Computer-Based Forage Management Tools: Historical, Current, and Future Applications

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Computer-based forage management tools: historical, current, and future applications

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Key points

1. Historical approach has been traditional, point-based, individual experiments combined with extension education to convey best management practices.
2. Budget cuts have forced efficient new approaches to field experiments.
3. Computer tools provide a means for improving understanding, creativity, and cost-effective visualization and integration of statistical and spatial data and expert knowledge into management decision-aids and improved priority-setting and resource allocation.
4. Vision is for better integration of the various disciplines and technologies to improve global collaboration and management decision-making.

Keywords: models, GIS, remote sensing, DSS, geospatial, quantitative eco-physiology

Introduction

Forage management has been an important human activity since the beginning of civilization. By comparison, the personal computer has been available only in the immediate past. The software developed to deal with the complexity of climate, soil, plant, animal, and socio-economic factors has seen huge changes in a few decades. Mainframe computers facilitated numerical calculations for exploring relationships among dozens of variables. Personal computers opened the door for more individual scientist creativity and routine communication. Web-based communication globalised the option for multidisciplinary teams to tackle problems. Forage-related computer applications abound, allowing farmers, ranchers, and others to more effectively manage the land. This paper describes historical, current, and future computer-based applications that improve understanding and efficiency leading to more economically and environmentally sustainable forage-livestock systems.

Historical review

Agricultural computer applications have come a long way in the past 20 years (Hannaway *et al*., 1997). In the mid- 1980s, relatively few individuals had access to computers on a daily basis. However, there were already early developments in the use of agricultural software for least-cost ration analysis for livestock, animal weight-gain analysis for various systems, crop simulation, and grazing models (Rasmussen *et al*., 1985). By the early 1990s, Expert System and Decision Support System (DSS) approaches were well-developed (Bolte *et al*., 1991; Hannaway *et al*., 1992). Some of the earliest DSS software included Grazing Land Application (GLA), Rangepack, Grazplan, Stockpol, and Beefman (Stuth *et al*., 1993).

Computer modelling allowed developers to explore the interactions in a farm system and test new technologies and ideas.

Crop and rangeland models

Crop modelling and systems analysis is still a relatively new discipline within agricultural sciences. However, significant progress has been made in the acceptance of modelling as a tool for research, teaching, and extension (Hoogenboom, 2000a). A few examples are SPUR, DAFOSYM, GRASIM, GrassGro, and the IBSNAT/DSSAT crop models.

SPUR

Originally released in 1987, Simulation Production and Utilization of Rangelands (SPUR) is a deterministic, mechanistic process model that operates on a daily time step. It was developed to design and analyse management scenarios (irrigation, fertilisation, seeding, and grazing systems) that affect rangeland sustainability (Wight & Skiles, 1987; Hanson *et al*., 1992). Specifically, SPUR simulates growth initiation, germination, carbon assimilation, translocation between roots and shoots, N mineralisation, and nitrogen uptake. In 1987 SPUR was unique, in that it was a multipoint model designed to allow for direct competition between several species of plants for water and nitrogen as well as incorporating the impacts of grazing by wild and domestic herbivores. Over the past seventeen years, modifications have been made to SPUR that reflect ongoing efforts to incorporate improved understanding of the interactions among ecosystem processes, climate dynamics, and management decisions (Baker *et al*., 1992; Foy *et al*., 1999; Pierson *et al*., 2001; Teague & Foy, 2002; Shafer, 2003; Skirvin & Moran, 2003).

DAFOSYM

The Dairy Forage System Model (DAFOSYM) simulates the performance, environmental impact and economics of a dairy farm over multiple years of weather (Rotz, 2001). The simulation includes the growth, harvest, handling and storage of *Medicago sativa* (lucerne), grass, *Zea mays* (corn), small grain, and *Glycine max* (soybean) crops. Farm produced feeds are supplemented with purchased feeds to meet a given level of production for a dairy herd. Manure is returned back to the land where nutrients are lost, accumulated in the soil or used in crop production. Costs of feed production and manure handling are compared to milk, animal, and feed sales to determine a net return. Other farm costs are then included to estimate the net return or profitability of the whole farm. Major submodels include crop growth, harvest, feed storage, feed use, manure handling, tillage, and economic analysis. Simulation of crop production and harvest is based on a daily time step using historical weather data for the location. Crop growth models determine the accumulation of dry matter and the change in quality (nutrient content) based on daily weather and available soil moisture. Total costs of production are subtracted from the various farm incomes to obtain the net return above feed and manure costs and the overall return to management and unpaid factors. DAFOSYM has been used extensively as a research tool and continues to be improved as part of the USDA-ARS Dairy-Forage research team's activities (http://www.dfrc.ars.usda.gov/).

GRASIM

GRASIM is a comprehensive grazing model designed to simulate intensive rotational grazing management linking all components of the pasture system (Mohtar, 2004). It predicts standing biomass, herbage nutritional quality, and nutrient leaching under pasture. It can be used to obtain a better understanding of the pasture system and determine management strategies to improve pasture utilisation. It generates information suitable for estimating the financial and environmental consequences of alternative dairy management strategies including partial mechanical harvest in the context of the year-round feed needs of the dairy herd, storage/harvest needs, year-to-year variability, and stocking rate impacts on supplementation and need for harvested feed. GRASIM operates on a daily time step. Data requirements include minimum and maximum daily temperatures, daily rainfall, average daily solar radiation, soil physical properties, grass growth parameters, soil nitrogen transformation coefficients, and initial levels of soil water and soil nitrogen. GRASIM models multiple paddocks, with each paddock budgeted separately. Paddocks share the same weather conditions but can have different crop and management practices. The grass component contains carbon compartments for storage and structure. The model accounts for root growth and maintenance, shoot growth (partitioned into leaf and stem), shoot respiration, senescence, and recycling. GRASIM models nitrification, mineralisation, uptake, volatilisation, denitrification, and leaching. Soil water is accounted for using a simplified water balance that considers runoff, evapotranspiration, soil matrix water dynamics, and leaching. The harvest component controls the grazing events and handles all pasture management input data. GRASIM is available on-line at: http://danpatch.ecn.purdue.edu/~grasim/grasim.html.

GrassGro

GrassGro is a decision support tool developed by CSIRO Plant Industry's GRAZPLAN group to examine whole enterprise production risk for grazing enterprises in high rainfall temperate zones of Australia (Moore *et al*., 1997). GrassGro simulates pasture growth and predicts the intake of herbage by ruminants and their productivity using daily weather inputs and user-specified descriptions of soil type, pasture species, and livestock. For any specified site, users can analyse grazing management systems in terms of pasture and animal production, gross margins, and year-to-year variability. Salmon & Moore (2001) reported on an assessment of the adoption of GrassGro based on a survey and training evaluation. Results demonstrated GrassGro's value to clients who had been trained to use the program. The range of problems analysed reflected the diversity of client occupations. The value of these applications was indicated by extrapolation of the results of an individual farm analysis to a regional level.

IBSNAT/DSSAT/CERES

The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project has helped improve agricultural production in developing countries, using a systems analysis approach. The project was headquartered at the University of Hawaii and funded from 1982-1993 by a grant from the United States Agency for International Development (Hoogenboom, 2000a). The Decision Support System for Agrotechnology Transfer (DSSAT) is a software system that facilitates the application of crop simulation models in research, teaching, extension, outreach, and policy and decision-making (Hoogenboom *et al*., 1999; 2000b). The core of DSSAT consists of 17 crop simulation models, with supporting software in the form of utilities and tools for data handling and analysis programs for applications. DSSAT provides standards for data file formats and naming conventions, and a standard protocol for communication between components and modules. The DSSAT crop models include the generic cereal model CERES for *Triticum* spp. (wheat), *Z. mays*, *Oryza* spp. (rice), *Sorghum bicolour* (sorghum), *Panicum miliaceum* (millet) and *Hordeum* spp. (barley) (Ritchie *et al*., 1998) and the generic grain legume model CROPGRO for *Glycine max*, *Phaseolus vulgaris* (common bean), *Arachis hypogea* (peanut) and *Cicer arietinum* (chickpea) (Boote *et al*., 1997, 1998). Other models include the SUBSTOR model for *Solanum tuberosum* (potato), the CROPSIM model for *Manihot* spp. (cassava), the OILCROP model for *Helianthus annuus* (sunflower), and the CROPGRO model for *Solanum lycopersicum* (tomato), *Paspalum notatum* (bahia grass) and a fallow crop.

Web information systems

One of the major computer developments in the past 10 years has been the World Wide Web. Web-based systems provide a means for governmental and university research and education programs to remain viable in spite of budget and personnel cuts. Working together provides many professional development benefits, as well as educational, informational and organization and integration benefits (Green & Hannaway, 1996).

Forage information system

The first comprehensive, forage-related web-based information system was the Forage Information System (FIS; http://forages.oregonstate.edu/). The FIS has been continuously hosted at Oregon State University since it became available to the world in November of 1994. The goal of the FIS is to provide comprehensive information about forage-related topics with contributions from forage scientists and educators worldwide. The FIS is a database-driven system using a combination of proprietary and open-source software to create and maintain segments. Segments of the system include a national forage and grasslands curriculum (Hannaway *et al*., 1999), and forage-related Classes, Organizations, People, Projects, Topics, and Resources. Segments for *M. sativa*, *Dactylis glomerata* (cocksfoot), *Lolium arundinaceum* (Schreb.) Darbysh. (tall fescue), and other species are under development by groups of experts working together (Hannaway *et al*., 2001). Recent progress has been made in the area of creating white papers for important forage species in cooperation with the American Seed Trade Association (http://www.amseed.com/). These include quantitative climate and soil tolerances and GIS-based suitability maps (http://forages.oregonstate.edu/main.cfm?Page ID=321). Work by Australian colleagues has led to a more extensive listing of international forage organizations (http://forages.oregonstate.edu/main.cfm?Page ID=246).

Other web system examples

During the late 1990s, many universities, agencies, and organizations in the USA and around the world developed web segments to serve their clients. In addition to Oregon State University, early US university leaders in these efforts have included:

- Cornell (http://www.css.cornell.edu/forage/forage.html);
- Penn State (http://www.forages.psu.edu/);
- Purdue (http://www.agry.purdue.edu/ext/forages/);
- Texas A&M University (http://stephenville.tamu.edu/~butler/foragesoftexas/);
- UC-Davis (http://alfalfa.ucdavis.edu/);
- University of Wisconsin (http://www.uwex.edu/ces/forage/).

The US National Dairy Database was an early leader in assembling information for dairy production (Eastwood *et al*., 1996). Today, a web segment represents nearly every agricultural content area in each university and agency. The current challenge is using database management techniques to make adding and updating information a simple process for non-computer experts.

Extensive forage-related information is now available in most countries. The following is a list of a few of these sites. A more detailed list is available in the FIS at the following URL (http://forages.oregonstate.edu/main.cfm?PageID=31):

- Australia: (New South Wales) http://www.agric.nsw.gov.au/reader/forage-fodder
  (Pasture Species Database) http://www.meu.unimelb.edu.au/grasslands/
- China: http://www.chinainfowww.com/caw/caw_e.htm
- Ireland: http://www.teagasc.ie/
- Sweden: http://www.ngb.se/Forage/
- UK: http://www.royagcol.ac.uk/flg/

GIS/RS-based geospatial/soil/landuse and landcover information

One of the most significant developments of the last 5 years has been the development and use of geospatial information for topography, climate, soils, land use and cover, and species suitability. This has been made possible by modelling and display software, and the capability of GIS software to display multiple layers of information. An early leader in this work was Engle *et al*. (1997), applying crop models over the landscape. The continuing challenge is availability and sharing of data among scientists, both within and between countries (Hannaway *et al*., 2000). Also important is the integration of the various layers of information, requiring the availability of similar resolutions for the various types of data needed.

Climate

Excellent progress has been made on climate mapping based on a state-of-the-science model known as PRISM. The Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly *et al*., 1994, 2002, 2003) is especially suited to mapping climate in complex landscapes. The regression-based PRISM uses point data, a digital elevation model (DEM), other spatial data sets, a spatial climate knowledge base, and expert evaluation to generate repeatable estimates of annual, monthly, daily, and event-based climatic elements. These estimates are interpolated to a regular grid, making them GIS-compatible.

The model adopts the assumption that for a localised region, elevation is the most important factor in the distribution of temperature and precipitation. PRISM calculates a linear climate-elevation relationship for each DEM grid cell, but the slope of this line changes locally with elevation as dictated by the data points. Beyond the lowest or highest station, the function can be extrapolated linearly as far as needed. A simple, rather than multiple, regression model was chosen because controlling and interpreting the complex relationships between multiple independent variables and climate is difficult and can produce misleading results. Instead, weighting the data points controls the effects of variables other than elevation.

PRISM is being actively developed and applied at Oregon State University's Spatial Climate Analysis Service (SCAS). Recent mapping efforts include peer-reviewed, official USDA precipitation and temperature maps for all 50 states and Pacific Islands (Daly *et al*., 2001); a new official climate atlas for the United States (Plantico *et al*., 2000); a continuing series of monthly temperature and precipitation maps for the conterminous 48 states beginning in 1895; precipitation and temperature maps for Canada, China, Mongolia, and Taiwan (Daly &

Hannaway, 2004), and the first comprehensive precipitation maps for the European Alps region. In progress are updates for the United States and possessions at better than 1-km grid resolution. Additional information can be accessed from the SCAS Web site at http://www.ocs.oregonstate.edu/prism/.

Soils

Digital soil resources are now available for most countries, though the classification systems are many and the scale/resolution varies widely. The availability, cost, and coarse resolution of these resources continue to be an impediment to widespread use in forage-based tools.

USA

The USDA–NRCS, through the National Cooperative Soil Survey (NCSS), has been developing soil geographic databases at three scales: local, regional, and national (Miller & White, 1998). At the regional level, the State Soil Geographic (STATSGO) database was released in 1992 for use in river basin, multicounty, multistate, and state resource planning. This database was created by generalising available soil survey maps (including published and unpublished detailed soil surveys), county general soil maps, state general soil maps, state major land resource area maps, and, where no soil survey information was available, Landsat imagery (Reybold & Tesselle, 1989). STATSGO consists of georeferenced digital map data and associated digital tables of attribute data. The compiled soil maps were created using the U.S. Geological Survey (USGS) 1° by 2° topographic quadrangles (1:250,000 scale, Albers equal area projection) as base maps, which were then merged on a state basis. The NRCS provides web-based access to STATSGO data as part of their web site: (http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html). Penn State University's Soil Information for Environmental Modeling and Ecosystem Management unit also provides downloadable files for each state as Arc/Info EXPORT format files (http://www.essc.psu.edu/soil_info/index.cgi?soil_data&statsgo). SSURGO is another primary national product that is available in the USA. It is the county survey in digital form at a resolution of 1:24,000. Access to SSURGO data sets in various formats is at: http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/data/. Both STATSGO and SSURGO are excellent soil information resources but require significant expertise for appropriate interpretation and use in integrated applications.

China

The Institute of Soil Science, Chinese Academy of Sciences, has successfully produced a 1:1,000,000 soil database of China, which is composed of 3 parts, 1) soil spatial data – the 1:1,000,000 digital soil map of the country, 2) soil attribute data, and 3) Chinese soil reference system (Shi *et al*., 2004a, 2004b). The soil spatial data are the most detailed countrywide digital soil map available and the Chinese soil reference system has been completed recently.

Canada

The Canadian Soil Information System (CanSIS) has supported the research activities of Agriculture and Agri-Food Canada by building the National Soil DataBase (http://sis.agr.gc.ca/cansis/nsdb/intro.html) and producing GIS products (Schut, 2000). Soils Landscapes of Canada (SLCs) were compiled at a scale of 1:1 million, and information was organised according to a uniform national set of soil and landscape criteria based on permanent natural attributes. Each polygon is described by a standard set of attributes, including surface form, slope, water table depth, permafrost, and lakes. SLCs provide a standardised database of major attributes important to plant growth, land management, and

soil degradation. These data are now used as a framework to support other databases, including Environment Canada's Ecological Land Classification System.
Australia - Australian Soil Resources Information System (ASRIS) is a national database of soil information, suitable for use at national to large regional scale. It was designed to provide nationally conformable information from the extensive soil data that was collected by the State and Territory agencies and CSIRO. It contains both primary data (soil point and soil survey map data) and modelled estimates of soil properties. Until the development of ASRIS, the best available digital coverage of soil information for all of Australia was the Atlas of Australian Soils. This was compiled in the late 1960's at a scale of 1:2,000,000 which provides only the broadest national overview of soil attributes. More detailed soil data have been collected over the last 10 years through national programs such as the National Landcare Program and the Natural Heritage Trust (Australian Natural Resources Atlas v2.0, 2004).

Europe
In collaboration with FAO, IIASA-LUC (Land Use Change program) has created a digitised soil map for North and Central EURASIA covering the countries of the Former Soviet Union, Mongolia and China (Enzlberger, 2001). The database consists of 4942 polygons. For each polygon, information is available on the dominant soil type, associated soils and inclusions, soil texture, slope and soil phases. The 1:5 million scale map, uses the legend of the FAO-UNESCO Revised Legend of the Soil Map of the World
(http://www.fao.org/ag/agl/agll/dsmw.stm).

Land use and land cover

The previously described climate and soils modelling and mapping efforts are based on information collected using ground-based weather stations and soil surveys. Land use and land cover projects typically involve satellite-based sensors.

LUTEA project
The growing concern over the impact of changes in land use and cover on environmental conditions, and the increasing human impact on the natural resources in the Temperate East Asian region, led to the formation of the Land Use in Temperate East Asia (LUTEA) steering committee and subsequent project (http://www.nrel.colostate.edu/projects/lutea). The overall objectives of LUTEA were; 1) to better understand the role and consequences of changes in climate, ecosystem dynamics, human demography, and socio-economic transitions on land use and land cover in temperate East Asia during the past 100 years, and into the next decade; and 2) develop a mechanism to assess the short-term and long-term changes in food security and environmental conservation in the region (Ojima, 2000). The region of study included China, Korea, Japan, Mongolia, and Eastern Russia. Project activities included workshops, regional database development for climates, soils, vegetation, and socio-economic factors, conferences, publications, modelling efforts, and analysis tools to better understand how changes in land use and cover in the region will interact with further global environmental changes. Factors affecting changes in pastoral systems were identified as an important regional research issue.

Australian example
Land use and land cover applications specific to forage-livestock systems have been studied in Australia since the mid 1980s. Patterns associated with soil fertility (Vickery & Hedges, 1987) and pasture botanical composition (Vickery *et al*., 1997) have been mapped in research projects aimed at better understanding the factors influencing pasture availability at the

paddock scale. More recently, the use of satellite imagery for practical decision-making has been piloted on commercial farms in Western Australia with promising results. The 'Pastures from Space' project used 30-m resolution imagery to derive estimates of feed on offer and predictions of pasture growth rate for up to 7 days into the future (Henry, 2002). Producers in 'precision sheep production groups' were supplied with this information for each paddock on their property in two successive growing seasons. At the end of the pilot project, 82% of the 63 farmers who were surveyed indicated that the satellite-based information increased their confidence in making pasture and stock management decisions (Gheradi & Oldham, 2003). Sixty-one percent of producers reported that the information helped them to manage risk better, and 59% responded positively when asked if the information had increased the profitability of their farm business.

Current research is seeking to extract better information on forage chemical composition from hypospectral sensors (Held & Hill, 2003), which would add feed quality information to data on feed quantity, and potentially improve animal nutrition decisions. The addition of new satellite platforms with greater spectral imaging capacity and more-frequent coverage of the Australian continent provides the opportunity to monitor pasture mass and composition at spatial resolutions of 250 m at daily intervals.

GPS-based fertiliser and lime applications

Precision agriculture is a management strategy that uses data and information technologies from multiple sources to optimise crop production. Soil type, soil organic matter, plant nutrient levels, topography, water availability, weed pressure, and insect pressure are recognized as parameters that affect crop growth (NESPAL, 2004). Precision farming has developed rapidly with global positioning system (GPS) sensors and intensive soil sampling and yield sensors to guide liming, fertiliser, and pesticide applications for optimal yield. Significant investment is required in equipment and software, but dividends for large-scale producers include reduced production costs and reduced negative environmental impacts. There are three main components of precision agriculture: 1) capturing data at an appropriate scale and frequency, 2) interpretation and analysis of that data, and 3) implementation of a management response at an appropriate scale and time (Sonka *et al*., 1997). A key difference between conventional management and precision agriculture is the application of high-resolution spatial and temporal data for crop production decision-making. A basic premise is that a larger quantity of better quality information can reduce the uncertainty producers face in decision-making and the unmeasured variability in agronomic conditions. Although there are few examples of cost-effective applications of precision agriculture in forage-livestock systems, these are likely to develop as high-resolution data becomes more generally available.

Integrated expert systems/decision support systems/knowledge based systems

Spatial and temporal variability pose a significant challenge for the management of forage production and utilization systems. In grazing systems, strategic decisions about stocking rate, flock or herd structure, animal management policies, and the grazing program have great bearing on the financial outcome and sustainability of farm businesses. These decisions often pivot around the seasonal cycle of feed supply/demand balance, with the common aim of maximising the proportion of total feed requirement met from home-grown pasture or fodder crop, and minimising dependence on purchased feeds. Many ES/DSS/KBS tools have been developed to assist decision-making in this area, mostly based on the principles and concepts outlined by Milligan *et al*. (1987), Sheath & Clark (1993), and Holmes *et al*. (2002). In all cases, these tools use measured or expected average pasture or crop growth rates to determine the supply side of the equation, which is then solved for some combination of animal management policies that make best use of available paddock-grown feed. The decision reached is a good decision (provided the technical data are sound), if it is based on the best information available at the time. However, whether it is the *right* decision depends on the intra- and inter-annual variability in climatic conditions and pasture growth outcomes subsequently experienced.

Climatic variability across many countries is substantial; both in space and time (Nicholls *et al*., 1997), and therefore production risk looms large in the management decision-making. Not surprisingly, the development of simulation models of pasture growth and animal production that are capable of analysing variability and risk in grazing systems has been a major focus of research activity over 2 decades, leading to several tools that have been applied to both practical and theoretical problems (White *et al*., 1983; McKeon *et al*., 1990; Stafford-Smith & McKeon, 1998; McCall *et al*., 1991; Finlayson *et al*., 1995; Cacho *et al*., 1999; Donnelly *et al*., 1997; Wastney *et al*., 2002; Johnson *et al*., 2003a, 2003b). When integrated with location-specific climate data (Jeffrey *et al*., 2001), these tools allow detailed description of the range of pasture growth outcomes for any particular site (Clark *et al*., 2003). Given the importance of the pasture base for cost-effective feeding, this can underpin the analysis of risk associated with major management decisions, such as changing the mix of pasture types and fodder crops used to supply feed to animals (Kenny *et al*., 2005), or changing the animal enterprise (Salmon *et al*., 2004).

Simulation tools can be integrated with spatial information layers from ground or remote sources to describe spatial variability in pasture growth outcomes at the paddock and farm scale (Hill *et al*., 1999). Used in this mode, these analytical tools move into the domain of precision agriculture technology for pasture-based systems, but the power of the information technology currently exceeds our capacity to interpret the data it can generate, and our capacity to apply it for the purposes of improved forage management decision-making. While this remains the case, this route seems unlikely to lead to greater on-farm use. However, integrated tools of this sort are being applied to improve farmer learning, and support risk management decision making for sustainable environmental and agricultural planning purposes in Australia (Webby, 2002; Laughlin *et al*., 2003; Brinkley *et al*., 2005). Here, simple simulators of pasture growth are used to analyse the reliability of seasonal growth using historical weather records for broad regions. The processing power of super-computers offers a future where pasture simulation models are distributed in virtual space across selected regions and connected to historical and projected weather data (from improved climate models) to predict pasture growth outcomes several weeks ahead. This information would be invaluable for forage management decision-making in pasture- and rangeland-based grazing systems and the down-stream industries that handle their products. Farmers could foresee trends in vegetation cover in response to their grazing management policies, and judge whether that cover will meet targets for environmental protection and/or herbage availability for animal feeding. They could be better positioned to know, for instance, whether or not to apply fertiliser, and if so, when and how much to use, so that the desired outcome (extra feed for animals) occurs at the time it is most needed. Processors may be able to forecast rates of supply for products coming largely from pasture feeding within their procurement regions, and adjust processing capacity and forward orders accordingly. Outcomes like these can add significantly and directly to economic and environmental outcomes, and it is tempting to argue that this should ensure the widespread adoption of such tools. However, history shows this is not a safe assumption, and our knowledge of the causes of persistent poor implementation of DSS products in farm businesses (McCown, 2002) will need to be applied to the solution of the problem for these applications, just as for others.

Optimal species selection

Oregon State University, Penn State University, and Cornell University are developing forage species selection tools. Cornell's forage selection tool (http://www.forages.org/) is made up of several programs which access numerous databases to provide forage species recommendations for New York State, taking into consideration both the available soil type and the intended forage use. Soil type can be selected from a list, or the program can estimate soil type based on zipcode, county, and basic soil characteristics. Similar to Cornell's product, Penn State's selection tool (http://www.forages.psu.edu/selection_tool/index.html) is based primarily on soil information and intended use. The Species Selection Information System at OSU (http://forages.oregonstate.edu/is/ssis/) is a collaborative project to create a web-based, comprehensive knowledge resource to assist land managers and other decision makers in choosing forage and conservation species that are optimally matched with their environment. OSU has integrated climate and soil information and a quantitative tolerances approach to matching species, including intended use and management level. All of these systems will improve as the underlying geospatial information improves and our knowledge of the quantitative ecology of the various species is improved.

Developing country challenges

Developing country challenges are often referred to as 'the digital divide' and include the entire spectrum of needs for computer infrastructure, up-to-date equipment, software, and trained professionals. One important issue is that of proprietary vs. 'open source' software. Developing countries often cannot afford the high price of proprietary software and license fees imposed by the major software companies. Since wages are much lower than in developed countries, time is often invested to develop similar function software. Although this requires less cash expenditure, it is an inefficient use of workers compared to joint development and improvement of 'open source' software.

Development of integrated solutions is often impeded by the cost of data or the regulations preventing the sharing or sale of base layer information (topography, climate, soils, rivers, roads, boundary files, etc.). Significant time is often spent in efforts to assemble data, quality checking, and putting the data in usable form. National and international geospatial data archives are needed in which information can be freely obtained or purchased for a reasonable price.

Well-trained scientists are needed for the development and use of geospatial approaches to agriculture and natural resource management. Strong university programs are a long-term approach that is needed, but international training programs and workshops of weeks to months in length are necessary to meet the immediate demand for trained professionals. On going needs for infrastructure and equipment upgrades need to be built into project budgets. International donors can be helpful in providing these infrastructure needs and training requirements.

Future developments and applications

Historical applications have included crop and rangeland simulation modelling, traditional field trials, and extension outreach provided by field days and extension education programs. Current GIS and RS-based technologies allow users to: 1) integrate information from multiple disciplines, 2) cost-effectively extend traditional point-based trial data, and 3) visualise spatial information across the landscape. Future applications will involve better integration of the various land-based and space-based technologies with the many disciplines that affect management (physiography, physical processes, eco-physiology, socio-economic, and cultural anthropological factors).

A probable development over the next 5 years will be the more routine use of geospatial approaches to agricultural and natural resource management. Refinements in spatial information for topography, climate, soils, and vegetation will allow better selection of crops, simulation of yields and quality, more precise production management, and recommendations for policy and economically and environmentally sustainable systems. Socio-economic elements that are today too often ignored in computer application product development will be more widely included as techniques are developed to routinely analyse, model, and map these factors. Both the 'bottom line' economics and the decision-making process will be included in integrated products.

Current difficulties of obtaining data, quality checking, and spatially modelling data will be more readily resolved due to extensive use of low-cost ground-based and space-based sensors. Basic and applied science fields will work together more seamlessly as cooperating scientists from around the world grasp the mutual benefit of such collaboration. 'Market analysis' approaches will be used and partnerships developed with end user groups (including agricultural lenders) to ensure that the product meets the user's needs. Widespread availability of high-speed networks will eliminate the need to limit products to currently available equipment or transmission speed problems. Focus will be on developing creative solutions to important natural resource management issues.

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