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Digital Technologies to Modernize Effective and Efficient Use of Plant Genetic Resources

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The genetic diversity of crop plants and their relatives is the raw material of plant breeding. Since the beginning of agriculture, farmers have attempted to identify and use the available variants to their advantage. More recently, plant breeders have identified and recombined useful variants to produce improved landraces and cultivars. Over the past 20 years, a series of technical innovations have opened opportunities to improve the efficiency and effectiveness of plant breeding programmes. Commercial seed companies in developed countries and in some developing countries have adopted these innovations. This paper will discuss some of these opportunities and obstacles to their deployment in the context of developing countries. The presentation will be illustrated by examples from projects supported by ACIAR.

From phenotype to genotype: cheaper, faster, whole genome, DNA profiling

DNA analysis technologies developed in the 1990's such as microarrays dramatically increased the throughput and reduced the costs of identifying and scoring genetic variants (1). For the first time it became practical to analyse the whole genome rather than a small set of genetic markers. Single Nucleotide Polymorphism chips assaying in parallel 9,000 to 90,000 markers are now widely used (2). Improvement in cost and throughput of DNA sequencing is now making it one method of choice to identify and score genetic variants. For species with large genomes, genotyping by sequencing (3), where a reproducible fraction of the genome – 1 to 10% - is sequenced, allows to determine marker profiles with a density of thousands to tens of thousands markers. The process costs about 5,000 USD for 96 samples. For species with small genomes such as rice, whole genome sequencing can be used. Prompted by technological development, genetic data production services have become available commercially. For most breeding programmes, it is now more cost-effective to outsource high density data production to commercial facilities, than to produce marker data in house. Data quality from commercial facilities is also higher.

The characterisation of the whole genome using high density marker profiles is now facilitating the use of agrobiodiversity in breeding. Traits of interest can be mapped in wild relatives, in landraces, or in elite cultivars and markers then used to transfer the traits into elite varieties (4).

Accurate phenotyping: electronic field data capture, electronic experiment management

The effectiveness of a breeding programme relies on its ability to generate high quality phenotypic data. The use of drones and other high throughput measurement methods increase the demand for rigorous management of field trials and experiments. Electronic tools to manage experiments and to capture field data are available, and help to reduce the error rate. A common source of error is the loss of accurate sample tracking. The use of barcodes to label plants and experimental plots, while not a complex technological innovation, reduces sample tracking errors. Handheld devices (smartphones and tablets) able to read barcodes and record field phenotypic data have now become affordable for most breeding programmes. These tools increase the productivity of staff and make their job more enjoyable. Larger experiments become possible, thereby increasing the potential genetic gain. Examples of Applications specifically developed for capturing plant phenotypic data on handheld devices include FieldScorer (5) and KDSmart (6).

Using data productively: data storage, management and analysis

While data can now be acquired or purchased more efficiently, their effective application requires a dedicated data management system. These systems need to respond specifically to breeders needs and be easy to use so that breeders adopt them readily. Their key functionalities include managing:

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- Lines, seed stocks, pedigrees, families;
- Field experiments;
- A large range of phenotypic data;
- Ideally genotypic (genetic marker) data: this is proving to be challenging.

Systems should be able to relate the various types of data and to interface seamlessly with data analysis tools for example: to map Quantitative Trait Loci; to identify genomic regions and markers associated with specific traits; to assist in the design of breeding strategies; or to decide which parents to cross. Several systems available to diverse breeding organisations have been designed over the past 15 years, each with their own strengths and limitations. Examples include the Breeding Management System of the Integrated Breeding Platform (7) initially developed under the Generation Challenge Programme initiative of the CGIAR, the commercial software Agrobase from Canadian company Agronomix (8), or KDDArT from Australian company Diversity Arrays Technology Pty Limited (9). The International Rice Research Institute has been developing its own system to manage rice breeding. The hardware required to use these systems has become affordable and with the development of cloud computing and the increasing availability of internet connectivity, many breeding programmes in developing countries can now use a breeding information management system. A would-be user of these systems should review their performance and their suitability for the specific purpose and context of the organisation. This presentation does not present an exhaustive view of available systems.

One institutional advantage of adopting a breeding information management system is to provide a vehicle for effective cooperation between breeders, pre-breeders and the gene banks. Within one organisation, it also ensures better collective memory of experiments, materials and results. A well-managed system reduces the risk of losing information through natural disasters. Adoption of data management systems will have a profound influence on how breeding programmes run.

Cooperation between breeding organisations will be facilitated if the systems they use can communicate and exchange information. Since multiple systems are currently used, future development will need to ensure their ability to exchange information.

Modelling the Genotype by Environment by Management Interactions to Breed Better Varieties

The use of plant and crop simulation is another area where digital tools are impacting plant breeding. Models such as APSIM (10, 11) are parameterised using high quality environment data (soil and climate) and crop performance measured under various environments and management strategies. Once properly established, models can simulate the effect of the new traits introduced by breeders, for example different maturity dates, different timing of using water, tolerance to high temperature, etc. (12). The increased sophistication of the models allows for predictions in the various environments so that breeders can estimate the value of specific traits in specific environments, before starting the breeding project. Integrating molecular genetic data, models can also guide parent selection before crosses are initiated (13).

From Genotype to Phenotype: Novel Approaches to Breeding

Similarly to the trend in other areas of research (for example in clinical research or economic research), the high density plant genotypic and phenotypic data now available lends itself to analysis using machine learning-based algorithms. Discoveries and inferences can be made with limited prior hypothesis or knowledge. Using Genomic Selection (14), experimental validation in the field can then be focused and more efficient. The phenotypic data collected limit the scope of this approach. No doubt the eye of the breeder in the field will remain an important tool to detect and exploit unexpected variation!

Modernising Breeding Programmes

Most of the technologies discussed here can increase the performance of breeding programmes in developing countries. Their costs are manageable, but their adoption may be limited by institutional obstacles and the lack of awareness, knowledge and skills in many plant breeders. Building institutional capacity to consider, and then to adopt, innovation is therefore a critical first step.

One limitation is the ability of breeding programmes to acquire goods and services, especially when it involves the use of foreign currency. Even when data produced commercially is of better quality, higher utility and lower cost than data produced in-house, some institutions will have difficulty accessing the small amount of foreign currency required. To benefit fully from innovations, breeding programmes will need reliable access to some high quality consumables (for example barcode labels and barcode printers, good quality seed bags), regular software maintenance and upgrades, and genotyping services.

Another limitation is the requirement for increased communication and cooperation between members of a breeding team: breeding is becoming more multidisciplinary. Successful programmes will integrate the contribution of multiple experts and will use these new tools to design the breeding programme itself. This will require institutional evolution in managing human resources, updating reward systems for individual performance, and recognising the contribution of multiple actors to the successes. Metrics of success may need to be updated: genetic gain of released varieties rather than number of releases needs to be considered. Compared to the traditional situation of a lone breeder responsible and recognised for the release of an improved variety, this may prove a challenge for some organisations.

Conclusion

While the technical innovations discussed above can increase the performance of breeding programmes, they are not sufficient to guarantee impact. Beyond technological innovations, impactful breeding programmes respond to clearly articulated demands from farmers. Defining the farmers' demands and needs, and the corresponding traits that improved varieties must have, remains one of the most demanding task of a plant breeder, and the most critical to ensure impact in the field. The impact pathway of an improved variety is also critically dependent on an effective seed system to make the improved varieties available to farmers. The impact pathway also requires an effective communication or extension system to make the farmers aware of the new varieties. Responsiveness to farmers' demand, ability to supply the seeds of improved varieties, and effective dissemination of the relevant information are challenges that have to be met for breeding organisations to fully capture the benefits of agrobiodiversity in the improved varieties they release.

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