as agroecological zones, AEZs) can only be evaluated with regard to specified uses, or "land utilization types" (LUTs). For agricultural purposes, LUTs are defined as combination of an economic product and a notional package of inputs and management (for example, low-input rainfed maize production), and each LUT is characterized according to its biophysical "requirements" in terms of temperature, rainfall (or length of growing period), soil pH, texture and so on. LUT requirements are defined for various levels of suitability (FAO 1996).[6]

LUT requirements are then "matched" against a (geo-referenced) inventory of biophysical attributes for the geographic area of study. The outcome of this matching is an evaluation of the extent to which each location is (biophysically) suited to each candidate LUT, and these results can be summarized and interpreted in a variety of ways. A key location attribute conceived and tested as part of the AEZ approach is the length of growing period, LGP. LGP is derived from a simple water balance using data from monthly rainfall and potential evapotranspiration data together with assumptions about the water holding capacity of soil and, in some cases, stylized crop-specific water use parameters (FAO 1978, Fischer et al. 1996). In this approach, a growing period is defined as starting when rainfall exceeds half the rate of potential evapotranspiration (PE). Rules for ending a growing season vary but, in the original FAO model, the growing season ends when soil moisture is depleted to a predefined minimum threshold. The result is a number of days in a year when available

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[6] The suitability terminology is clumsy. The manner in which these stylized production functions for biophysical inputs are constructed involves setting value ranges for each biophysical variable that correspond to different levels of suitability, from "very suitable"/"optimum" down to "unsuitable"/"prohibitive" with regard to each specific LUT. Suitability value ranges are determined by a mix of empirical evidence and expert judgment.

moisture is sufficient to support crop growth. LGPs of increasing length are generally associated with both higher crop yields as well as greater flexibility in the range of crops that can feasibly be grown (including opportunities for sequential cropping). LGPs of less than 70-80 days are typically too short for crop cultivation. Some traditional cereal varieties need growing seasons of up to 180 days to reach maturity, while some perennial crops require LGPs in excess of 270 days. The LGP variable has proved powerful in that its evaluation integrates multiple site-specific elements of climate[7] and soil data (e.g., PE values used in the LGP calculation are themselves derived from radiation, max and min temperature, humidity and wind speed data) into a single measure, and its estimation accounts for the temporal distribution of rainfall within the year (that can differ markedly for the same annual rainfall total).

In 1996 FAO reported 14 FAO-related global, regional and national studies that had explicitly adopted the AEZ approach, including 3 country studies in East Africa (Ethiopia, Kenya and Mozambique), but the approach has been much more broadly applied under other guises (e.g., Wood and Dent 1982, TAC/CGIAR 1993, Zheng 1994, Sivakumar and Valentin 1997, Inthavong et al. 2000). The objectives of these studies ranged from population supporting capacity, through national land use planning, agricultural development planning, irrigation suitability assessment, decentralized district planning, land degradation assessment, fertilizer recommendations and technology targeting.

The agricultural potential philosophy of the AEZ approach still underlies many global, regional and even national land use and agricultural planning studies. For example it has been used for assessing the potential global economic impacts of agricultural R&D investments (Davis et al. 1987, Ryan and Davis 1991), remains a key component of FAO's periodic global food projection studies (Alexandratos 1995, Bruinsma 2003), and continues to be used for global food security studies with and without assumptions of climate change, and linked to multi-criteria optimization frameworks (Fischer et al. 2001, 2002). Optimization is used to prioritize potential land use choices where the objective function is typically total agricultural output in a standardized metric (such as grain equivalent, value,

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[7] Climate data used in this and most other regional studies are derived from the spatial interpolation of primary data from climate observation (point) networks.

and total or per capita nutritional equivalents e.g., total calories or calories per capita) and land area is typically the only input constraint.

1.3 Agricultural potential measures: A synthesis

One striking feature of the majority of agricultural potential studies is their almost complete disregard of economic and behavioural aspects of land use and farm enterprise choices, existing land use patterns, and the costs of land use change. While notions of farm-level management and input conditions and choices form part of the LUT definitions in the AEZ approach, no other economic factors generally figure in an AEZ analysis (other than a total available land resource constraint).[8]

Another striking omission is the very limited extent to which the *variability* of production, e.g., the year-to-year yield variability induced by rainfall variability, is accounted for. The most likely reason is the formidable challenge of compiling time series data at a highly disaggregated spatial scale for input to potential yield models. The entire notion of risk and uncertainty of production is dealt with very poorly despite the large body of evidence of its importance in smallholder livelihood strategies (Anderson and Hazell 1989, Moschini and Hennessy 2002, Hardaker et al. 2004).

Another key obstacle to better grounded agricultural potential assessments has been the limited capacity of researchers and analysts to represent *existing* patterns of land use, particularly with regard to the distribution of the location and performance of individual crops and cropping systems. While in the past 30 years, satellite-based remote sensing has increased the availability of information on the spatial distribution of the overall extent of cropland and of vegetation vigour (NDVI), this has not been matched by greater capacity to describe either the existing spatial distribution of individual crops or the spatial variability of their yields. Some recent research methods for making plausible, pixel-scale assessments of crop distribution and performance are, however, starting to offer solutions to this significant data gap at a cross-country scale (You and Wood 2006).

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[8] In most AEZ applications protected areas and current urban areas, as a minimum, are excluded from the available land inventory, and allowance for future non-agricultural land uses are included in future projections. Some land-use polices, e.g., restriction of crop agriculture on slopes greater than 20% can, however, be incorporated into production-potential rule sets.

Despite these shortcomings, there do appear to be good theoretical and empirical grounds to hypothesize that regional location attributes, especially those that describe the physiographic, climatic and soil-related properties of location, can provide significant predictive power with regard to assessing the agricultural potential of specific locations. The larger challenge for this research is to define an appropriate dependent variable to test that hypothesis since, as shown in Table 1, some of the most commonly used proxies of agricultural potential are drawn from the pool of regionally-derived location attributes (i.e., the intended pool of explanatory variables to be used in this study).

The chief advantages of using generic proxies of agricultural potential, such as rainfall (proxies 1-7 in the table), are their simplicity and availability. Measures such as LGP and simulated (crop-specific) yields are more challenging to generate, but offer some analytical advantages. First, they help bypass problems of thresholds and non-linearities that using, say, rainfall or temperature directly sometimes present. Second, they utilize existing knowledge to aggregate multiple, related variables into a single combined metric, and do so in ways that are relevant from a crop growth perspective (e.g., taking monthly temperature, rainfall, evapotranspiration, and other climate, soil and crop-specific measures, and distilling them into a single estimate of growing season length, LGP, or potential yield).

However, there is also merit in taking a multivariate approach, using several proxies that capture different aspects of agricultural potential. While LGP, for example, has relevance in terms of growth cycle and water availability impacts on crop growth, there are other productivity factors influenced by biophysical conditions, e.g., mechanization options limited by slope, soil workability, pest/disease prevalence, harvesting conditions, tsetse infestation and so on. Using any single biophysical location attribute would likely be a poor proxy for many of these other factors. Soil quality and local groundwater reserves, are other important factors that would, if data were available, allow for a more complete measure of the absolute agricultural production advantage.[9]

The year-to-year variability of crop growth conditions will ideally also be reflected in an overall assessment of potential <see Production Risks>.

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[9] In defining the agricultural potential measure of the development domain illustrated in Figure 2.1, Omamo et al. (2007) used the following factors; LGP, elevation (high elevation cut-off), access to surface water bodies, a soil quality index, and protected area status.

Table 1 Commonly Used Proxies of Rainfed Agricultural Potential

Crop Specificity	Type of Proxy	Quantitative Proxy	Qualitative Proxy
Generic	Spatially-explicit observations (satellite-derived)	1. Normalised-Difference Vegetation Index – NDVI (index) 2. Net Primary Productivity – NPP (kgC/m^2)	
	Point observations spatially extrapolated	3. Temperature ranges (deg C) 4. Rainfall ranges (mm)	Land (capability) class
	Spatially-referenced predictions Greater analytical complexity	5. "Effective" Rainfall (mm) 6. Rainfall/Evapotranspiration (ratios) 7. Length of Growing Period – LGP (months or days)	*Rule-based methods e.g., AEZ*
Crop Specific		*Crop-specific interpretations of 3-7 above, plus* 8. Theoretically attainable yield 9. Water constrained yield 10. Nutrient and water constrained yield	Crop suitability class

Source: Author

Notes: 1-2: These measures represent *actual* productivity of all vegetation. Where vegetation is relatively undisturbed they reflect location-specific climax vegetation (long-term sustainable levels of greenness/biomass) which can be interpreted as predictors of rainfed crop growth potential. 3-4: Original observations of rainfall and temperature are based on measurements at point locations (climate stations). These point estimates are spatially-extrapolated for use in a regional context. 8-10: These measures are most often derived using process-based crop simulation models, and require crop/cultivar specific parameterization. 8: Theoretically attainable yield estimates are based on ambient radiation, day-length and temperature only (i.e., assuming no other forms of production constraint). 1-10: The *variability* of these measures, despite empirical evidence of importance to farmers, has seldom been incorporated into studies using agricultural potential approaches.

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