Using networks in plant disease diagnosis

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Abstract

Nowadays, hundreds of plant clinics are available for smallholder farmers especially in developing and less-developed countries in order to improve the yield and quality of agricultural products. Several investigations have been carried out to study the role of plant clinics as diagnostics and advisory centres in agricultural extension. However, it seems that there is no comprehensive study demonstrating the role of plant disease diagnosis networks and plant clinics in the development of the farmers' agricultural knowledge. This knowledge can cover a general understanding of integrated nutrient and pest management programmes, principles of agronomy, and simple disease diagnosis methods. In this review paper, the concept of the plant clinic is introduced and then the services which a plant clinic can provide to the farmers are investigated. Criteria for assessing the performance of plant clinics are reviewed to obtain an appropriate and reliable methodology to evaluate the efficiency of these clinics. The characteristics of successful plant diagnosis networks in collaboration with farmers and other entities are presented. Finally, several national and international plant diagnosis networks are introduced and their impact on global agricultural extension is discussed.

Keywords: Plant disease diagnosis networks, plant clinics, clinic services, developing countries, smallholder farmers

Review Methodology: Several information databases, including Scopus, Google Scholar and CAB Abstracts were used in this review paper. Keyword search terms used included: plant clinics, plant disease diagnosis networks, The National Plant Diagnostic Network and The Global Plant Clinic.

Introduction

From the beginnings of agriculture, farmers have realized that it is easier to solve their farming problems through consulting other farmers. This tradition has continued and no one can deny the influence and importance of intellectual cooperation in agricultural applications. The problems which usually occur during the maintenance and harvesting require complete attention of the farmers. These problems may change over time mostly because of climate change [1–4], environmental pollution [5, 6] and pathogen evolution [7–10]. If farmers cannot solve the problem using their own knowledge or experience, consulting an expert will be necessary.

Early detection and elimination of plant diseases in farmlands is important not only for improving the agricultural yield and economic benefits of the farmers, but also for food security [11, 12], environmental safety [13], mycotoxin elimination [14] and preventing endemic pathogens from becoming invasive species. This has resulted in the development of national and international plant disease diagnosis networks by governments and private sector all over the world [15, 16]. Plant clinics are the smallest elements of these networks, which are usually located in rural areas to interact directly with farmers and plant growers.

Although the importance of plant disease diagnosis networks and their plant clinics in sharing valuable information between agricultural scientists and farmers is investigated in several studies, there is little information about what kind of farm problems can be treated by these networks. The objectives of this review are: (a) to

investigate the role of the plant clinics in agricultural extension; (b) to study the useful services provided by plant clinics for farmers; (c) to review available criteria to evaluate the performance of plant clinics; and (d) to introduce some successful national and international plant disease diagnosis networks.

Concept of Plant Clinics

Except traditional techniques, which are usually done using naked eye, other plant disease diagnosis methods need particular instruments and expert operators. Smallholder farmers, especially in developing and less-developed countries, generally work on small farmlands inherited from their ancestors. In this situation, implementation of complex and expensive laboratory or in-field plant health diagnosis methods by farmers seems to be impossible. Even traditional techniques need some experience and expertise which not all farmers are able to carry out. Therefore, global efforts have been made to establish national or international organizations for cooperation with growers to achieve three important goals: increasing agricultural yield, food security and environmental safety. These organizations are widespread networks that consist of several linked elements. In this section, plant clinics as the smallest elements of these networks are investigated.

Ridings [17], in his pioneering research, revealed the role and prospects of plant clinics for the first time. Then, several studies tried to describe the concepts of newly-introduced expressions such as 'diagnostic services', and 'plant clinics' [18]. According to the literature: 'plant clinics are meeting places where local plant experts – plant pathologists and agronomists help farmers struggling with plant pests and diseases'.

The first efforts to establish plant clinics as cooperation centres with farmers to identify emerging pathogens in farmlands took place in North Carolina, Florida, Georgia, Indiana, Delaware and Hawaii [18]. Major activities of plant clinics during the last four decades can be summarized as follows: (a) to provide reliable, accurate, and fast disease diagnosis for farmers and agro-industry agents; (b) to give useful advices to smallholder farmers who have difficulties facing with bacterial, viral, fungal disease or unknown stresses in their farms; (c) to train local phytopathologists, part-time volunteers, and graduate agricultural students to create expert human resources for better cooperation with farmers; (d) to record disease occurrences in a geographical region and evolution of pathogens in specific time periods, and (e) to share information internationally either by communication with other plant clinics or by publication in scientific phytopathology journals.

Although the main role of plant clinics lies in diagnostics and advisory, the activities of these clinics emphasize working more closely with growers, farmers and organizations involved in promoting agricultural production [19].

Early detection and accurate disease diagnosis are of important tasks, which should be carried out by plant clinics. This may address the important role of scientists who have expertise about climate changes and ecosystem along with phytopathologists in plant clinics. To minimize the ultimate impacts caused by biological agents in an agricultural region, early detection by plant pathologists seems to be essential once the pathogen has become established or disease has been initiated [20]. A time delay between pathogen establishment and disease diagnosis and implementation of appropriate procedure increases the possibility of wide spreading of the pathogen. Therefore, early disease detection is an applicable solution to keep both the severity of the disease and the spread of the pathogen to a minimum level. On the other hand, accurate disease diagnosis is the most critical step in minimizing the negative impacts resulting from disease outbreaks [20]. Several studies have shown that an accurate diagnosis of plant diseases should have low false negatives and low false positives, similarly to other evaluation processes. False negative means that there are some diseases that clinics cannot detect because of errors in diagnostics protocols or human errors while false positive means that clinics report some plant diseases that have not actually occurred. Both these errors are unacceptable and can result in a major waste in money and time.

Diagnosis of the trends of inhibition or development of the detected plant diseases during the implementation of appropriate procedures is also essential. It is said that diagnostic support is critical throughout the entire response and recovery effort. If the disease is an epidemic, the growers will rapidly face a disease expansion phase, which may damage a major proportion of agricultural products. Some researchers have suggested that conduction of a survey to delimit the affected area after an incursion or a disease outbreak is useful [20].

The Role of Plant Clinics in Integrated Nutrient and Pest Management

Two important duties which can be provided by plant clinics are integrated pest management (IPM) and integrated nutrient management (INM) [19]. Plant diseases caused by nutrients deficiencies and pests have been reported as the main reason of yield reduction in agricultural fields worldwide [21]. Among different types of plant protection methods, pesticides are usually considered as the basic tools for managing plant pests. Although pesticides and herbicides play a crucial role in protecting plants from invasion of insect pests, diseases and weeds, their indiscriminate and unmanaged use can be undoubtedly responsible for health hazards to humans, domesticated and undomesticated useful animals, the environment and natural resources. The residues of these chemicals can be accumulated in soil and water and cause serious damages in ecosystem [22]. In order to reduce serious hazards through the use of

Table 1 The role of plant clinics in implementation of IPM and INM programmes

IPM programmes	INM programmes
Ecologically sound combination of available pest suppression techniques	Significant reduction of use of fertilizers
Keeping pest population in an agricultural region below economically damaging levels	Training and extension of applicable methods for organic agriculture
Rapidly and reliably establishment of the nature of any possible cause of diseases in the crop	Periodically checking the salinity of agricultural soil in the outreached area
Providing the basic identification services encompassing all possible causes for ill-health, either parasitic or non-parasitic	Highlighting the importance of food bio-security especially in developing countries
Supplying information on pest and disease occurrence and spread	Assisting the regulatory agencies to share data about the usage of chemical and inorganic fertilizers in agricultural fields
Highlighting field problems for research	
Records on pests and pathogens and the losses they cause	
Tuning pest management recommendations to local conditions	
Reducing dependence on pesticides	

pesticides in agricultural fields and to prevent ecological disruption and making pest control cost-effective and ecologically sound, IPM programmes have been emerged as an applicable strategy to utilize reliable and efficient pest control methods.

The importance of IPM programmes was first revealed internationally in the 1990s [19]. Since then, to minimize the hazards of pesticides, there has been growing awareness of the need to reduce the consumption of pesticides worldwide. Although the reasonable use of chemical pesticides is not forbidden in IPM, it has become strongly associated with biological control in practice. Since modern pesticides developed by responsible biological companies are more environment-friendly, it would be appropriate to use biocontrol agents instead of chemical pesticides.

INM refers to the maintenance of soil fertility and of plant nutrient supply at an optimum level for sustaining the desired productivity through optimization of the benefits from all possible sources of organic, inorganic and biological components in an integrated manner. INM programmes try to improve nutrient use efficiency in the plants. Table 1 shows the role of plant clinics in implementation of IPM and INM programmes.

Much research has shown that most of plant growth problems may be due to abiotic factors such as soil conditions and lack of nutrients, cultural factors or climatic factors including storm, hail, excessive rain or drought in one hand and biotic factors as parasitic pest organisms such as arthropods, nematodes, disease-causing microorganisms or weeds on the other hand [23, 24]. Sometimes, when the crops become weak due to inappropriate treatments, the interaction of these factors may cause serious problems in agricultural fields. In this condition, farmers are faced with complex decision-making situations which the decision can affect the agricultural yield. The role of plant clinics in preparation of valuable local information stated in Table 1 helps farmers to improve their decision-making.

For years, IPM projects have been implemented by agricultural organizations, plant clinics and local governments [25]. Studies show that these programmes have resulted in significant successes especially for individual pest problems (e.g. insect pests of rice in Indonesia) by reducing pesticide use and increasing incomes. However, according to qualitative research, the wider impact of these programmes such as country-level strategies has been less impressive [26–28].

Plant Clinic Services

This section is dedicated to the services, which plant clinics can provide to smallholder farmers.

On-site services

Each of plant varieties, species, genera and families has a vast diversity of pathogens, which can cause a wide set of diseases having particular symptoms, dynamics and host specificity. Growers, especially in less-developed and developing countries, are not usually familiar with these symptoms and therefore, it will be necessary for them to consult plant clinics. Particularly, farmers are often faced with complex decision-making under unstable environmental and marketing conditions.

Plant experts in plant clinics usually spend a part of their time answering the questions about plant diseases asked by farmers who come to the clinics in person. Plant clinics should be located in easily accessible regions in rural areas with a prominent name in regional language, which signifies the concept of plant hospital to the farmers [20].

Clinics have to be farmer-centric and local farmers with different financial situations should be welcomed to use on-site services of plant clinics. The clinic staff are mostly diagnosticians and advisors, including well-experienced pathologists, entomologists and agronomists who provide diagnosis and prescription for various plant diseases, insects, weeds and mineral deficiencies and toxicities detected for the plant samples, which farmers bring to the clinics. Table 2 shows the expertise which need to be provided by plant clinics and their functionalities.

In addition to diagnostics, clinics have an on-site responsibility of educating illiterate and inexperienced farmers about pest diagnosis and management, teaching students as

Table 2 The expertise that plant clinics need to provide

Expertise	Functionality
Plant pathology	Diagnosing diseases and disorders visually on the basis of symptoms and signs having in-depth knowledge of symptoms
Entomology	comprehensive knowledge about pesticides, choice of fungicides, compatibility with other pesticides and resistance management
Agronomy	Having a knowledge of plant breeding, plant physiology and soil fertility

short-term programmes in summer, informing farmers about bioterrorism and its neutralization techniques, promoting IPM to minimize the use of pesticides, monitoring pest/diseases distribution/outbreak and organizing plant health booths in agricultural fairs [20, 29].

Sometimes, plant clinics contain laboratories, which provide traditional and intermediate plant diagnostic methods for early detection of possible diseases. The diagnostic tools usually include high-resolution microscopes, laminar-flow, enzyme-linked immunosorbent assays, polymerase chain reaction (PCR) tests, lateral flow devices and so on. Although advanced methods such as bio-electronic noses and tongues are more reliable compared with intermediate diagnostic protocols, they need expensive biochemical instruments and expert biochemistry scientists and therefore, they are rarely provided by laboratories of plant clinics.

The laboratories of plant clinics should provide tests for detection of bacterial, viral and fungal diseases. One of the successful experiences of plant clinics, which has attracted scientists' attention is the use of complex PCR protocols for rapid and affordable diagnosis of tomato yellow leaf curl virus, which was firstly emerged in Eastern Mediterranean in the 1960s [30].

Furthermore, there are plant diagnostic laboratories located at airports and seaports of entry to inspect plant species transferred nationally or internationally by airplanes and ships [20]. This shows that plant clinics can be equipped with precise laboratory instruments to perform appropriate protocols for investigating the quality of transferred plant species in the shortest possible time.

In-field services

Sometimes, it is necessary for farmers to have an expert advisor in their filed to detect the emergence of a particular plant disease or monitor the health situation of the field crops. Many of plant clinics all over the world provide in-field services as a farmer-friendly method to simplify the process of disease diagnosis for farmers [31]. In case of emergency, a scientific team with their portable laboratory instruments and kits come to the suspicious farm to provide a reliable solution to the farmer. Such mobile plant clinics can simply rescue the growers by providing needed health care during epiphytotic outbreaks. Mobile plant clinics with modest diagnostic tools and trained professionals may provide on-the-spot diagnosis in field condition especially during disease outbreak [32, 33].

Several studies have shown the importance of timely and accurate plant disease diagnosis in agricultural sustainability and food security [4, 34–36]. Transferring suspicious or injured plant samples from the field to the plant clinics is usually time-consuming and there is possibility of damage to the samples during transportation [37]. The fastest way for efficient prevention of emerging pathogens in vast agricultural areas is in-field service.

De Boer and López [32] demonstrated that in addition to farmers, several groups including fruit and flower importers and exporters, seed producer companies, tree orchardists, grapevine viticulturists, extension agencies, and bioterrorism prevention organizations need in-field plant services.

Portable laboratories which are mostly utilized by mobile plant clinics consist of simple immunoassay and nucleic acid-based kits [38]. In general, enzyme-linked immunosorbent assays are more developed in comparison with other serological tests in plant disease diagnosis. However, they need some laboratory-based protocols, which portable plant clinics may not able to implement these protocols using portable instruments. Therefore, lateral flow devices based on the serological specificity of polyclonal or monoclonal antibodies are emerged as a useful technique in plant disease diagnosis [39]. The proper performance of commercially available lateral flow devices in plant disease detection – especially plant viral diseases is reported by many researchers [32, 40–42]. These tests are usually carried out very fast, e.g. 10 min and hence, they are suitable for portable plant clinics. Table 3 shows some examples of disease diagnostic methods, which can be utilized by mobile plant clinics.

Online services

The advent of compact computers and high-speed internet services during the last two decades has led to major and important changes, which has resulted in the emergence of advanced techniques in most areas of science and technology. Nowadays, people can share their thoughts and information with others all over the world simply using online services. The majority of people even in developing countries can access online services using their smartphones and computers.

Table 3 Some examples of disease diagnostic methods that can be utilized by mobile plant clinics

		Example	
Diagnostic method	Diagnostic tool	Application	Reference
Serological tests	Lateral flow devices	Detection of Potato Y potyvirus and Potato X potexvirus	[40]
		Detection of Pepino mosaic virus	[41]
		Detection of Citrus tristeza virus	[42]
		Detection of *Rhizoctonia solani*	[43]
		Detection of Satsuma dwarf virus	[44]
		Detection of *Erwinia amylovora*	[45]
	Direct tissue blot immunoassay	Detection of Citrus tristeza virus	[46]
	Double antibody sandwich immunoassay	Detection of Plum pox virus	[47]
Nucleic-acid-based kits	Portable polymerase chain reaction Machines	Detection of *Phytophthora ramorum*	[48]
		Detection of Plum pox virus	[49]
		Detection of *Candidatus* Liberibacter spp.	[50]
	Loop-mediated isothermal amplification	Detection of *Candidatus* Liberibacter spp.	[51]

Online services have entered in the field of plant disease diagnosis since there is possibility that plant clinics are not always available for the farmers to visit in person. In this situation, farmers can send an image from the infected plant to the clinics which may be located thousands of miles far away from the farmer's agricultural field using online services. The image is transmitted from farmers to the computer operators of plant clinics using E-mail or websites. Then, the operator shares the image to the plant experts for consultation and finally, a decision with possible solutions will be sent to the farmer using E-mail. This is one of the plant disease diagnostic methods which Holmes *et al.* called it digitally assisted diagnosis for the first time in 2000 [52]. Delivering health care and sharing medical knowledge over a distance using telecommunication systems has been called telemedicine by several researchers [53]. The first attempts to use telemedicine as an acceptable technique for transmitting diagnosis data through telecommunication were reported in the 1960s [54]. However, the active use of digitally assisted diagnosis and telemedicine in agricultural sciences began in the 1990s [52]. University of Georgia introduced 'distance diagnostics through digital imaging' for the first time in agricultural disease diagnosis purposes [52].

Digital images of plant specimens do not deteriorate and their transit time is negligible. Therefore, speed and elimination of the undesirable effects of shipping on the samples are of the advantages of digitally assisted diagnosis. The sample deterioration is especially critical during hot summer months and long weekends when samples are exposed to high heat even during overnight shipping.

Although computer and photography equipment is changing rapidly over time, the basic functions of digitally assisted plant diagnosis has remained similar with the sequence introduced by Holmes *et al.* [52]: acquiring the image in-field or in a laboratory equipped with digital CCD or CMOS cameras, sending the obtained image through E-mail or websites, and viewing the transferred image by an phytopathologist on his/her computer.

First efforts in documentation of the use of digitally assisted plant diagnosis have shown that each laboratory equipped to microscopes, video cameras and personal computers cost approximately US$10 000 to 15 000 [52]. However, with the extension of high-quality cameras on smart cell-phones with built-in internet and navigation systems, farmers can easily and efficiently send images of their plants to the online plant clinics. Furthermore, several companies have introduced some hand-held lenses, which can convert smart phones to microscopes with magnification levels as high as 100× and more. As an example, Bodelin (TM) has introduced such portable instruments for iPhone (http://www.bodelin.com/proscope).

In 2010, a platform called integrated pest information platform for extension and education (iPiPE) was introduced as a cooperative agricultural programme supported by USDA. It provides an infrastructure with cyber-age tools, information products, and expert commentary for detection and management of thousands of endemic and exotic pests [55]. This programme enables sharing of observations while protecting the privacy of participating individuals, companies, and government agencies by categorizing pests, data, and users [55, 56]. According to Isard *et al.* [55], the iPiPE provides a number of tools and products including a cell-phone application developed for Android and iOS platforms (for in-field data collection) and a personal electronic notebook (for recording pest observations) to authorized farmers to increase the efficiency of pest scouting and on-farm decision-making. Similar to other plant pest and pathogen diagnosis systems, the cell-phone application is able to transfer the gathered data to the server and automatically make decision about pest management [57, 58].

Going public

The term 'Going Public' is an expression for public plant health campaigns, which has been recognized as a valuable

service of plant clinics especially in less-developed and developing countries [59]. It is an agricultural extension method that agronomists and plant scientists of plant clinics gather hundreds of local farmers in an office or an agricultural farm and inform them about pest management, possible pathogen attacks or extension of plant diseases [60]. Some of successful experiences in going public have been reported in literature. It has been declared that going public was useful in raising awareness against banana Xanthomonas wilt in Uganda [61] and napier grass stunt in Kenya [62].

This kind of service can simply increase the outreach of plant clinics and is certainly effective in attracting smallholder farmers' attention to these clinics. In some countries such as Bangladesh, Going Public has been recognized as a regular programme, which plant agronomists use labelled booths in marketplaces and inform people about major potato pests and diseases.

Methods for Assessment of Plant Clinic Performance

As the plant health clinics are becoming more widespread, there is an increasing need to create basic procedures to assess performance of the plant clinics' operation. To date, dozens of standards and frameworks have been developed to assess performance and quality of human and animal health services [63–67]. The first efforts to implement an applicable quality assessment framework for plant clinics have focused on the quality assurance of diagnostic laboratories through standard operating procedures and proficiency testing [4, 68, 69]. Nowadays, it seems that functionalities of plant clinics have been extended due to the international collaborations among plant clinics in sharing findings and opportunities in documentation of experiences. Therefore, new parameters have to be considered to evaluate the quality and performance of plant clinics.

Danielsen and Kelly [69] have introduced several criteria for quality assessment of the plant clinics. To do this, they presented an appropriate framework for quality assessment and monitoring based on empirical evidence and iterative learning between plant clinic staff and supervisors in less-developed and developing countries including Bangladesh, Vietnam, Nicaragua, Bolivia and Uganda during 2008–2009. Their proposed framework has some functional aspects according to the 3-day workshops, which were organized by Global Plant Clinic (GPS)-CABI. This programme was held for the first time in Bangladesh in 2008 and later in 2009 in other developing countries associated with local organizations.

According to these workshops, the monitoring system for plant clinics followed a four-step procedure called plan-do-reflect-act sequence, which was applied in human and animal clinics earlier. The study of this programme reveals that plant clinics' quality measurements are based on at-most 12 quality criteria: technical quality, timeliness, feasibility of advice, organization, location, equipment/material, scale/outreach, accessibility to inputs, regularity and reliability, response to specific demands and safety of advice [69]. The importance of each criterion is comprehensively discussed by Danielsen and Kelly [69]. Researchers in a recent study have presented a similar framework but in a different categorization [70]. They introduced the quality criteria in three categories: plant health system components, plant clinic performance indicators and quality of plant healthcare. It seems that in the newer framework, some criteria such as financing and funding attributes are considered which are not embedded to the earlier framework. However, it should be noted that all the quality assessment frameworks have significant overlaps [71, 72]. They also introduced five methods to monitor these criteria for plant clinics: frequent monitoring visits, analysis of plant clinic registers, regular follow-up meetings with plant experts especially in scientific conferences, field visits and feedback from farmers. According to them, several functional parameters can be obtained through monitoring visits: quality of diagnosis, quality of advice and documenting and sharing the findings. It seems that a proper visiting team consisting of scientists and experienced members can record valuable data about the performance of plant clinics. Several studies have shown that data obtained from the analysis of plant clinic registers have resulted in useful information in plant clinic assessments [73, 74]. Furthermore, in some cases, plant experts publish their findings and share them in scientific journals and/or periodical events (e.g. workshops and conferences) [75].

Results of plant, animal and human clinics quality assessments in different countries have shown that staff shortage, inadequate technical and scientific skills, low motivation and retention of clinic members, lack of positive supervision, and inter-professional exchange, as well as poor management, are of the most general factors and limitations, which negatively affect the performance of these clinics all over the world [65, 76]. In addition, other limitations such as low quality of plant health service delivery and governance are also monitored by researchers in plant clinics of Africa [70].

Emergence of Plant Disease Diagnostic Networks

Plant clinics are the smallest elements of plant disease diagnosis networks. Academic institutions, universities, plant companies, local governments and international organizations, which have cooperative activities in the field of plant disease diagnosis, are other elements of these networks. In recent years, several national plant protection networks have been developed in Europe to standardize diagnostic procedures and expedition of the adoption or adaptation of new diagnostic techniques responding to the concerns about agricultural biosecurity [4, 16]. Similar networks can be seen in Asian and

Table 4 A summary of some of the national and international plant disease diagnosis networks

Network	Coverage	Reference
Global Plant Clinic-Centre for Agricultural Bioscience International (GPC-CABI)	More than 100 plant clinics in ten African, seven Asian, four South American and one Central American countries	[59, 73, 75]
National Plant Diagnostic Network (NPDN)	USA	[78, 79]
International Plant Diagnostic Network (IPDN)	Central America, East and West Africa	[4, 82]
Pest Information Platform for Extension and Education (PIPE)	USA	[83]
Mediterranean and European Plant Protection Organization (MEPPO)	15–50 European member countries	[15, 84]
European Union virtual biosecurity framework	A virtual biosecurity research and diagnostic network for Europe	[85]
Foundation for Technological Development of Agriculture, Livestock and Forestry of Nicaragua (FUNICA)	Nicaragua	[86–88]
Plant Health Australia (PHA)	Online plant biosecurity toolbox available for Australian and Southern Asian farmers	[4]
Plant Pest Management Network (PPMN)	Taiwan	[4]
XSGrowth plant health clinic	An online diagnosis system in India	[19, 89]
National Horticulture Mission	More than 120 plant clinics in India	[19, 90, 91]

African countries, which try to provide a confidant centre for smallholder farmers to troubleshoot their possible problems.

The concept of plant health network is not new. The American Phytopathology Society as a pioneering scientific organization introduced the functions and application of a plant disease network dealing with plant health emergencies almost 100 years ago [77]. First efforts to establish an integrated plant diagnosis network in the USA was commonly done by the Land Grant University and the United States Department of Agriculture in 2002, which resulted in the creation of the National Plant Diagnostic Network in 2002 [78, 79]. Due to the increasing needs to expert agricultural consultants in less-developed and developing countries, plant diagnosis networks have been established since 2003 in a number of countries across Africa, Asia and Latin America [80, 81]. Some of the national and international plant disease diagnosis networks are summarized in Table 4.

Some Successful Experiences of Plant Disease Diagnosis Networks

This section is dedicated to a brief introduction of effective plant disease diagnosis networks all over the world.

GPC-CABI

The GPC (also called PlantWise from 2012) is an association of Centre for Agricultural Bioscience International, UK [4]. GPC has aimed to provide cost-free or inexpensive plant diagnostic and advisory services for smallholder farmers in more than 20 less-developed and developing countries in Africa, Asia, South America and Central America with a clear motto: 'working more closely with farmers' [59]. To do this, GPC has piloted and organized dozens of in-field plant clinics in these countries since 2001 [59, 92].

The clinics belonging to GPC usually offer reliable advice on routine plant health problems affecting any field or greenhouse. To do this, trained agronomists and extension workers are available full-time or part-time for farmers to consult with as 'plant doctors'. Plant doctors either can provide control recommendations as prescriptions or collect data from agricultural fields to share valuable information with colleagues and other plant networks through scientific articles, annual reports, weblog posts and so on. It should be noted that plant doctors are not necessarily graduate scientists: sometimes, they have only basic knowledge on disease symptoms and plant health management, which allows them to diagnose and give applicable advice on common plant health problems. In this situation, they have limited ability in detection and diagnosis of complex and unfamiliar field problems [69, 75].

Studies have shown that the direct advice given by plant doctors about plant problems can result in a reduction of losses due to the quick attention and action by farmers and minimization of pesticide and fertilizer use [4]. To date, the GPC has done some valuable activities especially in developing countries such as increasing awareness on new diseases by collaboration with regional agricultural institutes and international organizations [93] and organizing farmer field schools [94] which have inspired other countries to set up similar plant clinics [80].

In 2000, the first plant health clinics began providing service to smallholder farmers in Bolivia, which were inspired with a key event: establishment a plant lab organized by CIAT (Centre for Tropical Agricultural Research) [95]. In 2003, the services provided by these clinics increased with the help of GPC and PROINPA (Promotion and Research of Andean Products) [55]. A detailed timeline of key events in the history of plant clinics in Bolivia is presented by Bentley *et al.* [95]. Studies show that over 6000 farmers consulted these plant clinics

between 2000 and 2009 [96]. Bentley *et al.* [96] carried out a research study to investigate the impact of plant clinics on net income and pest management of Bolivian farmers. They showed that plant clinics are not just for poor farmers to consult with, but farmers with good economic status have visited these clinics frequently. Furthermore, following the clinics' advice by farmers has resulted in an increase in their incomes, which can be interpreted as an appropriate motivation to extend plant clinics especially in developing countries.

Since 2005, GPC has established and organized many plant clinics in Nicaragua [97]. In total, Nicaragua owns the most extensive plant clinic operations out of all the countries where the GPC manages plant clinics [59]. This is a good example of international collaboration among GPC, academic universities and country-level organizations. Foundation for Technological Development of Agriculture, Livestock and Forestry of Nicaragua (FUNICA), National Commission for the Teaching of Agriculture (CNEA), Central American Integrated Pest Management Programme of Zamorano University (PROMIPAC), Nicaraguan Institute of Agricultural Technology (INTA), National Autonomous University of Nicaragua León (UNAN León) and National Technological Institute (INATEC) are some of the organizations which GPC has been partnered with to implement plant clinics in Nicaragua [88].

In 2006, GPC piloted several plant clinics in Uganda in collaboration with Ugandan Ministry of Agriculture, Animal Industries and Fisheries (MAAIF) and other organizations [98]. Studies have indicated that foster system strengthening is one of the most important programmes in these clinics [70]. In 2008, World Vision International Nepal (WVIN) established plant clinics with the help of GPC [74]. GPC piloted plant clinics in Sierra Leone in the same year [59].

GPC is now recognized as the pioneering network in development of an appropriate framework for quality assessment of plant clinics [69]. This framework has been used to assess the performance of several plant networks such as FUNICA [69]. Furthermore, CABI directs an expert diagnostic and advisory service where farmers and plant doctors all over the world can send unhealthy plant samples (patients) to the UK for disease diagnosis [59].

National plant diagnostic network (NPDN)

According to the literature, NPDN has been established with certain objectives in the USA in 2002: to promote early detection of plant pathogens and pests by training first detectors, to ensure accurate and rapid diagnostics by investment in diagnostic infrastructure and the training of diagnosticians in each state, and to facilitate timely and secure communications among diagnostic laboratories and regulatory agencies [20, 78, 99]. The most important difference between NPDN and established networks in developing countries is the use of more educated plant doctors to handle modern diagnostic techniques. Another difference is that all diagnostic data gathered by all clinics are collected centrally in a scientific repository at a university for further data analysis and decision-making purposes [4].

Agronomists and plant biologists in NPDN try to develop new diagnostic methods and collaborate with researchers nationally and/or internationally to improve protocols and techniques to control regulatory plant diseases. NPDN has developed some websites to make it possible for researchers in clinics to have internet-based videoconferences for timely sharing of findings. By using specific programmes such as improving through the promotion of training and standardization opportunities, NPDN tries to increase the experience of plant scientists in plant clinics.

Plant scientists in NPDN have shown that new plant disease diagnostic technologies such as DNA and protein-based methods can be used in clinic laboratories if less educated plant doctors learn how to implement these techniques [78]. Furthermore, charging farmers fees for experiments reduced the number of samples submitted to the clinics' laboratories [78].

NPDN has been successful in collaboration and cooperation due to the strong relationships with a variety of smallholder farmers and government-level agencies, which has resulted in development of reliable plant clinics all over the 50 states and all the US territories [100]. Many entities contribute to the NPDN's biosecurity infrastructure, including federal, state and local agencies. The responsible communication of NPDN with other networks and academic centres makes it possible to share valuable information about new detected pathogens and plant diseases throughout the USA [100, 101].

International plant diagnostic network (IPDN)

With the increase of international collaborations due to the advent of high-speed telecommunication systems and internet-based social networks, international plant networks have emerged as a way to increase the performance of local networks especially in developing countries. In 2005, IPDN was initiated by the USAID (United States Agency for International Development) to develop local capacity for plant health management and disease diagnosis using communication and data-sharing networks [4, 102, 103] on the one hand and training basic and advanced diagnosticians to recognize and report regular and new diseases on the other. As an example, IPDN reported the source of occurrence of tomato's wilt disease in Benin for the first time [104].

IPDN has developed three regional programmes: sustainable development in Central America (central lab located in Guatemala), East Africa (central lab located in Kenya) and West Africa (central lab in Benin). These laboratories can share questions, problems and solutions with other linked clinics and laboratories in other

countries. A scientific database has been considered for this network called CIMS/DDIS (Clinic Information Management System/Digital Distance Identification System) located in the University of Florida, which all these laboratories have access to [105]. To do this, a website is established to confidentially share unhealthy plant images with plant experts.

Summary and Future Perspectives

Experiences from all over the world, especially in developing countries, have revealed that advice for smallholder farmers should come from modern agricultural extension to obtain sustainable agriculture. Several national and international networks have been established to reduce the problems, which farmers may be faced with in their agricultural fields. To date, studies have shown that these networks have successfully directed and managed plant clinics which can provide useful advice to farmers with the lowest price or in many instances, free of charge. Nowadays, plant clinics give value for money and deliver defined service to the farmers in order to become a recognized community entity. In this regard, from individual clinics to global-level networks have worked closely with farmers to improve the yield and quality of agricultural production. Furthermore, plant diagnosis networks have been useful in food security and environmental issues by implementing IPM and INM programmes, especially in developed countries.

With the advent of new internet-based technologies, some networks and their clinics can share data and information timely through toll-free-telephony or free social networks providing online-advice, enhancing farmers' knowledge-bank using innovative training/print/electronic devices. Plant networks have got a long road ahead to be recognized as a reliable and confidant service centre by smallholders and traditional farmers either in developing or less-developed countries. It is the duty of governments and country-level organizations to introduce these networks to farmers and regulatory entities to achieve sustainable agriculture with the highest income rate all over the world.

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