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Review. Applications of ecogeography and geographic information systems in conservation and utilization of plant genetic resources

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Abstract

The present paper reviews the use of ecogeographical studies in the efficient conservation and utilization of plant genetic resources. While the use of genotypic information in agrobiodiversity studies has experienced a rapid boost during the last two decades, the use of environmental information on the collecting sites of the conserved germplasm (*i.e.,* ecogeographical characterization) has gained importance in a more gradual way. Today we know that ecogeographical characterization reveals the adaptive range of species conserved and shows the most important environmental factors or variables for adaptation. Progress in ecogeographical characterization has been helped by the development and popularization of geographic information systems (GIS) software applications and environmental data arranged in layers compatible with such applications. GIS are useful to manage and analyze georeferenced data, such as passport collection data and environmental variables. Thus, GIS have become the best tool to perform ecogeographical analyses. Other related tools such as species distribution models or gap analysis can be easily integrated in ecogeographical analysis, offering improved results. As a result, GIS, related tools and ecogeographical analysis can be useful in a wide range of applications in the collection, conservation, characterization, documentation and utilization of plant genetic resources.

Additional key words: adaptation; ecogeographical analysis; environment; gap analysis; genotype; phenotype; species distribution models.

Resumen

Revisión. Aplicaciones de la ecogeografía y los sistemas de información geográfica en conservación y utilización de recursos fitogenéticos

Se presenta una revisión de la incorporación de los estudios ecogeográficos en la conservación y utilización eficiente de los recursos fitogenéticos. Mientras en las últimas dos décadas la información genotípica ha experimentado un rápido auge en el estudio de la agrobiodiversidad, la información ambiental de los sitios de recolección (*i.e.,* caracterización ecogeográfica) ha venido ganando importancia de manera más gradual. Hoy sabemos que la caracterización ecogeográfica de los recursos fitogenéticos puede ayudar a revelar el rango adaptativo de las especies conservadas, a la vez que sirve para detectar los factores ambientales más importantes en términos de adaptación. Los progresos en la caracterización ecogeográfica han estado sustentados en el desarrollo y popularización de programas de sistemas de información geográfica (SIG) y la disponibilidad de datos ambientales en forma de capas compatibles con estos programas. Los SIG son útiles para el manejo y análisis de datos geo-referenciados, tales como los sitios de recolección descritos en datos de pasaporte y variables ambientales. Así los SIG se han convertido en la mejor herramienta para la realización de análisis ecogeográficos. Otras herramientas que se pueden integrar fácilmente en un análisis ecogeográ-

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Abbreviations used: ARS-USDA (Agricultural Research Service of the United States Department of Agriculture); CGIAR (Consultative Group on International Agricultural Research); ELC (ecogeographical land characterization); FIGS (focused identification of germplasm strategy); GIS (geographic information systems); SDM (species distribution model); SIERFE (ecogeographical information system for Spanish plant genetic resources).

fico, ofreciendo resultados más completos, son los modelos de distribución de especies y los análisis de faltantes. En definitiva, los SIG, las herramientas asociadas a los SIG y los análisis ecogeográficos resultan útiles en un amplio rango de aplicaciones relacionadas con la recolección, conservación, caracterización, documentación y utilización de los recursos fitogenéticos.

Palabras clave adicionales: adaptación; análisis ecogeográfico; análisis de faltantes; fenotipo; genotipo; medio ambiente; modelos de distribución de especies.

Introduction: environment, genotype and phenotype

It is a continuous challenge for scientists — particularly plant breeders — to solve the equation that relates phenotype, genotype and environment, expressed as P = G + E (Fisher, 1918; Lande, 1980; Falconer & Mackay, 1996; Walsh, 2002). Since the publication of its components (Johannsen, 1911) to the first green revolution, the trend has been to try to understand heredity and consolidate the genetic aspect of the phenotype instead of recognizing the importance of the environment. With the development of plant biotechnology, the environmental component was placed in a second place in some areas such as genetic engineering or molecular breeding. However, the environment has empirically been considered as a key factor by farmers and conventional plant breeders since agriculture began. In conventional plant breeding, the environmental component is usually determined indirectly by inferring its weight from its impact on the phenotype and its interaction with the genotype. This impact is usually assessed in the final stages of the plant breeding process and only in materials that could eventually become a new variety. What plant breeders ultimately want to know is whether their new variety behaves well in few or many environments and whether this behavior is maintained over time (Vallejo & Estrada, 2002).

Overall, environmental information has not been given more importance in the area of plant genetic resources than in plant breeding. Until DNA-based molecular markers appeared in the 1990s, phenotypic information was the most used for germplasm characterization studies. Most of the phenotypic information compiled involved monogenic or oligogenic traits, which are only mildly affected by the environment. This information is useful to determine kinship relationships between accessions, estimate the genetic diversity of the material conserved and, to a certain extent, assess redundancy in germplasm collections. The introduction of neutral DNA-based molecular markers improved the resolution of characterization studies, while the advent of genomics will make it possible to determine how much redundancy is conserved. There have historically been fewer agronomic germplasm evaluation studies — which include obtaining data on polygenic phenotypic traits, more influenced by the environment — than phenotypic (morphological or biochemical) or genotypic (DNA) characterizations. This may be due to the high financial and logistical cost of the first type of studies, which require a relatively higher number of individuals to be planted in various environments (Ferreira, 2006).

Plant breeders go to gene banks to seek the best parentals for their breeding programmes, that is, the genotypes that will donate their genes to cultivars at various stages of crop breeding. Therefore, any information provided by the gene bank curator that may lead to the discovery of genes or alleles of interest is extremely useful when selecting parentals. Herein lies a great deal of the importance of the characterization and evaluation of plant genetic resources. Depending on the objective of the breeding programme, geneticists may be interested in introducing monogenic or polygenic traits into modern cultivars. To do so, breeders need any information that may directly or indirectly help them to select parentals with the desired traits. They are often interested in germplasm adapted to specific biotic or abiotic conditions. The reduction in new land available (and suitable) for agriculture, environmental degradation and global climate change are making breeders look for plants that can grow on poor soils or soils with an excess of harmful ions or plants adapted to drought, waterlogging, extreme temperatures or very steep terrain, among others (Ceccarelli, 1994; Ober & Luterbacher, 2002; Vinocur & Altman, 2005; Berger, 2007; Witcombe *et al.*, 2008).

The kind of information provided to a plant breeder on the germplasm conserved is directly related to one of the greatest challenges of conserving plant genetic resources for food and agriculture: the utilization of such resources by breeders (FAO, 1996). Over the last few years, neutral genotypic information has been the main characterization type in gene banks. It has recently been argued that this kind of information is very useful to determine the genetic representativeness of the material conserved but is not a useful tool for breeders with a view to using these resources (Kresovich *et al.*, 2006). Morphological phenotypic information generated in gene banks is usually very helpful to improve some qualitative traits of crops. However, the most useful information to select parentals with interesting traits from a quantitative point of view is that obtained through agronomic evaluation. Unfortunately these types of studies are usually less abundant and data from them are scarce. Finally, when available, information on the environmental conditions of the collecting site is limited to geographic coordinates and sometimes elevation of the collecting site.

The limited human and financial resources, the technical and logistical complexity of obtaining useful information for breeders and the focus on production of data that are important for curators to the detriment of valuable data for breeders explain the bottleneck in the use of plant genetic resources. In this context, it is important to develop complementary initiatives to promote the use of germplasm and thus attract the attention of breeders. Such initiatives should make the most of the resources available, develop simple, low-cost and transferable methodologies and provide information as comprehensive and useful as possible to users of plant genetic resources; at the same time, they should represent a powerful tool for curators to manage existing and future collections.

In the search for such complementary initiatives, the underexploited environmental component is a promising area to explore. The environment has a direct influence on the phenotype and shapes genotypes through adaptation. It is therefore an appropriate route to understand and study phenotypic and genotypic representation in germplasm collections. In the early 1970s, when the idea of plant genetic resources was still being developed, the environment was given major importance in the book *Genetic Resources in Plants*, by Frankel & Benett (1970). The book includes chapters such as *Adaptation in wild and cultivated plant populations*, *Environmental physiology* or *Climate and crop distribution*. These chapters address issues such as the relationship between adaptation and genetic variability or the importance of certain environmental factors in the distribution of primitive cultivars and crop wild relatives. It is surprising and paradoxical to note that, 40 years later, the same issues are selected to project them into the future as new tools to improve the efficiency of the collection, conservation and utilization of plant genetic resources. Meanwhile, various technological and scientific developments have made it possible to analyze the environmental component of germplasm. These are essentially the generation of geographic information systems (GIS) and associated software, and the availability of ecogeographical data in a format compatible with GIS software.

Geographic Information Systems

GIS are tools designed to manage and analyze information with georeferencing as a common base. GIS have been defined as "computer-based systems for analyzing spatially referenced information" or "any system for handling geographical data" (Coppock & Rhind, 1991). They were developed in Canada in the 1960s as a tool to manage the vast forest areas of the country and restore marginal agricultural areas. Disciplines such as cartography, computer science, geography, surveying, remote sensing, data processing, mathematics and statistics have been integrated into what is known as GIS, which makes them powerful analysis tools. GIS are currently applied to disciplines as diverse as environmental protection, urban and regional planning, resource, land and soil management, land registry, optimization of infrastructure location (schools, businesses, hospitals, etc.) and military intelligence, among others (Savitsky, 1998; Gregory & Ell, 2007). Yet, apart from facilitating the analysis of georeferenced data, GIS have the advantage of expressing the results in maps, which are familiar and user-friendly graphic representations for people.

As regards the application of GIS to the management and conservation of plant genetic resources, several aspects should be highlighted. Given that collecting sites can be georeferenced, GIS make it possible to study the environmental conditions under which crop wild relatives and local varieties have acquired their adaptive traits. Moreover, GIS help to analyze the spatial aspect of germplasm collecting sites, which includes geographical distances or distribution patterns (Hijmans & Spooner, 2001). This can improve the efficiency of some activities that are typical of the conservation and use of plant genetic resources, such as collecting and field explorations, identifying under-conserved areas, creating core collections or selecting appropriate germplasm for breeding programs. When they are used to characterize the environment of collecting sites, GIS require environmental information as a basic input. This information, arranged in a format compatible with GIS software, initially (in the 1980s and part of the 1990s) had relatively low resolution and coverage; it was also quite inaccessible due to its high price, its mode of distribution and legal and political-administrative barriers (Guarino, 1995; Decker, 2001). Fortunately, the situation is different today: high-resolution and quality environmental information is available for direct use in GIS at a low cost — or even free of charge — for anybody who needs it (see Table 1). This "revolution" has been caused by several factors: a) greater public and private investment in the development of GIS, remote sensing, cartographic and modeling techniques; b) the development and massive use of the Internet as a vehicle to circulate this information between sources and users; and c) a growing interest of governments, scientists and non-governmental organizations in disseminating GIS and environmental information and making them available to citizens (Günther, 1998).

A list of the most common GIS computer software packages used in agrobiodiversity conservation is shown in Table 2. However there are many other GIS and remote sensing software packages with potential use in plant genetic resources.

Ecogeographical characterization

Although the definition of ecogeography in the area of plant genetic resources has changed over time, the idea remains the same: it deals with the adaptation of plants or crops to their environment. As applications of

Table 1. Some examples of sources of GIS-formatted layers suitable for ecogeographical studies on the Spanish, European and global level

Source	Type of information	Coverage	Institution/Project	Reference/website
Atlas Climático de la Península Ibérica	Abiotic (climatic)	Peninsular Spain and Portugal	Universidad Autónoma de Barcelona	http://opengis.uab.es/
Diagnosis Fitoclimática de la España Peninsular	Abiotic (climatic)	Spain	Organismo Autónomo Parques Nacionales	Gonzalo (2010)
WorldClim	Abiotic (climatic)	Global	Museum of Vertebrate Zoology, University of California, Centro Internacional de Agricultura Tropical (CIAT) and Rainforest CRC	http://worldclim.org
Shuttle Radar Topography Mission	Abiotic (geophysical)	Global	National Aeronautics and Space Administration (NASA)	http://www2.jpl.nasa.gov/srtm/
Modelos Digitales del Terreno 25/200	Abiotic (geophysical)	Spain	Instituto Geográfico Nacional	http://www.ign.es/
Spanish Soil Map (1:1,000,000), Web Map Service (WMS)	Abiotic (edaphic)	Spain	Instituto Geográfico Nacional	http://sig.marm.es/geoportal/
Harmonized World Soil Database	Abiotic (edaphic)	Global	The Food and Agriculture Organization of the United Nations (FAO), the International Institute for Applied Systems Analysis (IIASA), International Soil Reference and Information Centre (ISRIC), Institute of Soil Science/Chinese Academy of Sciences (ISSCAS) and Joint Research Centre of the European Commission (JRC)	http://www.iiasa.ac.at/
CORINE land cover	Anthropic	Europe	European Environmental Agency	http://www.eea.europa.eu
GlobCover	Anthropic	Global	European Spatial Agency	http://ionia1.esrin.esa.int/
Municipality limits	Administrative	Spain	Instituto Geográfico Nacional	http://www.ign.es/
Global Administrative Areas Database (GADM)	Administrative	Global	BioGeomancer project	http://www.gadm.org/

Table 2. Examples of GIS software applied in different aspects of conservation of plant genetic resources

GIS software	Distribution	Website	Observations	Example of use
Arc-GIS / Arc info	Commercial	http://www.esri.com	Specialized in vectorial format	Evaluation of ecogeographical representativeness in *ex situ* collections (Parra-Quijano *et al.*, 2008)
DIVA-GIS	Free	http://www.diva-gis.org	It provides specific tools for specialists in plant genetic resources	Analysis of the geographic distribution of wild potato species (Hijmans & Spooner, 2001)
GRASS GIS	Free	http://grass.osgeo.org	It can be used with R software environment	Evaluation of climate change on the distribution of tree species (Benito Garzón *et al.*, 2008)
gvSIG	Free	http://www.gvsig.org/web	Nothing remarkable	Evaluation of on-farm conservation (Montesano *et al.*, 2012)
IDRISI	Commercial	http://www.clarklabs.org	Specialized in raster format	Gap analysis in *Medicago* crop wild relatives (Greene *et al.*, 2012)
Marxan	Free	http://www.uq.edu.au/marxan	Specific to aid systematic reserve design on conservation planning. It is not a GIS, but it requires complementary GIS tools	Selection of areas for *in situ* conservation (Carwardine *et al.*, 2008)
R	Free	http://www.r-project.org	It is not GIS software, but some packages have GIS functionalities (for example raster, sp or dismo)	Focused identification of germplasm strategy (Bari *et al.*, 2012)

ecogeography appeared gradually, definitions were developed progressively. The term was introduced in the area of plant genetic resources by Peeters *et al.* (1990), who defined it as “combinations of climatic, ecological and geographical data”. This kind of information is also referred to as “agroecological” data (Tohme *et al.*, 1995) or “bioclimatic” data (Zuriaga *et al.*, 2009). Maxted *et al.* (1995) introduced the concept of “ecogeographical surveys” to refer to the compilation of necessary information prior to germplasm collecting on spatial distribution, intraspecific diversity patterns and relationships between ecological conditions and the survival of a given species. The term “ecological descriptors” was later introduced to refer to environmental variables that are useful in the collection and conservation of plant genetic resources (Steiner & Greene, 1996). Ecogeographical characterization at present is understood as the analysis of any environmental information about the site where an individual plant or population occurs that is related to its adaptation to the most important biotic or abiotic factors. Therefore, ecogeography is a subcomponent of the environment data that has special importance for a given taxon.

Ecogeographical information about the germplasm collecting site complements many of the activities in which phenotypic or genotypic information has traditionally been used, such as germplasm characterization. It can be also an alternative to phenotypic or genotypic information not in the sense that it should replace such information in sites where it is already available; instead, it is particularly indicated in sites for which there is limited characterization data and a limited budget due to its low cost and technical requirements.

Including ecogeographical data among the information necessary to manage the conservation and use of plant genetic resources usually improves decision making compared to considering only phenotypic and genotypic components. This is reflected in the increase in recent years of genetic and genotypic studies that include ecogeographical variables in their data analysis (Volis *et al.*, 2001; Liviero *et al.*, 2002; Chen *et al.*, 2004; Batchu *et al.*, 2006; Bhullar *et al.*, 2009). Moreover, ecogeographical information is usually requested by plant breeders and organic farmers to select parentals and local varieties adapted to certain regions and/or particular environmental conditions. Additionally, knowing how germplasm can adapt to specific environmental conditions will be key for agriculture to adapt to climate change (Jones & Thornton, 2003; Jarvis *et al.*, 2008).

GIS-related tools and ecogeography

GIS and the increasing availability of different types of environmental information made it possible for associated tools to appear and gradually become common in the study of plant genetic resources. Such is the case of species distribution models (SDM), which are usually based on hypotheses on how species distribution is determined by environmental factors (Guisan & Zimmermann, 2000). The management of environmental data and the nature of the SDM results make GIS an almost essential tool for its application. Such models can also be considered as a tool to develop the ecogeographical pattern of a given species and project it on areas where its occurrence is unknown. The many and successful applications of SDM in ecology facilitated their introduction into the area of genetic resources. They were first introduced in plant genetic resources by Jones *et al.* (1997) to find possible areas to collect wild forms of *Phaseolus vulgaris* still not represented in gene banks. In their study, Jones *et al.* (1997) also pioneered the use of "gap analysis" to find gaps in the representativeness of gene bank collections by comparing them with reports from other sources that indicate the presence of the species. Since then, gap analysis and predictive models have found a place in plant genetic resources conservation assessments (Lipow *et al.*, 2004; Parra-Quijano *et al.*, 2007; Upadhyaya *et al.*, 2009; Ramírez-Villegas *et al.*, 2010).

Ecogeographical land characterization (ELC) maps are another GIS-related tool. Their purpose is to identify all the possible adaptive scenarios of a species in a given region. They produce an ecogeographical characterization not of the germplasm itself, but of a spatial framework where the germplasm may or may not be present. The ELC maps represent a series of ecogeographical categories obtained through multivariate analysis of environmental variables (Parra-Quijano *et al.*, 2008; 2012a). Similar maps are also known as bioclimatic maps (Hossell *et al.*, 2003) or plant adaptation region maps (Vogel *et al.*, 2005). Maps which represent environments differ in the degree of objectivity-subjectivity of their preparation and the resolution of the adaptive scenarios defined. For example, highly subjective maps representing large areas as a single homogeneous environment are usually not very realistic or reproducible (Williams *et al.*, 2008).

When using ELC maps, characterization is done by assigning the germplasm the category represented in the map according to the location of the collecting site. These maps have multiple uses in the collection, conservation and use of agrobiodiversity. The first ecogeographical map used in the area of plant genetic resources was developed by Tohme *et al.* (1995). It was used along with other kinds of data to create a core collection of *P. vulgaris*. Since then, such maps have been applied to studies on representativeness of *ex situ* conservation (Parra-Quijano *et al.*, 2008) or used to determine appropriate sites to collect germplasm (Parra-Quijano *et al.*, 2012b). Recently, Parra-Quijano *et al.* (2012a) made an assessment of an ELC map for Spain and proved that it was able to reflect adaptive scenarios in six of the eight species assessed. This led to the conclusion that ecogeographical maps should ideally be developed *ad hoc* at the species level or the genus level at the most.

GIS and ecogeography applied to plant genetic resources in the last decade

The new millennium marked the beginning of a continuous trickle of studies that use GIS and ecogeography to perform, facilitate or improve various tasks related to *in situ* and *ex situ* agrobiodiversity conservation. This area has not experienced the quantitative leap (number of projects/studies/publications) of DNA-based markers applied to germplasm characterization in the decade 1995-2005. However, the quality of studies on GIS and ecogeography published to date and their applicability to the conservation and use of plant genetic resources clearly show that they are increasingly popular; this is particularly true in developing countries, where financial resources are scarce but agrobiodiversity is abundant.

In the last ten years, the interest in the applications of GIS and ecogeography in plant genetic resources that began in the 1990s has led to many publications and research projects. Guarino *et al.* (1999; 2002) produced a detailed list of applications, although their scope has broadened in the last decade and new techniques and methodologies have been developed, as it is showed in following paragraphs.

GIS are often applied to *in situ* conservation of endangered wildlife in protected areas (Rodrigues *et al.*, 2004). In respect of this, protected areas are also appropriate to conserve crop wild relatives (Maxted *et al.*, 2008), thus GIS has a wide research area in conservation of this type of genetic resources. As a result of the growing interest in crop wild relatives and their conservation, two major international projects on crop wild relatives have recently been implemented in Europe: PGR Forum (http://www.pgrforum.org) and AEGRO (http://aegro.bafz.de). In these projects, GIS have been used to determine how well a network of protected areas covers the geographical distribution of a particular group of species (Parra-Quijano *et al.*, 2003) or to select new areas fit for effective and efficient conservation of these species. However, few studies on *in situ* conservation on farm have been broadly disseminated, although the bases of GIS analysis of factors affecting cultivated diversity in agroecosystems were established by Jarvis *et al.* (2000).

As regards germplasm collection for *ex situ* conservation, the first report of field explorations supported by GIS and ecogeographical data were published by Greene *et al.* (1999a,b) for collection of wild species of *Trifolium*, *Lotus* and *Medicago*. After this, studies have explored several issues such as detecting areas fit for prospecting rare wild species of *Capsicum* of high value for plant breeding (Jarvis *et al.*, 2005) or collecting *Jatropha curcas* in various ecogeographical areas (Sunil *et al.*, 2008). GIS approaches have also identified biases in the collection of crop wild relatives of *Solanum tuberosum* (Hijmans *et al.*, 2000). Other studies have provided information on the distribution of crops or their wild relatives and helped to find areas with rich or abundant populations (Hijmans & Spooner, 2001; Ravikanth *et al.*, 2002). More recently an optimized germplasm collecting method, based on spatial and ecogeographical gap analysis and focused on improving the representativeness of an existing germplasm collection of *Lupinus* crop wild relatives, has been proposed by Parra-Quijano *et al.* (2012b). Another interesting example is the project, currently under way, to create a gene bank of the Annonaceae family in Colombia through collection of germplasm supported by GIS, ecogeographical maps and SDMs (Parra-Quijano, 2009).

These methodologies have also been applied to improve the ecogeographical representativeness of *ex situ* collections. Such is the case of *Trifolium spumosum* (Ghamkhar *et al.*, 2007) and several species of *Lupinus* (Parra-Quijano *et al.*, 2008). This kind of representativeness is based on the ecogeographical characterization of germplasm collecting sites. Other ecogeographical characterizations of germplasm have been performed with the aim of creating core collections of species such as *Sorghum bicolor* (Grenier *et al.*, 2001), *Manihot esculenta* (Lobo Burle *et al.*, 2003), *Trifolium spumosum* (Ghamkhar *et al.*, 2008), *Lupinus* spp. (Parra-Quijano *et al.*, 2011a) or *P. vulgaris* (Parra-Quijano *et al.*, 2011b). For the *P. vulgaris* case, the ecogeographical core collection was positively validated in terms of representativeness using phenotypic data (Parra-Quijano *et al.*, 2011b). On the other hand, ecogeographical characterizations of germplasm collections have also been performed with the aim of gaining greater knowledge on the biogeography of the target species. This is the case of those carried out with wild species of *Arachis* (Ferguson *et al.*, 2005), *Trifolium* (Bennett & Bullitta, 2003) or cultivated varieties of *Zea mays* (Ruiz Corral *et al.*, 2008).

GIS are also useful for documenting *ex situ* collections. They have been used to obtain geographic coordinates from the description of sites or improve georeferenced information of passport data (Guralnick *et al.*, 2006). Several projects are currently aimed at including ecogeographical information in documentation systems through the Internet, all of them are in progress. One example is the SIERFE initiative (*Ecogeographical Information System for Spanish Plant Genetic Resources*). The objective of SIERFE is to provide the Spanish National Inventory of Plant Genetic Resources with a web-based catalogue where germplasm can be selected based on ecogeographical criteria by applying filters to the passport and ecogeographical data of the collecting sites. This service will be available for users in 2012 (E. Torres, personal communication). Other example but at the global level is the GENESYS project (http://www.genesys-pgr.org), a web catalogue which includes bioclimatic variables from WorldClim project (http://www.worldclim.org) for georeferenced accessions from Consultative Group on International Agricultural Research (CGIAR) (http://www.singer.cgiar.org), Agricultural Research Service of the United States Department of Agriculture (ARS-USDA) (http://www.ars-grin.gov) and EURISCO (http://eurisco.ecpgr.org/home_page/home.php) databases.

The development of DIVA-GIS (Hijmans *et al.*, 2001) has been an important milestone for the plant genetic resources community. In addition to the typical utilities of a GIS, this software has specific tools that allow easily to create richness maps, to select areas for *in situ* conservation or to generate EcoCrop models. DIVA-GIS has been continuously updated to include new tools such as some SDM algorithms or facilitate the management and use of ecogeographical variables. To a large extent, the progress and dissemination of

GIS and ecogeography in the area of plant genetic resources is due to the availability of this kind of tools, which are not only useful for research but also for capacity-building and teaching activities.

Although the improvements mentioned above refer to applications of ecogeography and GIS in the conservation of plant genetic resources, progress is also being made in the use of genetic resources. A technique known as FIGS (focused identification of germplasm strategy) has recently been developed (Endresen, 2011; Mackay, 2011). Its aim is to select appropriate germplasm for genetic breeding of cultivars based on the study of ecogeographical patterns (Endresen, 2010; Endresen *et al.*, 2011; Bari *et al.*, 2012). The FIGS methodology is based on the relationship between these patterns and the occurrence of certain phenotypes/genotypes of interest in genetic breeding as trait donors. The FIGS methodology has similarities with the creation of ecogeographical core collections; yet, although the latter are designed to provide an accurate representation of ecogeographical variability for conservation purposes, the FIGS selection need not to be representative of the original collection. Bhullar *et al.* (2009) used the FIGS methodology in wheat germplasm collections and obtained excellent results in terms of efficiency in the selection of germplasm with resistant traits to powdery mildew, a serious and limiting disease in some cultivated areas.

Future prospects and final remarks

GIS and ecogeography have several applications for the collection, conservation and efficient use of plant genetic resources (see Guarino *et al.*, 1999; 2002). Some of them have been considered but not developed yet. One of them is to determine the most suitable sites for the regeneration or propagation of germplasm depending on the adaptive characteristics of the species. This may be a key factor in reducing genetic erosion during regeneration or propagation, preventing the change of allele frequencies or the disappearance of traits caused by non-adaptation of some individuals from the population. It is also important to ensure greater use of these tools in on farm *in situ* conservation programmes.

Besides promoting full development or application of ecogeography and GIS, it is important for these tools and their associated methodologies to reach the users that need them most: national programmes for plant genetic resources in developing countries. Research teams are currently working actively on these issues in the United States (National Genetic Resources Program, ARS-USDA), Australia (Centre for Legumes in Mediterranean Agriculture, University of Western Australia), Spain (Universidad Politécnica de Madrid — Centro Nacional de Recursos Fitogenéticos/Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria — Universidad Rey Juan Carlos) and some centers of the CGIAR (especially in the International Center for Tropical Agriculture, CIAT). Independent efforts involving use of these tools are also sporadically made in countries such as Brazil, China, India, Mexico or Colombia (Lobo Burle *et al.*, 2003; Yawen *et al.*, 2003; Ruiz Corral *et al.*, 2008; Sunil *et al.*, 2008; Parra-Quijano, 2009). Yet, in spite of the quality of some of these projects, they are clearly insufficient. In developing countries, national programmes for the conservation and use of agrobiodiversity lack staff with enough training to apply these technologies. This even applies to developed countries in some cases. Paradoxically, the technologies that support the developments mentioned above are very inexpensive and easy to apply. The highest cost they imply is that of training the staff, since little equipment and expendable material are necessary. Still, capacity-building costs are recovered very fast, since GIS and ecogeography are not only applicable to plant genetic resources but also to plant breeding, precision agriculture, environmental conservation, rural development, and so on. Therefore, a person with the right training in GIS and ecogeography can support projects and studies in various areas of agriculture.

Finally, a considerable increase in the use of GIS and ecogeography in conservation and sustainable use of agrobiodiversity is expected in the present decade, particularly as regards the challenges implied by global climate change for agriculture (Hijmans, 2003; Jones & Thornton, 2003; Jarvis *et al.*, 2008). Moreover, the importance of the environmental component in explaining the phenotype should continue to grow with an increase in the number of studies on adaptation of crops and wild crop relatives. The abiotic aspect of adaptation is currently the subject of most studies because of the abundance of this kind of variables available for GIS analysis. In the future, the greater availability and quality of biotic information will lead to more detailed analyses of the biotic aspect of adaptation, and it will be possible to scientifically assess the influence of farmers on the ecogeographical patterns of cultivated plants.

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