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Harnessing Information Technologies for More Efficient Crop Development

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New crops face formidable competition from established crops. Management practices for established crops are well understood, and their productivity gains over time are often spectacular, such as the nearly linear increase in maize yields from 1955 to the present (Troyer 2004). Their long success reflects well-organized research, extension and marketing efforts. For new crops to prosper against such competition, researchers and promoters must ensure that they maximize the efficiency with which they capture and manage information relating to crop improvement, agronomy, and utilization. The need for reliable information is especially critical when moving to commercial-scale production where especially positive or negative experiences may establish the reputation of a crop for years to come.

Information technologies (IT) can benefit crop development by integrating data management and utilization across disciplines and software systems. Efforts to develop new crops must progress from individual, isolated data sets and software tools to a realm where information flows smoothly from field and laboratory studies to diverse types of software capable of linking crop-specific data to information on climate, soils, production regions, markets, or other topics relevant to the interests of stakeholders.

This paper argues that an integrated approach to managing and using information is essential for attaining the efficiencies required for new crop development. The foundation of efficient new crop development is research in agronomy, plant breeding, and related fields. However, efficiency includes reducing risks of disputes over intellectual property rights, satisfying regulatory concerns related to adverse environmental or health impacts, and providing producers, processors, and buyers with accurate, current information. We start by examining needs for efficient data management and defining integrated information management. Experiences developing integrated systems for lesquerella (*Lesquerella* spp., Brassicaceae) and vernonia (*Vernonia galamensis* Less., Asteraceae) are then discussed. Ecophysiological models and geographic information systems (GIS) are considered briefly to show how integrated information is used by more complex tools. Finally, we examine strategies for moving toward greater integration and use of information on new crops.

EFFICIENT DATA MANAGEMENT FOR NEW CROPS

Efficient data management is key to any crop research or promotion effort. Projects to develop novel crops are no exception. However, new crop development requires especially robust management due to the often insecure resourcing, the potentially narrow genetic base, uncertainty over intellectual property rights, and the need to document performance and risk for growers, promoters, and regulatory agencies.

Perceptions of a crop's potential may fluctuate with largely external factors such as progress with alternative sources of target products and societal expectations (Finlay 2004), and research support is highly sensitive to external circumstances, such as federal and state budgets, periods of crisis such as the recent increases in oil prices, or poor markets for crops currently in production causing growers to look for new crop or market solutions. Thus, projects for novel crops may be suspended or downsized for extended periods. The history of guayule, *Parthenium argentatum* A. Gray (Asteraceae) (Ray et al. 2005), is illustrative. In the early 1900s, guayule was an important source of latex for pneumatic tires. When demand exceeded supplies from guayule, however, tire manufacturers shifted to rubber from *Hevea brasiliensis* (Wild.) Mull. Arg. (Euphorbiaceae). In 1942, during World War II, the Emergency Rubber Project was organized by the US Department of Agriculture to promote domestic production of natural rubber. The war effort ended when foreign supplies from Southeast Asia were reestablished, but records were not maintained. The oil crisis of the late 1970s stimulated the US Congress to pass the Natural Rubber Act, which resulted in another phase of activity, but the act was allowed to lapse with increased oil availability. In the mid-1990s, interest surged again in order to establish guayule as a reliable source of hypoallergenic latex due to increased incidence of Type I allergies to *Hevea* rubber products (Ray et al. 2005). Given the uncertain prospects for new crops, robust data management can protect valuable knowledge over periods of inaction and ideally, this should include detailed records of crosses, selections, and evaluations.

The foundation of genetic diversity for new crops is a concern since new crops are often viewed as part of the agricultural solution to the shrinking global biodiversity. There is usually limited information and frequently, availability of genetic resources for a potential new crop. Historic sites for germplasm have disappeared in many cases due to development. Good phenotypic and genotypic information on these valuable resources may be limited or lacking, and these limitations can be a hindrance to the formation of genetically diverse landraces or varieties that form the start of a new crop industry.

A third characteristic of new crops is that while intellectual property rights issues are problematic for established crops (Kimpel 1999), novel crops present special challenges. These range from ownership of source germplasm, to exploitation of indigenous knowledge about potential uses (Greene 2004), to exclusive licensing of products in order to stimulate early investment. Careful documentation of the crop development process will provide stakeholders the information needed to manage intellectual property economically and ethically.

Finally, since new crops typically have a short and limited production history, information on expected performance is especially valuable. While the foremost interest will concern yield and market value, producers also need solid information on management, including assessments of risk factors such as from pests or drought. Buyers or processors may seek additional information on interactions of quality with growing conditions and management, and regulators may variously require data on agrochemicals, environmental impacts, product safety, or other topics. Again, efficient management of information can help ensure that stakeholder concerns are answered reliably and quickly.

INTEGRATED INFORMATION MANAGEMENT

Agricultural research requires managing large sets of data. Plant breeding requires tracking the performance of large numbers of genetically distinct plants or populations. Agronomic studies often involve experiments conducted over multiple years and locations, with recorded data including management practices, weather conditions, nutrient levels in the plant and soil, as well as crop development and performance attributes, including final yield. Databases are widely used in agricultural research (Table 1) but usually have a discipline or project focus. While of indisputable utility, such databases typically represent islands of data, are not updated regularly and have limited utility beyond their initially intended use.

An integrated information system differs from a database in the scope of the data to be managed and the emphasis on tools to facilitate use of data for objectives that span multiple disciplines. Thus, integration involves joining together diverse types of data (Fig. 1) and joining those data with analytical tools. Integrating data from diverse sources requires mechanisms for documenting data sources and for updating the central data holdings.

The International Crop Information System

To our knowledge, the only widely used public integrated system for agriculture is the International Crop Information System (ICIS, www.icis.cgiar.org). Developed through collaboration among international centers, universities, national research services, and the private sector, ICIS has been implemented for field crops such as rice (*Oryza sativa* L., Poaceae), wheat (*Triticum aestivum* L. and *T. durum* L., Poaceae), barley (*Hordeum*

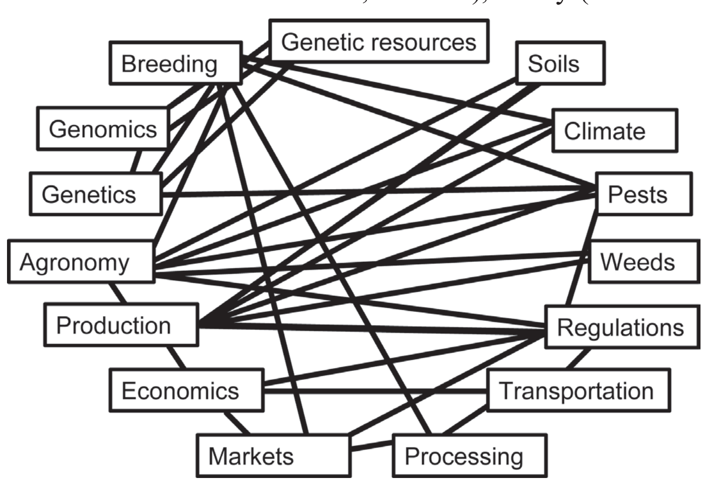

Fig. 1. Examples of the numerous linkages among data sources required for different crop research or promotion activities.

vulgare L., Poaceae), potato (*Solanum tuberosum* L., Solanaceae), and common bean (*Phaseolus vulgaris* L., Fabaceae), as well as for horticultural crops (Fox and Skovmand 1996; Boom 2005; McLaren et al. 2005). ICIS currently has two main components, the Genealogy Management System (GMS) and the Data Management System (DMS).

The ICIS GMS documents the entire plant breeding process. For each possible event in a breeding project, such as crossing, selection, multiplication, embryo rescue, and mutagenesis, the source and resulting genetic entities are linked to a breeding method (Table 2). Each genetic entity, whether a single seed, seed packet, tissue culture, or tree, is uniquely identified, and the identifier can be associated with alternate names as needed. Sequences of generations are seamlessly linked, allowing historic pedigrees to be traced as far back as records allow, e.g., to the 1800s for wheat. Genetic entities may be characterized using user-specified attributes ranging from origin of germplasm, to plant descriptors and to resistance levels for key diseases (Table 3). The user

Table 1. Examples of agricultural databases or information systems.

Name	Description	Address or reference
Agbios GM Database	On-line database on safety information on all genetically modified plant products that have received regulatory approval.	www.agbios.com/dbase.php
CottonDB, The Cotton Genome Database	On-line database for genetic, genomic and taxonomic information for cotton (*Gossypium* spp.).	www.cottondb.org
GERMINATE	Downloadable generic plant data management system that is designed to hold passport data and a range of additional data types including molecular markers. It uses ICIS-GMS for pedigree data.	germinate.scri.sari.ac.uk/cgi-bin/germinate
GrainGenes	On-line database for Triticeae and *Avena*, with emphasis on molecular and genetic data.	wheat.pw.usda.gov/GG2/index.shtml
GRIN, Germplasm Resources Information Network	On-line database of collection and evaluation data for genetic resources held by USDA-ARS.	www.ars-grin.gov/npgs/searchgrin.html
GWIS, Global Wheat	On-line implementation of ICIS. It includes germplasm pedigrees, field evaluations, structural and functional genomic data (including links to external plant databases) and environmental data. Downloadable version also available.	mendel.lafs.uq.edu.au:8080/ICIS5
IRIS	Rice implementation of ICIS. It includes germplasm pedigrees, field evaluations, structural and functional genomic data (including links to external plant databases) and environmental data. Downloadable version also available.	www.iris.irri.org
LesquIS	On-line Lesquerella implementation of ICIS-GMS, which contains accession attributes and pedigrees.	199.133.210.23/ICISWeb/GMSSearch.asp
ICASA Data Exchange	On-line database of field experiments in standard format for simulation modeling.	www.icasa.net/data_exchange
LIS	Legume information resource that integrates genetic and molecular data from legume species.	comparative-legumes.org
Komugi	On-line database of wheat genetics with emphasis on genetic stocks.	shigen.lab.nig.ac.jp/wheat/komugi
Wheat Pedigree and Identified Alleles of Genes On Line	On-line database of genealogies and identified alleles of wheat germplasm.	genbank.vurv.cz/wheat/pedigree/

interface allows tracking pedigrees and selections, new germplasm entry, preparing field books, and calculating coefficients of parentage (COP).

The ICIS DMS manages data from any type of evaluation, whether from field experiments, laboratory studies, or observations in commercial fields. Complete flexibility is allowed in defining variables and specifying experimental designs. The minimum requirement for data entry is that values be associated with a study, a genotype or population, and a variable name. Data entered may include raw, unprocessed data and indeed, this is encouraged to permit subsequent reanalysis. Users are encouraged to document crop management, including details such as dates and amounts of irrigations and applications of agrochemicals. The main user interface for

Table 2. Examples of breeding methods used to describe genealogies in LesquIS.

Name	Description
Generative	
Interspecific cross	Cross between two species.
Allo-polyploid	Formation of a polyploid by doubling the chromosomes from two or more species.
Auto-polyploid	Formation of a polyploid by doubling the chromosome number of a single species.
Derivative	
Collection wild species population	The original collected sample of seed or vegetative material, without multiplication. An accession of a cross fertilizing species.
Single plant selection	Selection of a single plant, inflorescence, fruit or seed from a cross fertilizing population.
Half mass selection	Production of next generation by selecting after pollination; selection on female side only.
Maintenance	
Seed increase, open pollination	Open pollination of an unselected set of individuals in isolation and all seed bulked to maintain the population.
Synthetic formation	Formation of a synthetic cultivar in a cross fertilizing crop.
Clone increase tissue culture	Propagation of a clone via tissue culture.

Table 3. Examples of descriptors used to characterize germplasm accessions in LesquIS. All values are considered representative of the accession and for quantitative traits may represent means of multiple observations.

Full name	Code	Description
WEIGHT IN GRAMS PER 1000 SEEDS	KSDWGT	Seed weight in grams per 1000 seed
OIL CONTENT OF SEEDS	OIL	Oil concentration in seed (% of seed weight)
SEEDS/SILIQUE	SDSLQ	Number of seed per silique (pod)
CHROMOSOME NUMBER	CHRNO	2*n* chromosome number
SPECIES NAME	SPEC	Species name ("specific epithet" of a scientific binomial)
LINOLEIC ACID	C18:2	Concentration of linoleic acid in seed (% of total oil)
LINOLENIC ACID	C18:3	Concentration of linolenic acid in seed (% of total oil)
DENSIPOLIC ACID	C182OH	Concentration of densipolic acid in seed (% of total oil)
LESQUEROLIC ACID	C201OH	Concentration of lesquerolic acid in seed (% of total oil)
AURICOLIC ACID	C202OH	Concentration of auricolic acid in seed (% of total oil)
GUM CONTENT OF SEEDS	GUM	Concentration of gum in seed
UNKNOWN PORTION OF NMR RESULTS	UNKN	Portion of seed contents that cannot be assigned readily to a specific fatty acid using NMR (% of total oil)
COMMENTS	COMM	Any special observations on an accession

the DMS is through an Excel™ application that allows data to be up-loaded from a spreadsheet and similarly, for queried data to be downloaded.

An additional dimension to ICIS is that it accommodates multiple users, without assuming that users will maintain data on a single computer. Rather, ICIS allows a user to maintain a local installation, which can provide updates to the central version at the user's discretion. ICIS is evolving rapidly, and features under development include tools for managing molecular data and for curating germplasm collections. Internet interfaces permit simple queries from the central database.

Experiences with ICIS as Applied to Lesquerella

The US Arid Land Agricultural Research Center (USALARC) has established an ICIS implementation for lesquerella (*Lesquerella* spp.) as part of our efforts to facilitate the breeding, evaluation and commercialization of this novel oil-seed. The crop shows promise for its elevated levels of hydroxy fatty acids with unique attributes (Dierig et al. 1993). Current research aims to develop unique industrial products and provide a replacement for castor oil. Wild *Lesquerella* species, originally collected in the 1960s and then more extensively over the past 12 years, are the initial sources of genetic diversity for the breeding effort. Thus, the first data entered in the system, christened "LesquIS," were for germplasm accessions, including collection locations, names of collectors, and collection notes. Data were then added for cycles of crosses, selections and other germplasm evaluation and breeding procedures. Interspecific crosses required use of ovule culture and polyploid induction to recover fertility; these steps were readily documented through the GMS methods (Table 3; Fig. 2). Data loading was initially expected to proceed in a linear process. However, the logical consistency imposed by ICIS revealed problems in data completeness, nomenclature for lines, and interpretation of steps in the breeding process, which required multiple test loadings and revisions. An example of reinterpretation involved distinguishing single plant selections at the same time as tetraploid induction and similarly with amphidiploid formation of interspecific crosses. Since the tetraploids or amphidiploids resulted from a single plantlet or ovule culture (respectively), and it was considered important to track individual plants, the decision was made to note a step of single plant (seed) selection concurrently. Otherwise, either the distinction among plants would be lost, or LesquIS would incorrectly have to describe an extra generation following tetraploid formation.

LesquIS is now used on a routine basis to record breeding activities at USALARC and contains records for over 7000 genetically distinct entities. This represents records dating to 1961, when the first germplasm accessions were named. The LesquIS DMS is being tested for management of oil evaluations, starting with historic records. LesquIS has proven its value by allowing the entire breeding record to be consolidated and documented.

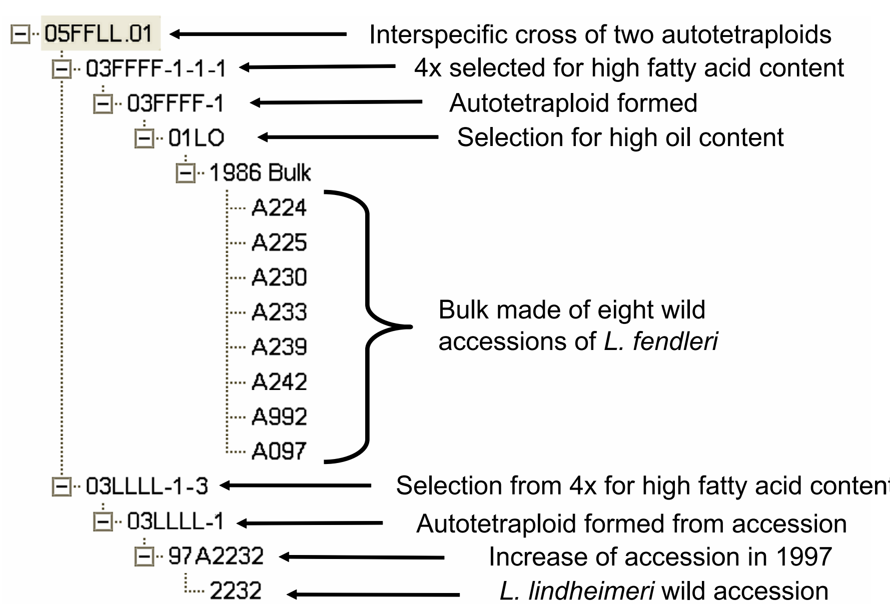

Fig. 2. Annotated genealogy from LesquIS for the lesquerella synthetic allotetraploid 05FFLL.01, which was created by crossing induced autotetraploids of *L. fendleri* and *L. lindheimeri.*

Providing similar security for evaluation data is obviously desirable for research purposes. We anticipate that introducing data into LesquIS from initial efforts at field production will prove invaluable for guiding discussions on where to promote lesquerella production and how to manage crops on a commercial scale.

Based on this positive experience with ICIS, we started VernIS, an information system for vernonia, and we are organizing data for a cuphea (*Cuphea* spp., Lythraceae) system. Experiences to date with VernIS confirm that ICIS can be readily adapted to other novel crops.

Applications of ICIS and Predecessors in Meta-Analysis

Taken alone, gains in research efficiency through better data management justify systems like ICIS, but further benefits are expected through analysis of data across studies or meta-analysis (McLaren et al. 2005). Example applications of ICIS implementations *per se* are few due to the newness of the system, but the International Wheat Information System (IWIS), a predecessor of ICIS that was developed by CIMMYT (Fox and Skovmand 1996; Fox et al. 1997), provides instructive examples.

Examinations of pedigree records for modern wheats in IWIS demonstrated that genetic diversity has been maintained through crossing wheats from geographically distant sources (Smale and McBride 1996; Manifesto et al. 2001). Pedigree information from IWIS was combined with data from PCR markers to show that a widely disseminated high molecular weight glutenin subunit, which improves bread making quality, came from a single Uruguayan land race in the mid-nineteenth century (Butow et al. 2004). Coefficient of parentage values calculated from pedigrees showed genetic relations among wheat lines that were consistent with results from molecular markers (Dreisigacker et al. 2004; Sud et al. 2005). Crossa et al. (2006) used COP values calculated with the ICIS Browse tool and IWIS pedigree data to improve prediction of breeding values from wheat multienvironment trials. Christopher et al. (2006) demonstrated a system for using pedigree and phenotypic data to create genome maps.

Large assemblages of phenotypic data also can support valuable analyses. DeLacy et al. (1994) examined 26 years of spring bread wheat trials conducted at 74 locations to assess the CIMMYT's classification of wheat producing regions into "mega-environments" (MEs) and concluded that the classification failed to consider an important major division typified as European vs. Asian. IWIS data were also used to identify wheat research locations, which were then classified into MEs and used to map wheat MEs (White et al. 2001). Temperature responses of spring wheats have also been examined using IWIS data on phenology and grain yield (White et al. 2000).

ECOPHYSIOLOGICAL MODELS

Agricultural research often seeks to understand crop response in terms of genotypes, environments, and management system components. Ecophysiological models, which integrate knowledge on physiology, genetics, soil chemistry, and climatology, can predict both crop performance and effects of the crop on the environment, such as water and nutrient requirements and impacts on soil organic matter (Hanks and Ritchie 1991; Tsuji et al. 1998). Model applications of potential interest to new crops range from plant breeding to guiding growers on crop management decisions, especially in relation to climate risk. Use of models to specify ideal plant types (ideotypes) has generated numerous publications, but the recommendations have seen limited adoption. Using models to analyze specific questions such as how traits interact to affect crop response to planting date (Acosta-Gallegos and White 1995) or to water deficits (Jones and Zur 1984) has proven more useful. Recently, sorghum and maize models have been used to characterize stress patterns across regions in order to delimit a "target population of environments" for breeding (Chapman et al. 2003; Loffler et al. 2005). Applications of models in breeding may increase with progress in incorporating information from genetics and genomics into models, examples include common bean (White and Hoogenboom 1996), soybean [*Glycine max* (L.) Merr., Fabaceae; Messina et al. 2006], and wheat (White 2006). Similar to applications of models in breeding, initial enthusiasm for using models to guide in-season field management has evolved toward use of models to provide probabilistic recommendations driven by climate forecasts (e.g., Fraisse et al. 2006).

A typical model requires as inputs data on daily weather, initial soil conditions, crop management, and cultivar characteristics. Daily growth is estimated as gain from photosynthesis less losses through respiration and senescence. Photosynthesis depends on light intercepted by current leaf area and influences of air temperature, plant water balance, and plant nutrient status. Allocation of growth to plant parts is influenced by timing of developmental events, such as flowering or tuber initiation, which are estimated by assuming that a baseline developmental rate is slowed by effects of photoperiod and temperature.

Models vary tremendously in the level of process detail considered. Simpler models evaluate processes with a single daily time step and may represent the soil as a single reservoir of water and nitrogen. Complex models may calculate a complete energy balance at intervals of 15 minutes or less and characterize soil in two-dimensions (horizontal layers and vertical slices along rows or furrows). Simpler models often see applications in crop management, while complex models are valued as tools for research. However, the required level of process detail is widely debated (Passioura 1996; Sinclair and Seligman 1996). With expectations that models will guide green house gas credits and estimate compliance with regulations on nitrogen, phosphorus, or water use, there is a trend toward increasing model complexity.

The quality of model predictions depends largely on the data used for model development and calibration and to run the simulations. Thus, discussions on the utility of models (Landau et al. 1998; Jamieson et al. 1999) often involve data quality. Efforts to facilitate data management for modeling date to international development projects started in the late 1970s (Nix 1984; Bouma and Jones 2001). Initial products floundered with limitations of software and hardware, but steady progress resulted in packages such as DSSAT4 (Hoogenboom et al. 2003), which includes tools for managing data for daily weather, soil profiles, and field experiments, as well as for testing models and analyzing outputs. An intermediate level of integration is provided through use of standard file formats and internal databases to track file information.

Recently, the tool for managing data for describing field experiments has been linked to a flexible database (J.W. Jones, 2006, pers. commun.). In parallel with this work, the International Consortium for Agricultural Systems Analysis (ICASA) is promoting data-interchange standards for describing experiments and field production (Hunt et al. 2001, 2006).

GEOGRAPHIC INFORMATION SYSTEMS

Geospatial technologies, especially geographic information systems (GIS), provide powerful tools for analyzing plant response over the landscape. Scales vary from sub-meter in precision agriculture to national, continental or global. A GIS includes data entry and display functions, a data management system, and analytic tools. As such, a GIS intrinsically integrates data with analytic tools, with the requirement that data precisely indicate location, i.e., that data sets be georeferenced, so they may be analyzed considering geographic position.

GIS is being applied throughout agricultural research and allied fields, although usage arguably lags expectations (White et al. 2002). Examples of interest related to crop development range from germplasm collection, to pest and disease monitoring, to risk assessment and analysis of production trends. Analyses of distribution of wild or cultivated species in relation to climate and soils can guide germplasm collection and *in situ* conservation strategies (Beebe et al. 1997; Jones et al. 1997). Similar approaches can be applied to pest and disease distributions, including predicting likely ranges of invasive species. The DIVA GIS (Hijmans et al. 2001, 2004) provides tools for importing location data for germplasm and then analyzing the distribution in relation to climate or other factors. A climate-based distribution model was generated with DIVA for collections of *L. fendleri* (Fig. 3). We emphasize, however, that techniques for modeling species distribution are evolving rapidly (Araujo and Guisan 2006; Elith et al. 2006).

Information on agronomic management traditionally comes from field experiments at a limited number of sites, but geospatial tools also increase options for analyzing crop response across environments. By working with numerous large plots, often entire fields under commercial production, recommendations may prove more robust than from traditional research plots (Calviño and Sadras 1999).

Beyond germplasm collection and improvement and crop management, GIS has application for planning extension efforts, locating processing plants, and developing pricing and marketing strategies. To locate bioenergy plants, Noon and Daly (1996) considered location of production *per se*, mills, power plants, consumers, and transportation networks. Zhan et al. (2005) used similar approaches and data to evaluate suitability of locations for a switchgrass-conversion-to-ethanol facility and examine payment strategies for switchgrass at the proposed facility.

FURTHER DIMENSIONS TO INFORMATION INTEGRATION

For activities such as plant breeding or agronomic evaluation, systems like ICIS provide a solid foundation. It seems unrealistic and probably unwise, however, for researchers to seek a single software and data systems with encyclopedic capabilities or data. A comprehensive system would be too complex for most users and, given likely resource limitations, too difficult to maintain. An alternative is to seek balanced integration where core tools such as ICIS, DSSAT, or DIVA meet needs of substantial user communities, but these tools communicate using file interchange protocols or methods such as Open Database Connectivity (ODBC). Any such approach benefits from use of standards. The ICASA standards for field data (Hunt et al. 2006) hold promise but await wider testing.

While integration has appeal for people synthesizing data, the need also exists for simple tools to assist data acquisition. We suggest as the lowest common denominator, simple spreadsheet- or web-based tools for data entry or for performing specific tasks such as preparing seed packets prior to planting.

ICIS, crop models, and GIS are only examples of information technologies that can increase the efficiency of crop development. Hand-held data loggers have replaced clipboards in many research programs, but further efficiency might be gained through use of wireless communication (Wang et al. 2006), including use of radio frequency identification (RFID) tags for linking samples with data. RFID tags also appear useful for tracing harvested materials. Remote sensing, whether from satellites or aerial platforms, is a logical partner of GIS and has shown promise for detecting abiotic and biotic stresses (Jackson 1986) and estimating yield (Lobell et al. 2004). Tractor-mounted sensing enables collection of real-time data that can characterize crop status at sub-meter scales (Raun et al. 2002).

CONCLUSIONS

Information technologies have much to offer in efforts to develop and establish new crops. Systems such as ICIS illustrate the power of integrated information management. ICIS can facilitate routine tasks, serve as a long-term repository for breeding records, and facilitate analyses to guide breeding. Improved record management may appear to be a modest objective, but having access to well-structured data provides the foundation for accessing and utilizing other technologies. These range from advanced data analyses, to simulation modeling and GIS. Groups seeking to develop new crops should emphasize sound data management with the goal of achieving full integration across disciplines and software tools.

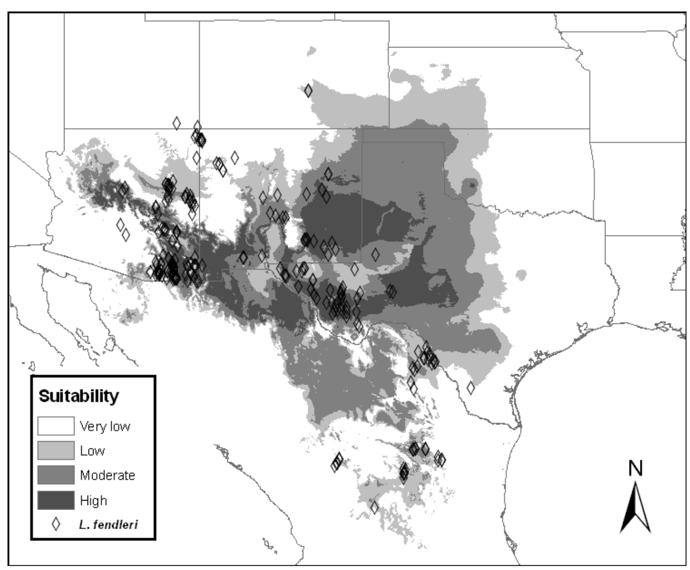

Fig. 3. Model of potential distribution of *L. fendleri* based on climatic conditions at sites where germplasm has been collected. Climatic parameters considered were mean temperatures during the wettest and coolest quarters and total precipitation during the wettest quarter. The model was generated using the Bioclim tool of DIVA and the associated climate database (Hijmans et al. 2001).

REFERENCES

Acosta-Gallegos, J.A. and J.W. White. 1995. Phenological plasticity as an adaptation by common bean to rainfed environments. Crop Sci. 35:199–204.

Araujo, M.B. and A. Guisan. 2006. Five (or so) challenges for species distribution modeling. J. Biogeogr. 33:1677–1688.

Beebe, S., J. Lynch, N. Galwey, J. Tohme, and I. Ochoa. 1997. A geographical approach to identify phosphorus-efficient genotypes among landraces and wild ancestors of common bean. Euphytica 95:325–338.

Boom, C. aan den. 2005. ICIS at Nunhems 2001–2005. www.icis.cgiar.org:8080/workshops/report/2005/reports/1_Mon_02_Casper_ICIS_at_Nunhems.pdf.

Bouma, J. and J.W. Jones. 2001. An international collaborative network for agricultural systems applications (ICASA). Agr. Systems 70:355–368.

Butow, B.J., K.R. Gale, J. Ikea, A. Juhász, Z. Bedö, L. Tamás, and M.C. Gianibelli. 2004. Dissemination of the highly expressed Bx7 glutenin subunit (*Glu-B1al* allele) in wheat as revealed by novel PCR markers and RP-HPLC. Theor. Appl. Genet. 109:1525–1535.

Calviño, P.A. and V.O. Sadras. 1999. Interannual variation in soybean yield: interaction among rainfall, soil depth and crop management. Field Crops Res. 63:237–246.

Chapman, S., M. Cooper, D. Podlich, and G. Hammer. 2003. Evaluating plant breeding strategies by simulating gene action and dryland environment effects. Agron. J. 95:99–113.

Christopher, M., E. Mace, D. Jordan, D. Rodgers, P. McGowan, I. DeLacy, P. Banks, J. Sheppard, D. Butler, and D. Poulsen. 2006. Applications of pedigree-based genome mapping in wheat and barley breeding programs. Euphytica (in press).

Crossa, J., J. Burgueno, P.L. Cornelius, G. McLaren, R. Trethowan, and A. Krishnamachari. 2006. Modeling genotype × environment interaction using additive genetic covariances of relatives for predicting breeding values of wheat genotypes. Crop Sci. 46:1722–1733.

DeLacy, I.H., P.N. Fox, J.D. Corbett, J. Crossa, S. Rajaram, R.A. Fischer, and M. van Ginkel. 1994. Long-term association of locations for testing spring bread wheat. Euphytica 72:95–106.

Dierig, D.A., A.E. Thompson, and F.S. Nakayama. 1993. Lesquerella commercialization efforts in the United States. Indust. Crops Prod. 1:289–293.

Dreisigacker, S., P. Zhang, M.L. Warburton, M. van Ginkel, D. Hoisington, M. Bohn, and A.E. Melchinger. 2004. SSR and pedigree analyses of genetic diversity among CIMMYT wheat lines targeted to different megaenvironments. Crop Sci. 44:381–388.

Elith, J., C.H. Graham, R.P. Anderson, M. Dudik, S. Ferrier, A. Guisan, R.J. Hijmans, F. Huettmann, J.R. Leathwick, A. Lehmann, J. Li, L.G. Lohmann, B.A. Loiselle, G. Manion, C. Moritz, M. Nakamura, Y. Nakazawa, J.M. Overton, A.T. Peterson, S.J. Phillips, K. Richardson, R. Scachetti-Pereira, R.E. Schapire, J. Soberon, S. Williams, M.S. Wisz, and N.E. Zimmermann. 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography 29:129–151.

Finlay, M.R. 2004. Old efforts at new uses: A brief history of chemurgy and the American search for biobased materials. J. Indust. Ecol. 7:33–46.

Fox, P.N., R.I. Magaña, C. Lopez, H. Sanchez, R. Herrera, V. Vicarte, J.W. White, B. Skovmand, and M.C. Mackay. 1997. International Wheat Information System (IWIS), Version 2. Mexico, D.F.: CIMMYT. On compact disk.

Fox, P.N. and B. Skovmand. 1996. The International Crop Information System (ICIS): Connects genebank to breeder to farmer's field. p. 317–326. In: M. Cooper and G.L. Hammer (eds.), Plant adaptation and crop improvement. CAB Int., Wallingford, UK.

Fraisse, C.W., N.E. Breuer, D. Zierden, J.G. Bellow, J. Paz, V.E. Cabrera, A. Garcia y Garcia, K.T. Ingram, U. Hatch, and G. Hoogenboom. 2006. AgClimate: a climate forecast information system for agricultural risk management in the southeastern USA. Comput. Electron. Agr. 53:13–27.

Greene, S. 2004. Indigenous people incorporated? Culture as politics, culture as property in pharmaceutical bioprospecting. Cur. Anthropol. 45:211–237.

Hanks, J. and J.T. Ritchie (eds.). 1991. Modeling plant and soil systems. ASSA, CSSA, SSSA, Madison, WI.

Hijmans, R.L., L. Guarino, M. Cruz, and E. Rojas. 2001. Computer tools for spatial analysis of plant genetic resources data: 1. DIVA-GIS. Plant Genet. Res. News 127:15–19.

Hijmans, R.J., L. Guarino, C. Bussink, P. Mathur, M. Cruz, I. Barrantes, and E. Rojas. 2004. DIVA-GIS, version 4. A geographic information system for the analysis of biodiversity data. Manual. hwww.diva-gis.org.

Hoogenboom, G., J.W. Jones, P.W. Wilkens, H.H. Porter, W.D. Batchelor, L.A. Hunt, K.J. Boote, U. Singh, O. Uryasev, W.T. Bowen, A. Gijsman, A. du Toit, J.W. White, and G.Y. Tsuji. 2003. Decision support system for agrotechnology transfer version 4.0. CD-ROM. Univ. Hawaii, Honolulu.

Hunt, L.A., G. Hoogenboom, J.W. Jones, and J.W. White. 2006. ICASA Version 1.0 data standards for agricultural research and decision support. www.icasa.net/standards (verified Oct. 10, 2006).

Hunt, L.A., J.W. White, and G. Hoogenboom. 2001. Agronomic data: Advances in documentation and protocols for exchange and use. Agr. Syst. 70:477–492.

Jackson, R.D. 1986. Remote sensing of biotic and abiotic plant stress. Annu. Rev. Phytopath. 24:265–287.

Jamieson, P.D., J.R. Porter, M.A. Semenov, R.J. Brooks, F. Ewert, and J.T. Ritchie. 1999. Comments on "Testing winter wheat simulation models predictions against observed UK grain yields by Landau et al. (1998)". Agr. For. Met. 96:157–161.

Jones, J.W. and B. Zur. 1984. Simulation of possible adaptive mechanisms in crops subjected to water stress. Irrig. Sci. 5:251–264.

Jones, P.G., N. Galwey, S.E. Beebe, and J. Tohme. 1997. The use of geographical information systems in biodiversity exploration and conservation. Biodivers. Conserv. 6:947–958.

Kimpel, J.A. 1999. Freedom to operate: Intellectual property protection in plant biology and its implications for the conduct of research. Annu. Rev. Phytopath. 37:29–51.

Landau, S., R.A.C. Mitchell, V. Barnett, J.J. Colls, J. Craigon, K.L. Moore, and R.W. Payne. 1998. Testing winter wheat simulation models' predictions against observed UK grain yields. Agr. For. Met. 89:85–99.

Lobell, D.B., J.I. Ortiz-Monasterio, and G.P. Asner. 2004. Relative importance of soil and climate variability for nitrogen management in irrigated wheat. Field Crops Res. 87:155–165.

Loffler, C.M., J. Wei, T. Fast, J. Gogerty, S. Langton, M. Bergman, B. Merrill, and M. Cooper. 2005. Classification of maize environments using crop simulation and geographic information systems. Crop Sci. 45:1708–1716.

Manifesto, M.M., A.R. Schlatter, H.E. Hopp, E.Y. Suarez, and J. Dubcovsky. 2001. Quantitative evaluation of genetic diversity in wheat germplasm using molecular markers. Crop Sci. 41:682–690.

McLaren, C.G., R.M. Bruskiewich, A.M. Portugal, and A.B. Cosico. 2005. The International Rice Information System: A platform for meta-analysis of rice crop data. Plant Physiol. 139:637–642.

Messina, C.D., J.W. Jones, K.J. Boote, and C.E. Vallejos. 2006. A gene-based model to simulate soybean development and yield responses to environment. Crop Sci. 46:456–466.

Nix, H.A. 1984. Minimum data sets for agrotechnology transfer. Proc. Int. Symp. Minimum Data Sets for Agrotechnology Transfer. ICRISAT Center, Patancheru, India. p. 181–188.

Noon, C.E. and M.J. Daly. 1996. GIS-based biomass resource assessment with bravo: Strategic benefits of biomass and wasteful fuels. Biomass Bioener. 10:101–109.

Passioura, J.B. 1996. Simulation models: Science, snake oil, education, or engineering? Agron. J. 88:690–694.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815–820.

Ray, D.T., T.A. Coffelt, and D.A. Dierig. 2005. Breeding guayule for commercial production. Indust. Crops Prod. 22:15–25.

Sinclair, T.R. and N.G. Seligman. 1996. Crop modeling: From infancy to maturity. Agron. J. 88:698–704.

Smale, M. and T. McBride. 1996. Understanding global trends in the use of wheat diversity and international flows of wheat genetic resources. Part 1 of CIMMYT 1995/96 World Wheat Facts and Trends: Understanding Global Trends in the Use of Wheat Diversity and International Flows of Wheat Genetic Resources. CIMMYT, Mexico, D.F.

Sud, S., N.S. Bains, and G.S. Nanda. 2005. Genetic relationships among wheat genotypes, as revealed by microsatellite markers and pedigree analysis. J. Appl. Genet. 46:375–379.

Troyer, A.F. 2004. Background of U.S. hybrid corn II: Breeding, climate, and food. Crop Sci. 44:370–380.

Tsuji, G.Y., G. Hoogenboom, and P.K. Thornton (eds.). 1998. Understanding options for agricultural production. Kluwer Academic Publ., Dordrecht, The Netherlands.

Wang, N., N. Zhang, and M. Wang. 2006. Wireless sensors in agriculture and food industry: Recent development and future perspective. Comput. Electron. Agr. 50:1–14.

White, J.W. 2006. From genome to wheat: Emerging opportunities for modeling wheat growth and development. Eur. J. Agron. 25:79–88.

White, J.W., J.D. Corbett, and A. Dobermann. 2002. Insufficient use of meso-resolution spatial analysis in the planning, execution and dissemination of agronomic research? Field Crops Res. 76:45–54.

White, J.W. and G. Hoogenboom. 1996. Simulating effects of genes for physiological traits in a process-oriented crop model. Agron. J. 88:416–422.

White, J.W., M. van Ginkel, S. Rajaram, S., and J.D. Corbett. 2001. A GIS-based approach to revising CIMMYT's wheat megaenvironment classification. Annu. Meetg. Am. Soc. Agron. Raleigh, NC.

White, J.W., P. Grace, P.N. Fox, A. Rodriguez-Aguilar, and J. Corbett. 2000. A global perspective on modeling the response of wheat yield potential to temperature. p. 39–43. In: J.W. White and P.R. Grace (eds.), Modeling extremes of wheat and maize crop performance in the tropics. CIMMYT, Mexico, D.F.

Zhan, F.B., X. Chen, C.E. Noon, and G. Wu. 2005. A GUS-enabled comparison of fixed and discriminatory pricing strategies for potential switchgrass-to-ethanol conversion facilities in Alabama. Biomass Bioener. 28:295–306.