Global Plant Health Assessment

An international peer-reviewed evaluation of the state of plant health across ecoregions of the world, and of the effects of plant disease on ecosystem services

ISPP INTERNATIONAL SOCIETY FOR PLANT PATHOLOGY
OECD

Global Plant Health Assessment

An international peer-reviewed evaluation of the state of plant health across ecoregions of the world, and of the effects of plant disease on ecosystem services

Edited by Laetitia Willocquet, Manjari Singh, Sonam Sah, Federica Bove, Serge Savary, and Jonathan Yuen

The Global Plant Health Assessment (GPHA) is an initiative under the *aegis* of the International Society for Plant Pathology (ISPP)

Published by Jonathan Yuen (jonathan.yuen@telia.com) and Laetitia Willocquet (Laetitia.Willocquet@inrae.fr)

First Edition:

ISBN (epub) 978-91-988233-0-1

ISBN (pdf) 978-91-988233-1-8

Acknowledgments

We are grateful to the Executive Committee of the ISPP for its continuous support over this 3-year effort. The Global Plant Health Assessment is grounded on the volunteer contributions of a large community of colleagues (see Table 1 in Section Background and Overall Approach to Assessing Global Plant Health). Financial support to organise the GPHA International Workshop and Conference held in Toulouse in October 2021 in Toulouse was provided by the OECD-CRP (Co-operative Research Programme: Sustainable Agricultural and Food Systems), by direct support of GPHA participant's institutions, and a small complement from INRAE. We wish to thank Ms. Janet Schofield (OECD-CRP Office, Paris) for her kind support and availability as this OECD-CRP project was materialising. We wish to thank Dr. Arnaud Reynaud (Director) and Ms. Aline Couratier (Administrative Assistant) of the Toulouse School of Economics - Research, Toulouse, Ms. Stéphanie Risser (Events Coordinator, TSE, Toulouse), and Ms. Sophie Collet (Administrative Assistant, IGEPP-INRAE, Rennes) for their kind and efficient support in organising these events.

The Scientific Secretariat of GPHA (L Willocquet, M Singh, S Sah, F Bove, S Savary) is supported by the GB Pant University of Agriculture & Technology, Pantnagar, India, and by the Università Cattolica del Sacro Cuore, Piacenza, Italy, which are gratefully acknowledged.

Credits and description of icons

representing Plant Systems on the cover page as well as on the section headings of reports for: Cereals; Roots, Tubers, Banana & Plantain; Perennial Crops; Peri-Urban Horticulture and Household Gardens; Urban Vegetation; and Forests.

All icons were drawn by Serge Savary, and are derived from copyright-free photos, mainly Wikipedia.

Description of icons for plant systems: **Rice**: Ifugao Sculpture, Philippines. The Louvre. **Wheat**: Demeter, goddess of harvest and agriculture, on a silver coin, 4th century BC, Middle-East. Demeter also presides over the sacred law, and on the cycle of life and death. **Maize**: Maya maize god. He also is the patron of scribal arts, which he invented. Classic Period (200-900 AD). **Potato**: Axomamma, goddess of potato. Inca mythology. **Cassava**: Head from Ife (Nigeria): 14th-15th century AD, bronze. Height: 36 cm. **Banana and Plantains**: Kifwebe mask; wood. Luba Kingdom, Democratic Republic of Congo. Royal Museum for Central Africa, Tervuren, Belgium. **Grapevine**: Dionysos in a ship, sailing among dolphins. Attic black-figure kylix, ca. 53 B.C. Vulci, Italy. **Perennial fruits and nuts**: Reputed descendant of Newton's apple tree at Trinity College, Cambridge. **Coffee**: Coffee (*Coffea Arabica*) originates from Ethiopia and the southern tip of Arabia, then the Saba Kingdom and later Arabia Petrae. Coffee was drunk in Arabia long before being known to Europe. Sidamo coffee is one of the best in the world. **Orange**: O Meu Pé de Laranja Lima (My sweet Orange Tree) was written by José Moro de Vasconcelos in 1968, in Brazil. **Peri-urban horticulture and household gardens**: Annapurna, Hindu goddess of food and nourishment. Anna means "food"; pūrna means "full, complete and perfect". **Urban trees**: The Pulitzer Fountain is an outdoor fountain located in Manhattan's Grand Army Plaza in New Yor, USA. **Softwood forests**: *Pinus contorta* needles and cones. Background: totem pole in Ketchikan, Alaska, in the Tlingit style of Pacific North-West. **Oak forests**: *The Big Oak*: Painting by Gustave Courbet (1843). **Eucalypts**: Aboriginal bark painting. Eucalypts were important ceremonial elements for Australian aborigines. **Amazon forest**: The Izapa stela 5 features a Mesoamerican World Tree. Olmec art, 300-50 BCE. Fragment redrawn. American *ceibas* are genetically close to African *fromagers* and Asian *Kapoks*. All these trees have profound spiritual value.

Foreword for *Global Plant Health Assessment*

Jan E. Leach

President, International Society of Plant Pathology

Agricultural Biology, Colorado State University, Fort Collins, CO 80523-1177

Our planet's health is in a precarious state, and the health of our planet is undeniably linked to plants, and, of course, the health of those plants. The *Global Plant Health Assessment* initiative was the vision of an international group of dedicated volunteers who have keen knowledgeable and deep insight into the global state of plant health and its implications for the planet and humanity. The group's proposal of the initiative and this book was enthusiastically endorsed by the International Society for Plant Pathology's Executive Committee in 2019.

The *Global Plant Health Assessment* provides a snapshot of plant disease impacts on diverse plant systems in defined ecoregions. Trends in effects on ecosystem services are described for each plant system X ecoregion. All evaluations are presented using standardized rating methods, which is particularly valuable as it allows for easy comparison of impacts across systems, and provides a baseline for comparison into the future. Undoubtedly, because of the careful planning, design, execution, and review of the study, the *Global Plant Health Assessment* will be widely cited. Furthermore, it will serve as a unique and important resource to guide international policy.

The International Society for Plant Pathology is deeply indebted to the coordinators and experts who contributed to the conception and accomplishment of the *Global Plant Health Assessment*. It was a herculean effort with an aggressive timeline. It involved the coordination of over 100 plant health experts from over 30 countries. A study of this scale is unprecedented and it could not have been accomplished without the vision, planning, organization, guidance, and determination of the Coordination group and the support of the Scientific Secretariat. The *Global Plant Health Assessment* clearly meets the goals of the authors; it provides the first science-based overall assessment of plant health in diverse ecosystems globally. Congratulations and thank you!

Jan E Leach

Jan E. Leach
President, International Society for Plant Pathology

Contents

Background and overall approach to assessing global plant health

Global Plant Health Assessment context: the meaning of plants

The Global Plant Health Assessment (GPHA) is an initiative of the International Society for Plant Pathology (ISPP) involving an international, volunteered, peer-reviewed evaluation of the state of plant health across ecoregions of the world, and of the effects of plant disease on ecosystem services. The initiative was motivated by the International Year of Plant Health (IYPH, 2020), to which ISPP has contributed in various ways.

2020 was declared the International Year of Plant Health by the General Assembly of the United Nations in order to raise global awareness on the importance of plant health for humans, societies, and the world. This book reports volunteered efforts made by a community of scientists worldwide who are concerned by the global state of plant health, and by the implications of faltering plant health on the balance of world’s human-made or natural ecosystems, on the state of global food security, and on the daily contribution of plants to the beauty of our world.

Plants play a key role, globally to locally, in climate, air quality and composition, soil biophysical properties, biodiversity, landscapes, water quality, food and feed, pollution as well as the biophysical environment in our cities. Plants also are essential to human well-being as a source of beauty, inspiration, and re-creation. However, these roles are overlooked in many ways, and are taken for granted. Recognising the role of plants in human health and well-being is needed to safeguard the sustainability of Earth ecosystems.

Plant systems in the biosphere are strongly impacted by their state of health, which is in turn importantly influenced by plant pathogens. Yet, there seems to be no scientifically-grounded statements on the current state of plant health globally, or on its evolution in recent years.

Aim of the Global Plant Health Assessment

The Global Plant Health Assessment aims to provide a first time-ever overall assessment of plant health in the natural and human-made ecosystems of the world. Plant health is assessed through the functions that plants ensure in ecosystems: "ecosystem services" (Millennium Ecosystem Assessment, 2005). The GPHA assesses plant health on the basis of published, science- and fact-based, expert evaluations. The GPHA considers plant health from the angle of infectious diseases, yet addresses plant health as a whole. Its goal is an overview of the current status and trends in plant health, and their outcomes on ecosystem services: provisioning (food, fibre, material), regulating (climate, water, soils), and cultural (re-creation, spiritual, beauty).

Policies must be grounded on scientific evidence. With the Global Plant Health Assessment, we hope to produce material that would help developing policies globally and locally which would strengthen the ability to ensure plant health in a sustainable manner.

The GPHA addresses four broad types of Plant-Systems: forests, agricultural systems, peri-urban horticulture and household gardens, and urban vegetation. Each Plant-System in each ecoregion is being addressed by a small team composed of a Lead Scientist and a group of 3-4 Experts. The initiative therefore involves some 100 scientists in the world.

Overall principles and organisation of the Assessment

The Assessment has been sanctioned by the Executive Committee of the ISPP in November 2019, so that this work would be conducted under its *aegis*. The efforts underpinning the GPHA are therefore not institutional.

The conduct of the GPHA is entirely based upon volunteered contributions of international experts in the field of plant pathology, most of them, members of the ISPP. Participants to the GPHA are contributing in three different ways: to the overall coordination of the GPHA, as Lead Scientists of a given team, or as Experts involved in one of the GPHA teams.

The GPHA work is led by a **Coordination group**:

Serge Savary (INRAE, France; GB Pant University of Agriculture & Technology, India; UC Davis, USA); Didier Andrivon (INRAE, France); Paul D. Esker (PennState University, USA); Pascal Frey (INRAE, France); Daniel Hüberli (U. Western Australia); J Kumar (GB Pant University of Agriculture & Technology, and Graphic Era Hill University, India); Bruce McDonald (ETH, Zürich, Switzerland); Neil D. McRoberts (UC Davis, USA); Andy Nelson (Twente University, the Netherlands); Sarah J. Pethybridge (Cornell University, USA); Vittorio Rossi (Università Cattolica del Sacro Cuore, Italy); Pepijn Schreinemachers (World Vegetable Center, Thailand); Laetitia Willocquet (INRAE, France; GBPUAT, India).

The Coordination group is supported by a **Scientific Secretariat**: Laetitia Willocquet; Federica Bove (Università Cattolica del Sacro Cuore, Italy); Sonam Sah (GB Pant University of Agriculture & Technology, India); Serge Savary; and Manjari Singh (GB Pant University of Agriculture & Technology, India).

Lead scientists, who are lead authors of reports in this book, as well as **Experts** associated to the report writing, are listed in Table 1.

Some **key features** of the GPHA are:

- All terrestrial ecosystems in the world are considered. These are referred to as "Plant Systems", which can be human-made (such as agricultural systems, household gardens, or again, urban forests) or not (that is, ecosystems where human perturbations are limited, such as tropical rain-forests).
- Among the human-made ecosystems considered, we address: (1) agrosystems, (2) peri-urban horticulture (3) household (kitchen) gardens, and (4) urban vegetation. The Assessment attempts to address all these different forms of Plant Systems. The Assessment also considers a range of forest systems across the world, which involve varying degrees of human intervention.
- Plant health is seen through the lens of infectious plant diseases. However, because plant health is not restricted to infectious diseases, attention is also paid when appropriate to factors, biological (e.g., insects), physical (e.g., droughts, fires, and floods), and chemical (e.g., pesticides, ozone), which may influence the course of healthy life of plants.

The **concepts and guiding principles** of the GPHA can be summarised in a few points:

- The Global Plant Health Assessment is entirely based on volunteered time, mainly from members of the ISPP.
- The Coordination group is interdisciplinary, involving expertise in, e.g.: Geography, Climatology, Sociology, Environmental Sciences, Systems Sciences, and in Plant Pathology: Integrated Pest Management, Molecular Plant-Pathogen Interactions, Epidemiology, and Crop Loss Analysis. Members of the coordination group come from very different parts of the world.
- The project uses the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005) as a template in its construction and development: first, a series of Ecoregions of the world have been defined; and second, key "PlantSystems" have been identified, in each of these Ecoregions.
- For each identified [PlantSystem x Ecoregion] pair, teams have been established, involving a Lead Scientist mobilising a few (2-3) Experts.
- Each team produced a report on the state of plant health in a chosen [PlantSystem x Ecoregion]. These reports are standardised in format and size, and address a specified, limited set of questions.
- Standardisation of reports is a critical way to: (1) minimise the (volunteered) time inputs of every Lead Scientists and Experts; (2) produce homogeneous reports in their formats and sizes, which (3) enables comparisons of plant health. These comparisons may be made across Ecoregions for similar plant systems, or across plant systems within Ecoregions.
- Results of the Global Plant Health Assessment must be verifiable and transparent. Each report must therefore be grounded on scientific, published, evidence.
- The GPHA considers the health of plants from the angle of infectious diseases in their effects on plant health. It does not consider abiotic stresses. Non-infectious, biotic and abiotic factors, however, are considered as factors of infectious diseases and their consequences.
- The assessment therefore concentrates on viruses, bacteria, fungi, oomycetes, nematodes, as well as on organisms (e.g., parasitic plants) which behave (specialisation/adaptation) as plant pathogens. Vectors of plant pathogens are also full part of the GPHA.

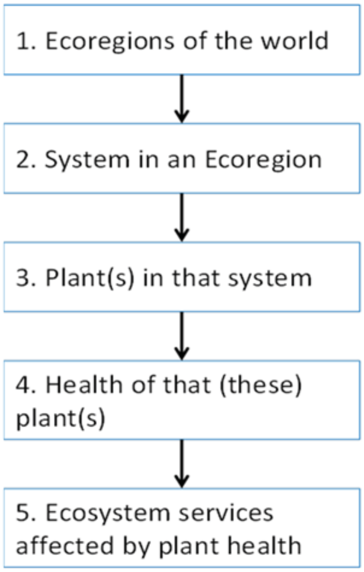

Figure 1. Steps in the Global Plant Health Assessment

Critically, the assessment considers plant health as a whole. The GPHA does not focus on individual, specific plant diseases, even though these are necessarily included in the assessment. Direct reference to specific plant disease or pathogen may occur when judged appropriate (as in the case of key diseases, major threats, or potentially grave and emerging diseases). As in the Millennium Ecosystem Assessment, plant health assessment is built from the collection of science- and fact-based expert opinions on the state of health of plants in specified plant systems within chosen ecoregions of the world.

The assessment does not attempt to address all plant species in the biosphere. Instead, the GPHA considers keystone plant species, the status of 'keystone' being assigned to plants that play a critical role in natural (including managed) ecosystems or in human-made agro-ecosystems. The approach therefore follows a series of steps as shown in Figure 1.

Recognising that plant health is an abstraction which cannot be quantitatively measured, the GPHA Project (1) is designed to produce qualitative assessments based on verifiable, published data, and (2) focuses on the consequences of plant health on ecosystem services (provisioning, regulating, and cultural), because these can be quantified.

As a result, 26 [PlantSystem x Ecoregion] reports were developed, considering 33 [PlantSystem x Ecoregion] (Figure 2), including: (1) cereal systems; (2) roots and tubers, banana and plantain systems; (3) fruit trees and grapes; (4) peri-urban horticultural systems and household gardens; (5) urban vegetation; and (6) forest systems in (a) North America, (b) Central and South America, (c) sub-Saharan Africa, (d) Europe, (e) South, East and Southeast Asia, and (f) Australasia.

Figure 2. Plant Systems assessed across Ecoregions of the world

Steps taken to develop and conduct the Global Plant Health Assessment

The conduct of the GPHA included two main groups of steps: first the conceptualisation, methodology development, and building of a network of contributors, and second the development of the reports.

Identification of Ecoregions, Plant Systems and Lead Scientists

1. The choice of Ecoregions is based on climatic and ecological environments, as well as on the social and economic context (10 Ecoregions defined).

2. Choice of PlantSystems: a selection of plant-based systems that matter most to human societies in terms of ecosystem services (8 major PlantSystems defined).

3. Prioritisation, among the (10 x 8 = 80) [PlantSystem x Ecoregion] resulting combinations, of those which are most relevant, based on human population, biodiversity, agriculture and food production, food consumption, and size of ecosystem services.

4. Within each prioritised [PlantSystem x Ecoregion] combination, identification of a reference (keystone) plant, or reference type of plants on which plant health is to be assessed.

5. Within each prioritised [PlantSystem x Ecoregion] combination, identification of a Lead Scientist who will co-ordinate the assessment of plant health in this specific [PlantSystem x Ecoregion] combination.

Development of reports

Reports were developed according to the following main steps:

1. Building of teams by Lead Scientists with Experts for each [PlantSystem x Ecoregion] combination.

2. Writing of reports according to a standardised procedure developed by the Coordination Group (**see Annex**). The metric to assess plant health is based on the ecosystem services generated by the Plant System, their increase, stability, or decrease. The considered ecosystem services belong to three broad groups: Provisioning (of food, fibre, materials), Regulating (of the climate, biodiversity, water, soils, pollutions), and Cultural (spiritual and cultural value, beauty, and re-creation).

3. Peer-review of reports: All reports are internally peer-reviewed. Peer review is led by one member of the Coordination as an Editor who identifies a Lead Scientist who acts as a Reviewer of a report she/he has not been involved into. Revisions are requested to each Lead Scientist by the Editor, and each report is revised accordingly to the Editor’s satisfaction.

4. Presentation and discussion of reports during a Workshop held in October 2021 in Toulouse, France (see box below).

5. Final edition of reports.

ISPP Global Plant Health Assessment Workshop & International Conference held at the Toulouse School of Economics, France, 5 - 8 October 2021.

Both the Workshop (5-7 October 2021) and the Conference (8 October) were held in a hybrid format, with physically attending or remotely connected participants.

Participants to both events represented a diversity of facets in the plant sciences (plant biology, agriculture, forestry, ecology) and of institutions from academia, national institutes, NGOs, and international research.

The Workshop included presentations and discussions on 26 reports, as well as discussion sessions in workgroups, some of which had initiated exchanges prior to the Workshop: (1) Analysis and synthesis across reports, (2) Risks associated with plant health, (3) Initial work on policy recommendations, and (4) Dissemination of results from the GPHA.

The GPHA Conference (October 8) was open to the scientific public. It included keynotes and discussion panels on cross-cutting themes related to the GPHA: Climate change and plant health; Plant health and global food security; Plant health in a One Health world; The economics of plant health; Molecular plant pathology; State of plant diseases and their evolution across the world; Plant disease emergences; Population genetics and biodiversity; Plant disease risk assessment; Successes and failures in integrated pest management; Plant diseases in the networks of life and human societies; and Policies of plant health protection.

Further details of the Workshop and Conference are available on the GPHA website as well as in the ISPP Newsletter of December 2021 at: https://www.isppweb.org/newsletters/pdf/51_12.pdf

Other sources of information

Website for further details: The Global Plant Health Assessment is housed at: https://sites.google.com/view/global-plant-health-assessment/home

or, alternatively *via* the ISPP website newsletters: https://www.isppweb.org/

Reference

Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC.

Table 1. Participants to the Global Plant Health Assessment

Name	Country	Affiliation	Role*
Ivette Acuña	Chile	Inst. de Invest. Agropecuarias, Osorno	E
Jorge Andrade-Piedra	Peru	International Potato Center (CIP), Lima	E
Didier Andrivon	France	INRAE, Rennes	C, KS
A. Elizabeth Arnold	USA	U. of Arizona	E
Jacques Avelino	France	CIRAD	L
R. Bandyopadhyay	Nigeria	International Institute of Tropical Agriculture	E
Clive Bock	USA	USDA ARS	L
Federica Bove	Italy	U. Piacenza	S
T. Brenes-Arguedas	Spain	UC Davis, California	L
Agnès Calonnec	France	INRAE, Villenave d'Ornon	E
Angus Carnegie	Australia	NSW Dept Primary Industries	L
Nancy P. Castilla	the Philippines	International Rice Research Institute	E
Xianming Chen	USA	USDA Washington	L
Helvecio Della Coletta-Filho	Brazil	Centro de Citricultura	E
Phyllis D. Coley	USA	U. of Utah	E
Kerik (Denton) Cox	USA	Cornell AgriTech	E
Triona Davey	United Kingdom	SASA, Edinburgh	E
Emerson Del Ponte	Brazil	U. Viçosa	L
Sandra Denman	United Kingdom	Forest Research, Alice Holt, Surrey	E
M-L. Desprez-Loustau	France	INRAE, France (Ret.)	L
Megan Dewdney	USA	U. of Florida	E
Annika Djurle	Sweden	SLU	E, KS
André Drenth	Australia	University of Queensland, Brisbane	E
Alexis Ducousso	France	INRAE, Cestas	E
Paul Esker	USA	PennState U.	C, L
Komi Fiaboe	Cameroon	IITA, Yaoundé	E
Josep Armengol Forti	Spain	U. Politècnica de València (UPV), Valencia	E
Sautua Francisco	Argentina	U. de Buenos Aires	E
Susan Frankel	USA	USDA	L
Pascal Frey	France	INRAE	C, L
Sara García-Figuera	USA	UC Davis, California	L
Paul Hendrik Fourie	South Africa	Citrus Research International & U. Stellenbosch	E
Karen Garrett	USA	U. Florida	L, KS
Maxime Guérin	France	Plante & Cité, Angers	E
Hans Hausladen	Germany	TUM School of Life Sciences, Freising	E
Daniel Hüberli	Australia	U. Western Australia	C
Jennifer Juzwik	USA	U.S. Forest Service, St. Paul	E
Zhensheng Kang	China	Northwest A&F U., Yangling	E
Lawrence Kenyon	Taiwan	World Vegetable Center	L, E
Jan Kreuze	Peru	Intl. Potato Center (CIP), Lima	E
Peter Kromann	The Netherlands	Wageningen University & Research	L
Jerome Kubiriba	Uganda	Nl. Ag. Research Organization (NARO), Kampala	E
Paulo Kuhnem	Brazil	Biotrigo Genética, Passo Fundo	E
Lava Kumar	Nigeria	International Institute of Tropical Agriculture	L, E
Jatinder Kumar	India	GB Pant U. of Agriculture and Technology	C, E
Marc-Henri Lebrun	France	INRAE, Grignon	KS
Anna Leon	USA	Weyerhaeuser Com	E
Wubutu Bihon Legesse	Ethiopia	World Vegetable Center	L, E
James Legg	Tanzania	Intl. Inst. of Tropical Agriculture, Dar es Salaam	L
Zhanhong Ma	China	China Ag. U., Beijing	L
George Mahuku	Tanzania	Intl. Inst. of Tropical Agriculture, Dar es Salaam	E
Robert O. Makinson	Australia	Australia Network for Plant Conservation, Sydney	E

Carmona Marcelo	Argentina	U. de Buenos Aires	E
Cristina Marzachì	Italy	Instit. Protezione Sostenibile delle Piante, Torino	E
Bruce McDonald	Switzerland	ETH, Zürich	C, KS
Neil McRoberts	USA	UC Davis, California	C
Abebe Menkir	Nigeria	Intl. Inst. of Tropical Agriculture	E
Alexey Mikaberidze	United Kingdom	U. of Reading	KS
Isabel (Alvarez) Munck	USA	USDA Forest Service	E
Andy Nelson	The Netherlands	Twente U.	C, KS
Emer O'Gara	Australia	Parks and Wildlife Service, Perth	E
Peter Ojiambo	USA	North Carolina State U.	E
Alejandro Ortega-Beltran	Nigeria	International Institute of Tropical Agriculture	E
Pierce Paul	USA	Ohio State U.	E
Sarah Pethybridge	USA	Cornell U.	C
Jean Pinon	France	INRAE, Champenoux (retired)	E
Srinivasan Ramasamy	Taiwan	World Vegetable Center	L, E
Tod Ramsfield	Canada	Natural Resources Canada	E
David M. Rizzo	USA	U. of California - Davis	E
Vittorio Rossi	Italy	U. Piacenza	C, L, KS, E
Irda Safni	Indonesia	Universiy of North Sumatra	E
Sonam Sah	India	GB Pant U. Agriculture & Technology (GBPUAT)	S, E
Alberto Santini	Italy	Nl. Research Council of Italy, Sesto Fiorentino	E
Serge Savary	France	INRAE, GBPUAT, UCDavis	C, L, S, E
Pepijn Schreinemachers	Thailand	World Vegetable Center	C, KS, E
Manjari Singh	India	GBPUAT	S, E, KS
Erin R. Spear	USA	Smithsonian Tropical Research Inst.	E
Giles E. St.J. Hardy	Australia	Murdoch U.	E
Nga Thi Thu Nguyen	Vietnam	Can Tho U.	E
Leena Tripathi	Tanzania	IITA, Dar es Salaam	L
Antonio Vicent	Spain	Instituto Valenciano de Investigaciones Agrarias	E
Altus Viljoen	South Africa	Stellenbosch U.	E
Laetitia Willocquet	France	INRAE, Toulouse	C, L, S
Alex Woods	Canada	BC Public Service British Columbia	L
Boming Wu	China	China Ag. U., Bejing	E
Xianchun Xia	China	Chinese Academy of Ag. Sciences	E
XiangMing Xu	United Kingdom	Nl. Inst. of Ag. Botany	L, E
Xiaoping Xu	China	Northwest A&F U., Yangling	E
Jonathan Yuen	Sweden	SLU	KS, e-book
Paul-Camilo Zalamea	USA	U. of South Florida	E
Changyong Zhou	China	Southwest University	E

* C: GPHA Coordination; L: Lead Scientist; E: Expert; S: GPHA Scientific Secretariat; KS: Keynote Speaker (8 oct 2021 Conference)

Reports

Maize in Sub-Saharan Africa

Lead Author: **Lava Kumar**, L.kumar@cgiar.org;
International Institute of Tropical Agriculture
(IITA), PMB 5320, Ibadan, Nigeria

Contributing Authors:
- **Ranajit Bandyopadhyay**, r.bandyopadhyay@cgiar.org; IITA, PMB 5320, Ibadan, Nigeria
- **Alejandro Ortega-Beltran**, A.beltran@cgiar.org; IITA, PMB 5320, Ibadan, Nigeria
- **Abebe Menkir**, A.menkir@cgiar.org; IITA, PMB 5320, Ibadan, Nigeria

Background information

Maize (*Zea mays* L.), which was introduced to Africa in the 16th century from Latin America, has become a major staple food and a source of caloric intake in SSA (Krishna et al 2021; Shiferaw et al 2011). Maize represents about 40% of the total cereal production in Africa (FAOSTAT 2020) and has the highest per capita calorie consumption of 348 kcal/person/day, followed by rice (341), wheat (245), and cassava (193) in developing countries (Abate et al 2017; Shiferaw et al 2011). In 2018, maize was grown on 37.6 million ha in SSA, representing 19% of the global maize area, but only produced 6.2% (71.5 million tons) of the global maize grain. This is due to the very low average maize yields of 1.6 t/ha in SSA, compared to the world average of 5.9 t/ha (FAOSTAT 2020). Nigeria, South Africa, Tanzania, Democratic Republic of Congo, Angola, Ethiopia, Kenya, Mozambique, Malawi, and Cameroon are the top 10 maize producing SSA countries (FAOSTAT 2020). For many years, maize uses have diversified from mainly being a food security crop to becoming a cash crop enabling to meet the growing demand for feed, fodder, and food processing industries. This is reflected in the increase in production area (36.9%) and in the near-doubling of overall production (98.9%) between 1990 to 2018. However, productivity gains were modest, from 1.2 to 1.6 t/ha. The highest SSA maize yields of 5.4 t/ha were recorded in South Africa in 2018, whereas yields in most other countries ranged from 1 to 3 t/ha in 2018.

PlantSystem considered in this report

As an introduced species, maize has no wild relatives in SSA. However, landraces with prolonged exposure to endemic pathogens and pests in the various environments are presumed to have evolved and diversified in their respective adaptation to environments (Abate et al 2017).

Maize is an annual crop cultivated under a wide range of growing conditions broadly defined based on seasonal rainfall, evapotranspiration, temperature, length of the growing season and elevation. Thus, six mega environments are distinguished in SSA: 1) dry lowland (Sudanese savanna); 2) wet lowlands (moist savanna) below 900 meters above sea level (masl); 3) humid forest; 4) upper wet mid-altitude; 5) dry mid-altitude (mid-altitude) in the range of 900 to 1,600 masl; and 6) highlands above 1,600 masl (Badu-Apraku and Fakorede 2017; Menkir et al 2000; Sonder 2016). A wide variety of cultivars are grown, which are classified based on the maturity cycle as extra-early (80 to 85 days), early (90 to 95 days), intermediate (105 to 110 days), late (110 to 130 days), and extra-late (130+ days) (Abate et al 2017).

The majority of maize producers in SSA are small- and medium-scale farmers who mostly cultivate open-pollinated varieties (OPVs) under rainfed conditions with zero, or low inputs. However, in the past 15 years, smallholders are increasingly using improved OPVs or hybrids, sometimes with input supplements, which are mainly subsidized

Maize fields, Saminaka, Nigeria (photo: IITA)

Maize field, Nigeria (photo: IITA)

by government schemes (Abate et al 2017). Maize accounts for 40% of the cereal production in SSA, where about 65% is used as food and 35% for feed (Ekpa et al 2019; FAOSTAT 2021). Almost all maize plant parts – leaves, stalks, tassels, cobs, and grains – are used for food, animal feed, or industrial raw material. Green maize is popular in peri-urban markets for roasting, boiling, or preparation of steamed products (Badu-Apraku and Fakorede 2017). Maize flour is processed by different processing methods into various products for consumption.

Maize production in all mega environments is affected by different pests and pathogens, causing moderate to high production and quality losses. This report mainly focuses on the provisioning ecosystem service rendered by maize in SSA.

Maize health in sub-Saharan Africa

↘ P

State of maize health in the past 30 years

Maize production in SSA is affected by several endemic pests and pathogens which differ across mega environments (Bandyopadhyay et al 2019a; White 1999). Losses from pests and pathogens include yield losses caused by injuries occurring during crop growth, quality losses from mycotoxin contamination, and post-harvest losses during storage. Exposure to pest injuries predisposes maize to fungal infection and sometimes to mycotoxin contamination. The most important insect pests are stalk borers, including *Busseola fusca*, *Chilo partellus*, *Eldana saccharina*, and *Sesamia calamistis*. The two major parasitic weeds, *Striga hermonthica* and *S. asiatica*, are responsible for significant yield losses in maize production zones across SSA. The most important diseases are southern corn leaf rust (*Puccinia polysora*), common rust (*Puccinia sorghi*), northern corn leaf blight (*Exserohilum turcicum*), southern corn leaf blight (*Bipolaris maydis*), gray leaf spot (*Cercospora* spp.), downy mildew (*Peronosclerospora sorghi*), stalk and ear rots (caused by *Fusarium verticillioides* and *Diplodia macrospora*), and kernel and ear rots (*Fusarium* spp., *Aspergillus flavus* and other *Aspergillus* species). Among the known 10 viruses affecting maize in Africa, the maize streak virus (MSV) causes the most economically significant losses (Martin and Shepherd 2009). Heavy post-harvest losses are attributed to beetle pests, ear rot due to Fusarium infection, and aflatoxin contamination due to pre-harvest infection by *A. flavus* and other species (Bandyopadhyay et al 2019a).

The health status of maize in SSA was altered in the last decade by two introductions: (i) the maize chlorotic mottle virus (MCMV), first detected in 2011 in Kenya, which together with endemic sugarcane mosaic virus (SCMV) and other potyviruses has caused the devastating maize lethal necrosis (MLN) outbreak in East Africa (Mahuku et al 2015); and (ii) the fall armyworm (FAW) (*Spodoptera frugiperda*), which was first detected in 2016 in West Africa (Goergen et al 2016), and is now established as a pan-African threat to maize. Heavy post-harvest losses are attributed to *Prostephanus truncates*, introduced into Africa in the 1980s. The direct and indirect annual losses caused by MLN and FAW exceed US$ 1 billion (Eschen et al 2021; Groote et al 2020). In addition, maize mycotoxin contamination has become a significant constraint in the health and trade sectors, especially in East Africa. Most of the endemic and introduced pests and pathogens are persistent threats to maize production in all the production environments, contributing to significant production losses and low average yields per ha in SSA (1.6 t/ha) (FAO 2020).

Significant progress has been made during the last 30 years in developing suitable technologies to manage pests and pathogens through breeding for resistance, IPDM, and biocontrol approaches (Bandyopadhyay et al 2019a; Coyne et al 2019; Krishna et al 2021). However, losses from pests and pathogens continue to represent important reducing factors to maize production in SSA (Savary et al 2019).


A maize plant affected by maize lethal necrosis, Tanzania, November 2015 (photo: IITA)

This is despite significant progress and scientific advances, which have not yet reached fully farmers' fields and production environments. Despite research advances, the overall state of maize health in SSA may be assessed as poor.

Evolution of maize health over the recent 10 years

The adverse effects of common pests and diseases have been significantly reduced through advances in breeding maize for high levels of resistance to several foliar fungal diseases, MSV, *Striga*, and with advances in IPDM and biocontrol for reducing pre- and post-harvest losses from pests and mycotoxin contamination (Ayalew et al 2017; Badu-Apraku and Fakorede 2017; Bandyopadhyay et al 2019a, b; Gedil and Menkir 2019; Menkir and Meseka 2019). All these solutions have shown the potential to reduce losses and stabilize and increase maize productivity. Simultaneously, additional efforts are being pursued to gain better understanding of the pathogen and pest population diversity, ecology, and epidemiology as well as preventing pest and pathogen spread when exchanging


Fall armyworm on a maize leaf (photo: IITA)

maize genetic resources among countries (Kumar et al 2019). Due to the difficulty in predicting pest and disease outbreaks, the lack of field-based reliable surveillance data, the limited or inadequate scientific/technical capacity among national programs, and because of the limited level of technology adoption by farmers, many of these pests and pathogens remain a significant yield-reducing factor. For instance, the national average MSV incidence is expected to be 5% in non-endemic vs. about 40% in endemic areas (Martin and Shepherd 2009). The pest and disease burden has increased in the last 10 years, with the introductions of MCMV (one of the two viruses leading to MLN) and FAW. MLN, first recognized in Kenya in 2011-12, was estimated to affect maize production in 26,000 ha worth about US$54 million (Groote et al 2020). The disease has spread to neighbouring Tanzania, Uganda, Rwanda, DRC, Burundi, and Ethiopia, before its further spread was contained through quarantine, regulation of seed movement within the region, and IPDM strategies (Mahuku and Kumar 2017). MLN has severely impacted the maize seed industry in Eastern Africa (Boddupalli et al 2020). On the other hand, the FAW outbreak of 2016 in West Africa, with its subsequent rapid spread across Africa causing severe maize yield losses, has created extreme panic among maize growers. About 20 to 50% of the maize production was estimated to have been lost due to FAW injuries in farmers' fields during outbreak years (Eschen et al 2021). Research and technology transfer efforts have however contributed to minimizing the negative impact of MLN and FAW in the last few years.

Because of the magnitude of the challenges faced by maize health, and despite ongoing research efforts, the health status of maize in SSA is assessed as declining during the recent decade.

Ecosystem services, as affected by plant disease

F ↗

Level of provisioning ecosystem service generated by maize, as affected by plant disease, in the past 30 years

Maize is a staple food crop in SSA. In the past 30 years, maize production in East, Central, and West Africa increased in area by 49%, production by 65%, and yield by 29% (FAOSTAT 2020). Although the production area for maize decreased by 70% in Southern Africa, production increased by 26% due to a 56% increase in productivity resulting from use of improved cultivars and agronomic management practices. Low yields in most parts of SSA were due to multiple factors including the persistent injuries from pests and pathogens, poor agronomic management, use of old varieties susceptible to pests and diseases, drought, and parasitic weeds. Mycotoxin contamination, of which aflatoxin was most pervasive, is another significant contributing factor for indirect losses, including a negative impact on health and commodity trade (Bandyopadhyay et al 2019b).

There are three main areas of interventions to improve maize production in SSA. The first one is development and promotion of multiple stress resilient varieties. Several decades of efforts devoted to the genetic improvement of maize have resulted in remarkable genetic gains. The breeding strategies have generated maize varieties and hybrids with high yield potential and resistance to major diseases prevalent in humid forests, moist savannas, and mid-altitude areas in SSA. More efforts are being made to generate more productive cultivars of varying maturity with tolerance to drought- and heat-stress, resistance to *S. hermonthica* and foliar diseases as well as ear rots (Badu-Apraku et al 2021; Gedil and Menkir 2019). Several high yielding and stress tolerant cultivars that have been released are currently cultivated by farmers and making significant contribution to productivity gains (Gedil and Menkir 2019). Better strategies are being pursued to improve the adoption of improved varieties through improvement of seed delivery systems and promotion of use of appropriate agronomic management to realize the full yield potential of improved cultivars. The second intervention is biocontrol for aflatoxin contamination. Excellent progress has been achieved through the application of biocontrol product, Aflasafe®, that reduces aflatoxin contamination by over 90% in maize and other commodities such as groundnut (Agbetiameh et al 2020; Bandyopadhyay et al 2019b; Senghor et al 2020). Use of aflatoxin biocontrol allows farmers to produce crops with safe aflatoxin content for their own consumption but also to reach previously locked premium aflatoxin-conscious markets. The third intervention area is the use of IPM to mitigate the impact of pre- and post-harvest pest damage in storage using predators, entomopathogens, and hermetic storage bags. The "push-pull technology" is another approach used for integrated management of *Striga* and FAW as part of the natural resource management approaches for pest control (Khan et al 2018).

The ecosystem services generated by maize research can be rated as fair.

Evolution of the level of provisioning ecosystem service generated by maize, as affected by plant disease, over the recent 10 years

In the last 10 years, the maize production area in East, Central and West Africa increased by 39 to 63%, production in tonnes by 49 to 69%, and productivity by 8 to 31%. Maize production area decreased in Southern Africa by 67%, but production and yield increased by 8% and 45%, respectively (FAOSTAT 2020). This period is also marked by high private sector investment in the maize processing industry, increased participation of the private seed sector in production, and supply of good quality seeds of high yielding hybrids in SSA. However, epidemics caused by the emerging FAW infestation has caused significant damage to maize production in certain seasons (Boddupalli et al 2020). The introduced MLN has affected maize production mainly in Eastern Africa (Kumar et al 2019). The rapid international action has alleviated maize production and leads to the development of solutions to mitigate MLN and FAW. In the last decade, the capacities of national regulatory bodies, including national plant protection organizations (NPPOs) and biopesticides registration agencies, have shown improvements to monitor invasive pests, improved capacity for deploying emergency response action, seed health testing and commercial registration of biocontrol agents for pest and mycotoxin control (Kumar et al 2019; Mahuku and Kumar 2017; Moral et al 2020). But these developments are skewed to a few countries with limited investments. Moreover, efforts are necessary for sustainable action to contain emerging maize pests and diseases.

Based on these observations the overall rating in SSA is "improving." However, in some countries, especially central Africa, it can be rated as stable due to the limited capacity to adopt improved technologies and to manage emerging diseases.

Complementary information

Pests and pathogens are a significant concern to maize in all production systems in SSA. Almost all the economically important pests and pathogens of maize are widely distributed in SSA. MLN is presently restricted to East Africa although it is a threat to maize production in other parts of Africa. Except for a few cases (e.g., MSV, FAW, MLN, *A. flavus*), there is a dearth of fundamental knowledge of pathogen and pest ecology, epidemiology, and population diversity, which are hampering the establishment of effective control measures, and development of models for predicting and forecasting or understanding the impact of climate change on pest and pathogen dynamics. Despite these limitations, significant progress has been made towards mitigating the impact of pests and diseases on maize production. The adoption of technology can be low and slow in SSA — as a result of diverse, interacting and complex factors. Breeding efforts have succeeded in developing resistant varieties to foliar diseases, and significant progress has been made in developing and deploying resistance to MLN. IPM and biocontrol approaches are showing promise against several persistent pests as well as against aflatoxin contamination. Sustained efforts, including development of sustainable national R&D capacity, along with a better technology adoption, are necessary to reduce the economic impact of pests and pathogens in SSA.

Climate change is a significant threat to maize production. Climate scenarios A1B (a balanced emphasis on all energy sources, rapid economic growth) (Tesfaye et al 2015) and A2 (continuous increasing population, high emissions) emission scenarios project a loss of climatic suitability area for maize cultivation in SSA by 7 and 11% (by 2050) and 29 and 36% (by 2100), respectively (Ramirez-Cabral et al 2017). Climate change may also alter the current pest and pathogen dynamics and increase production volatility. Considering the demand for doubling and tripling maize production to meet the growing population in order to provide food for three billion humans by 2050 in Africa, maize productivity needs to increase by 3- to 4-fold (Tadele 2017; Tesfaye et al 2015). Achieving this depends on controlling different yield-reducing factors, including the existing and the emerging pests and pathogens, and other potential invasive threats.

There is a strong need for research to identify climate-resilient solutions, including modelling, to simulate various scenarios and develop best-bet disease management strategies. The severe outbreaks caused by two introduced pests (MLN and FAW) and frequent occurrence of aflatoxin episodes demonstrate that maize production and food systems are vulnerable; and that R&D gains can be rapidly compromised. Lessons learned from managing maize pests and diseases should direct future solutions. Given the significance of the challenges encountered by maize producers and the looming climate change in SSA, protecting and enhancing the health status of maize in the continent will contribute immensely to productivity gains to meet the huge demand for maize grain.

We are reasonably confident about the main findings of this report.

References

Abate T, Fisher M, Abdoulaye T, et al (2017) Characteristics of maize cultivars in Africa: How modern are they and how many do smallholder farmers grow? Agric Food Secur 6:30

Agbetiameh D, Ortega-Beltran A, Awuah RT, et al (2020) Field efficacy of two atoxigenic biocontrol products for mitigation of aflatoxin contamination in maize and groundnut in Ghana. Biol Control 150:104351

Ayalew A, Kimanya M, Matumba L, Bandyopadhyay R, Menkir A, Cotty PJ (2017) Controlling aflatoxins in maize in Africa: strategies, challenges and opportunities for improvement. In: Watson D (ed) Achieving Sustainable Cultivation of Maize. Volume 2: Cultivation Techniques, Pest and Disease Control. Burleigh Dodds Science Publishing Limited, Cambridge, UK, pp 1-24

Badu-Apraku B, Fakorede MAB (2017) Maize in sub-Saharan Africa: importance and production constraints. In: Advances in Genetic Enhancement of Early and Extra-Early Maize for Sub-Saharan Africa. Springer, Cham, pp 3-10

Badu-Apraku B, Bankole FA, Ajayo BS, et al (2021) Identification of early and extra-early maturing tropical maize inbred lines resistant to *Exserohilum turcicum* in sub-Saharan Africa. Crop Prot 139:105386

Bandyopadhyay R, Cardwell KF, Ortega-Beltran A, et al (2019a) Identifying and managing plant health risks for key African crops: maize. In: Neuenschwander, Tamò (eds) Critical Issues in Plant Health: 50 years of Research in African Agriculture. Burleigh Dodds Science Publishing Limited, Cambridge, UK, pp 173-212

Bandyopadhyay R, Atehnkeng J, Ortega-Beltran A, Akande A, Falade TDO, Cotty PJ (2019b) "Ground-truthing" efficacy of biological control for aflatoxin mitigation in farmers' fields in Nigeria: from field trials to commercial usage. Front Microbiol 10:2528

Boddupalli P, Suresh, LM, Mwatuni F, et al (2020) Maize lethal necrosis (MLN): efforts toward containing the spread and impact of a devastating transboundary disease in sub-Saharan Africa. Virus Res 282:197943

Coyne D, Abberton M, Adetonah S, et al (2019) Making integrated pest management (IPM) work in sub-Saharan Africa. In: Neuenschwander, Tamò (eds) Critical Issues in Plant Health: 50 years of Research in African Agriculture. Burleigh Dodds Science Publishing Limited, Cambridge, UK, pp 397-414

Ekpa O, Palacios-Rojas N, Kruseman G, Fogliano V, Linnemann AT (2019) Sub-Saharan African maize-based foods - processing practices, challenges and opportunities. Food Rev Internat 35:609-639. DOI: 10.1080/87559129.2019.1588290

Eschen R, Beale T, Bonnin JM, et al (2021) Towards estimating the economic cost of invasive alien species to African crop and livestock production. CABI Agric Biosci 2:18. https://doi.org/10.1186/s43170-021-00038-7

FAOSTAT (2020) FAO Maize production data for the year 2018. http://www.fao.org/faostat/en/#data/QC (accessed on 20 Sep 2020)

FAOSTAT (2021) Food Balance Sheet 2018 – Maize. http://www.fao.org/faostat/en/#data/FBS (accessed on 5 July 2021)

Gedil M, Menkir A (2019) An integrated molecular and conventional breeding scheme for enhancing genetic gain in maize in Africa. Front Plant Sci 10:1430. doi: 10.3389/fpls.2019.01430

Goergen G, Kumar PL, Sankung SB, et al (2016) First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), a new alien invasive pest in West and Central Africa. PLoS ONE 11(10), e0165632

Groote HD, Kimenju SC, et al (2020) Spread and impact of fall armyworm (*Spodoptera frugiperda* J.E. Smith) in maize production areas of Kenya. Agric Ecos Envir 292:106804

Khan ZR, Pittchar JO, Midega CAO, Pickett JA (2018) Push-pull farming system controls fall armyworm: lessons from Africa. Outlook Pest Manag 29:220-224.

Krishna VV, Lantican MA, Prasanna BM, Pixley K, Abdoulaye T, Menkir A, Bänziger M, Erenstein O (2021) Impacts of CGIAR Maize Improvement in sub-Saharan Africa, 1995-2015. Mexico, CDMX, International Maize and Wheat Improvement Center (CIMMYT). https://repository.cimmyt.org/bitstream/handle/10883/21292/63451.pdf?sequence=1&isAllowed=y (accessed on 2 July 2020)

Kumar PL, Legg JP, Ayodele M, Mahuku G, Ortega-Beltran A, Bandyopadhyay R (2019) Disease surveillance, diagnostics and germplasm health in crop protection. In: Watson D (ed) Achieving Sustainable Cultivation of Maize. Volume 2: Cultivation Techniques, Pest and Disease Control. Burleigh Dodds Science Publishing Limited, Cambridge, UK, pp 41-73

Mahuku G, Lockhart BEL, Wanjala B, et al (2015) Maize lethal necrosis, an emerging threat to maize-based food security in sub-Saharan Africa. Phytopathology 105:956-965

Mahuku G, Kumar PL (2017) Rapid response to disease outbreaks in maize cultivation: a case study of maize lethal necrosis. In: Watson D (ed) Achieving Sustainable Cultivation of Maize. Volume 2: Cultivation Techniques, Pest and Disease Control. Burleigh Dodds Science Publishing Limited, Cambridge, UK, 339–70

Martin DP, Shepherd DM (2009) The epidemiology, economic impact and control of maize streak disease. Food Secur 1:305–315

Menkir A, Kling JG, Jagtap SS, Aliu BA (2000) GIS based classification of maize testing locations in West and Central Africa. Maydica 45:143-150

Menkir A, Meseka S (2019) Genetic improvement in resistance to *Striga* in tropical maize hybrids. Crop Sci 59:2484-2497

Moral J, Garcia-Lopez MT, Camiletti BX, et al (2020) Present status and perspective on future use of aflatoxin biocontrol products. Agronomy 10:491

Ramirez-Cabral NYZ, Kumar K, Shabani F (2017) Global alterations in areas of suitability for maize production from climate change and using a mechanistic species distribution model (CLIMEX). Scientific Rep 7:5910.

Savary S, Willocquet L, Pethybridge SJ, Esker P, McRoberts N, Nelson A (2019) The global burden of pathogens and pests on major food crops. Nature Ecol Evol 3:430–439

Senghor LA, Ortega-Beltran A, Atehnkeng J, Callicott KA, Cotty PJ, Bandyopadhyay R (2020) The atoxigenic biocontrol product Aflasafe SN01 is a valuable tool to mitigate aflatoxin contamination of both maize and groundnut cultivated in Senegal. Plant Dis 104:510-520

Shiferaw B, Prasanna BM, Hellin J, et al (2011) Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. Food Secur 3:307–27.

Sonder K (2016) Global map of maize mega-environments. CIMMYT Research Data & Software Repository Network V4. https://hdl.handle.net/11529/10624 (accessed on 4 Oct 2020)

Tadele Z (2017) Raising crop productivity in Africa through intensification. Agronomy 7:22 doi:10.3390/agronomy7010022

Tesfaye K, Gbegbelegbe S, Cairns JE, et al (2015) Maize systems under climate change in sub-Saharan Africa: Potential impacts on production and food security. J Clim Chang Str 7:247-271

White DG (ed) (1999) Compendium of Corn Diseases, 3rd ed. The American Phytopathological Society, St Paul, MN