













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

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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)

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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

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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
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.

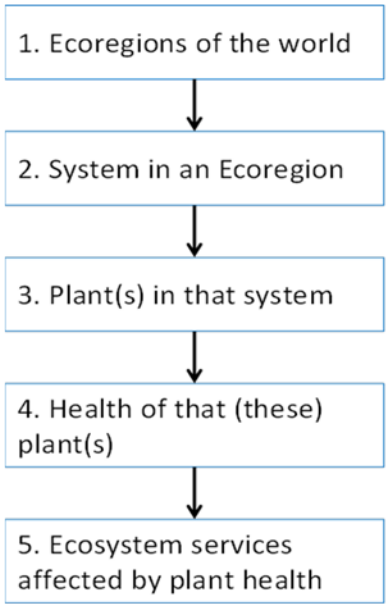

Figure 1. Steps in the Global Plant Health Assessment

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
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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

Cereals

rice

wheat

maize

Rice in South-East Asia

Lead Author: **Serge Savary**, ssavary01@gmail.com; INRAe, France; Honorary Professor of Plant Pathology, GB Pant University of Agriculture & Technology, India; Visiting Scholar, University of California - Davis, USA

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Background information

South-East Asia is home to 655 million people (UN 2019) where the first source of food is rice. Rice and rice cultivation has been the basis of political, economical, social and cultural development for millennia, and remains today an essential element of daily life (Mutert and Fairhurst 2002).

This report therefore focuses on rice and considers only one ecosystem service: food production. We however briefly address the environmental context of rice production.

PlantSystem considered in this report

The sustainability of rice production and of rice farming has historically been and is still closely related to that of society in South-East Asia. Rice production remains highly labour-intensive, requires major infrastructure (e.g., irrigation systems; storage facilities), involves collective management and cooperation over water and labour, and thus extensive networking and linkages among social components, needs intensive crop care (including crop establishment, water flow supervision, bird control, fertilizer application) and requires significant inputs. Maintaining a balance between rice production and rice demand, and between rice production and the environmental footprint of agriculture, among others, are the focus of permanent efforts (research, policy, development) in order to maintain and if possible improve the overall performances and sustainability of rice-based agrosystems (e.g., Greenland 1997).

In South-East Asia, as elsewhere, rice production and its sustainability is influenced by rice diseases and their impacts in terms of yield output and grain quality (Zeigler and Savary 2009).

There is a wide range of rice production systems across South-East Asia (Greenland 1997), even if one considers only, as in this report, the lowlands of South-East Asia, as these environments correspond to the bulk of the rice production. However, at very different speeds, rice production situations are evolving all over South-East Asia, and this has direct consequences on the patterns of plant diseases occurring in farmers' fields (Savary et al 2000a). Changes in production situations also have profound consequences on the impacts of plant diseases in terms of crop losses (Savary et al 2000b).

Rice field with farmer and water canal, Indonesia (photo: I Safni)

Rice health in South-East Asia

State of rice health in the past 30 years

The number of plant pathogens which affect rice in South-East Asia is very large (Ou 1985; see Table 1). This is associated with the large diversity of agricultural contexts, cropping practices, landscapes and cultivated rice varieties (Savary et al 2000a). Here, we focus on rainfed and irrigated rice in the lowlands, which generate most of the rice in South-East Asia. Over the years, there have been a large number of IPM projects (Norton et al 2010; Teng 1990) where pathogens and animal pests (mostly insects) are considered jointly. Speaking of rice health therefore involves considering pests, which we briefly address here too. Another reason for considering insects in this assessment is that insects are vectors of several important viral diseases of rice in the Region.

The past 30 years correspond to the Post-Green Revolution period in South-East Asia: a period where progressively new high yielding rice varieties (HYV), carrying resistance genes to major rice diseases, were deployed in the irrigated and rainfed lowlands of South-East Asia. These varieties carried resistance genes against bacterial leaf blight (BLB), blast (BL), and several viral diseases of rice *via* resistance to insect vectors: rice tungro disease (RTD), ragged stunt (RS), and rice grassy stunt virus (RGSV). While resistance to these rice diseases had been specifically targeted in breeding programmes, other diseases had also been considered, so that the new HYVs carried incomplete resistance to other diseases such as bacterial leaf streak (BLS), narrow brown spot (NBS), false smut (FSM), bakanae (BK), and brown spot (BS). The period, overall, also corresponds to advances and improvements in infrastructure, including: irrigation systems, advisory systems, distribution of healthy (i.e., pathogen-free) seed, and supply in fertilisers.

Rice health training, Thailand (photo: S Savary)

Sheath Blight, North Sumatra, Indonesia (photo: I Safni)

Across South-East Asia, the period may be characterised by

- the persistent occurrence of rice sheath blight (SHB) and stem borers;

- sporadic local outbreaks (1) of BPH associated with viral disease epidemics (RSV); and (2) of rice tungro disease (RTD);
- an overall adequate control, over this 30-year period of time, of epidemics of two major rice diseases, bacterial blight and blast (through host plant resistances), despite some geographical gaps across South-East Asia, and recent, more frequent, epidemics in some growing regions.

As a result, the overall state of plant health across the Region may be considered as good.

Rice field damaged by bacterial leaf blight, Philippines (photo: S Savary)

Evolution of rice health over the recent 10 years

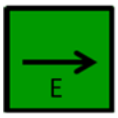
Trends in the evolution of importance for the main rice diseases over the past ten years are summarised in Table 1. Surveys covering a total of 1051 farmers' fields across the Region at 14 different sites and over a period of 23 years (Savary et al 2022) suggests that, while some diseases have been declining in intensity (RSV, SHB, NBL, SHR), the intensity of other diseases has been increasing (BLB, BLS, NBS, FSM, LBL). Change in the importance of viral diseases may be attributed to changes in vector management (see e.g., for BPH, Cuong et al 1997), and generally to shifts in virus prevalence in South-East Asia (Cabauatan et al 2009; Zhou et al 2013). Shifts in importance of other diseases may be attributed to a number of factors, including varieties and cropping practices (e.g., Ham et al 2013).

In summary, while the intensity (i.e., the levels)of some diseases has subsided during this period, the levels of other diseases has increased. Therefore, one can assess the overall trend in rice health during the past 10 years as stable.

Table 1. Major rice diseases and pests of rice in South-East Asia and their evolution

Disease (pest)	Code	Scientific name	Importance - past 30 yrs	Evolution - past 10 yrs
Ragged stunt	RSV	Rice ragged stunt virus	Moderate	Decrease
Sheath blight	SHB	*Rhizoctonia solani*	High	Decrease
Tungro	RTD	Rice tungro bacilliform badnavirus and Rice tungro spherical waikavirus	High	Stable
Bacterial leaf blight	BLB	*Xanthomonas oryzae* pv. *oryzae*	High	Increasing
Bacterial leaf streak	BLS	*Xanthomonas oryzae* pv. *oryzicola*	Low	Increasing
Bacterial Panicle Blight/ grain rot	BPB	*Burkholderia glumae*	Moderate	Moderate , Increasing
Narrow brown spot	NBS	*Sphaerulina oryzina*	Low	Increasing
False smut	FSM	*Ustilaginoidea virens*	Low	Increasing
Bakanae	BK	*Fusarium fujikuroi*	Low	Stable
Leaf blast	LBL	*Pyricularia oryzae*	High	Increasing
Neck blast	NBL	*Pyricularia oryzae*	High	Stable
Brown spot	BS	*Bipolaris oryzae*	Moderate	Stable
Sheath rot	SHR	*Sarocladium oryzae*	Moderate	Decrease
Stem rot	SR	*Nakataea oryzae*	Low	Stable
Grassy strunt virus	GSV	Rice grassy stunt virus	Low	Stable
Black Streaked Dwarf Virus	SRBS DV	Southern rice black streaked dwarf virus	low	Increasing
Brown plant hopper	BPH	*Nilaparvata lugens*	High	Stable
Stem borers	SB	*Scirpophaga innotata; Chilo suppressalis; S incertulas*	High	Stable
Leaf folder	LF	*Cnaphalocrocis medinalis, Marasmia patnalis*	Moderate	Stable

Ecosystem services, as affected by plant disease



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

There has been a steady increase in rice production over the past 30 years (data for 1990 - 2018, FAOSTAT, 2020) across the Region. For the most important rice producers, the national production figures (million tons) are: Indonesia: 10.50 - 16.00 (+52%); Myanmar: 4.76 - 6.71 (+41%); Philippines: 3.32 - 4.80 (+45%); Thailand: 8.79 - 10.41 (+18%); Vietnam: 6.04 - 7.57 (+25%). The level of ecosystem service rendered, in terms of rice production only, may therefore be considered excellent.

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

Among the important trends observed during this period (Savary et al 2022), one notices the combination of: (1) increased inputs of total mineral fertiliser (i.e., 110 to 170 kg.ha^{-1}); (2) shortened average duration of fallow period (i.e., ca 15 to less than 10 days); (3) increased average number of insecticide applications per season (i.e., from about 1 to over 2 applications per season); and, (4) critically, a jump in average fungicide use from nearly 0 to about 1 application per season: fungicide use, earlier absent has now become the norm. These changes, however, are associated with: (1) the absence of significant reduction in yield losses to diseases and pests, and (2) a marginal, often non-significant, increase in actual yield.

Therefore, while one can assess the overall trend in the effects of rice diseases on production during the past 10 years as stable, a clear decrease in the total factor productivity (Pingali and Heysey 1999) in rice production in indicated (Savary et al 2022).

Complementary information

The above-mentioned decline in total factor productivity indicates an increasingly negative impact of rice cultivation on the environment, with increasing effluents of insecticides, fungicides, and fertilisers (especially nitrogen). This may have negative impacts on the flora and fauna of rice-based ecosystems, as well as on the quality of water.

We are reasonably confident in the terms of this report, because a number of studies, publications, support your views. We however recognise that there are gaps in the literature.

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Rice in East Asia

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Background information

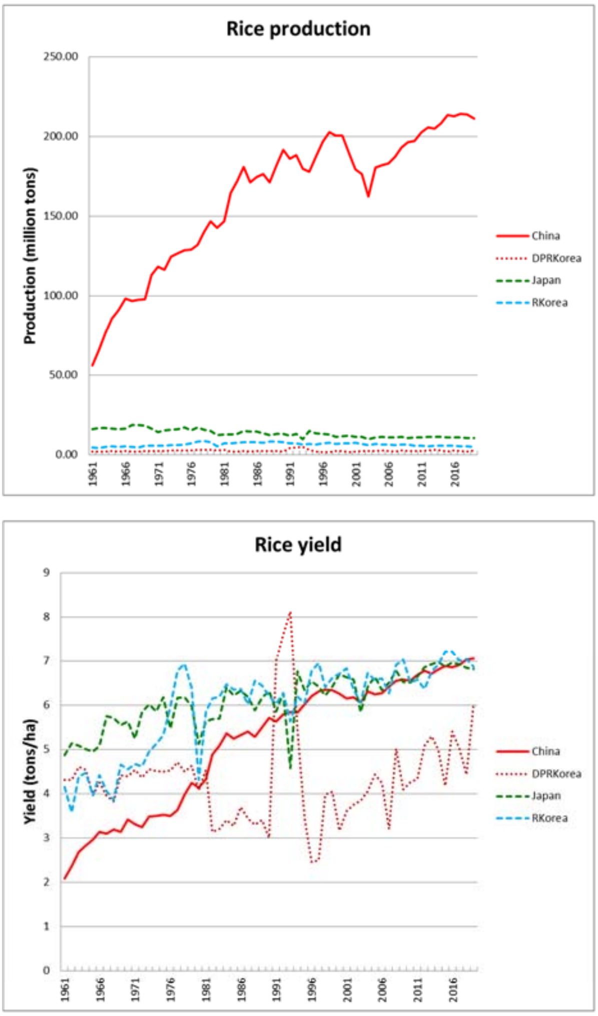
East Asia consists of four main countries: China, Japan, North Korea, and South Korea. The four countries profoundly differ, but have one key element in common: rice. Rice has been the basis of the cultural and historical development of East Asian countries for centuries (Harlan 1992). It has always been, and still remains today the basis of East Asian diets. This report therefore concerns [East Asia x Rice].

There are large differences between the four countries (Figure 1). China has, by far, the largest population and the largest rice production (FAOSTAT 2021). Japan, on the other hand, has the second largest population of the region, but its rice production has been slightly declining over the years. This is not because of decreasing yields: Japan has among the highest rice yields of East Asia; it is because the area under rice cultivation has slowly declined. Japan has, over the past 30 years, entered a double transition: a population transition (with a slow decline) and a nutritional transition (where rice is becoming less important in the diet). This contrast with China, where the national population continues its steady increase, and where rice remains the main staple: the rice production per person is the highest of the region. North Korea and South Korea occupy positions that are intermediate between China and Japan.

PlantSystem considered in this report

Rice production in China has more than tripled in the past five decades mainly as a result of increased grain yield rather than increased planting area (Fig. 1; Peng et al 2009). The planting area has recently stabilised at about 30 million hectares. Increased yields mainly result from the breeding of high-yielding varieties, as well as from the improvement of management practices involving fertilization and irrigation. With the increase of its population, it has been estimated (Peng et al 2009) that China will need to produce about 20% more rice by 2030 (compared to 2009) in order to meet its domestic needs, assuming that rice consumption per capita remains the same. This will have to be achieved in a sustainable way. Achieving this will be difficult because of trends and difficulties in the rice production systems.

Rice field landscape, Jiangxi Province, China (photo: Bo Ming)



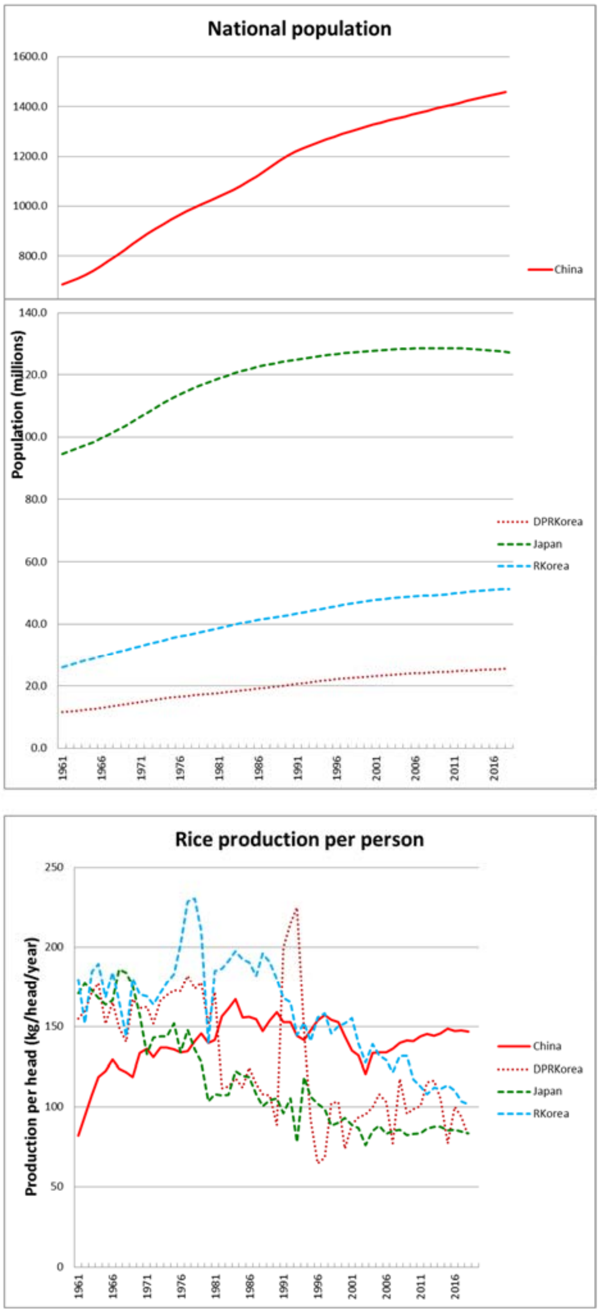


Figure 1. Rice production, rice yield, rice production per person, and national populations of four main countries of East Asia (Source: FAOSTAT (2021) Consulted 15 Aug. 2021 http://www.fao.org/faostat/en/#data

The current trends are: (1) a decline in arable land; (2) an increasing water scarcity; (3) global climate change; (4) a shortage of rural labour; and (5) the increasing consumer demand for high-quality rice (which often is produced by low-yielding rice varieties). The difficulties include (1) a narrow genetic background of rice varieties; (2) the overuse of fertilizers and pesticides; (3) the difficulties of maintaining complex irrigation systems; (4) the implementation of oversimplified crop management; and (5) a weak extension system (Peng et al 2009). Yet, research can overcome these problems, through (1) the development of the new rice varieties with higher yield potential, and (2) better resistance to rice pests and pathogens; (3) varieties with tolerance to abiotic stresses; and (4) improved, integrated, crop management (Peng et al 2009).

Rice health in East Asia

State of rice health in the past 30 years

Rice health has historically been related to a number of fungal, bacterial, and viral diseases in East Asia (Ou 1987). There are numerous historical records of grave rice blast (*Pyricularia oryzae*) epidemics in both China and Japan, sometimes causing grave food shortages. Another important rice fungal disease in East Asia is sheath blight (*Rhizoctonia solani*), with very severe losses. Bacterial blight (*Xanthomonas oryzae* pathovar *oryzae*) is a third, extremely important disease. There has been sporadic insect-transmitted viral diseases, which have generally been less important the period 1990-2020, except for the later part of this period. Since 2000, Rice Black Streaked Dwarf disease has become a serious threat to rice production in China. Overall, disease management has been successful (Mew et al 2004), especially in the case of blast and bacterial blight, through the deployment of host plant resistance genes. Management of sheath blight has been much harder, in part because no strong source of genetic resistance has been found so far, and in part because sheath blight epidemics are particularly favoured by dense, dark, and humid rice crop canopies: these are the canopies of crop stands with high attainable yield, where the seeding rate, the fertilizer input, the human labour, and the water supply are high. Agricultural intensification in rice therefore favours sheath blight, and disease management involves crop management, biological control, and, mostly, fungicide application (Savary and Mew 1996).

Evolution of rice health over the recent 10 years

The state of rice health in East Asia has been particularly eventful in the recent decade. Rice health has been dominantly affected by insect-borne viral disease. An important example is the Rice Black-Streaked Dwarf (RBSDV) fijivirus, which also infects maize (Fang et al 2001) and several non-cultivated plants (Wu et al 2017), and which is transmitted by the white-back plant hopper (WBPH, *Sogatella furcifera*; Zhou et al 2013) across the entire region as well as the Indo-China peninsula.

Another is the Rice Stripe Virus (RSV), which is transmitted by the small brown planthopper (SBPH) *Laodelphax striatellus* (Wang et al 2008). As RBSDV, RSV is of concern to the entire East Asia region, including Korea (Cho et al 2015).

The entire region is exposed to the summer monsoon South-East to North-West winds which carries the much-needed water for agriculture but also typhoons, which transport viruliferous vectors over very large distances. This makes neighbouring Vietnam and Philippines, together with southern China, regional sources of virus inoculum. Once epidemics are initiated, viruliferous vectors are transported, and epidemics progress northwards as rice crop establishment takes place over the wide landscapes across the region (Otuka 2013). The problem is compounded by the emergence of insecticide resistances among insect populations (Matsumura and Sanada-Morimura 2010).

Rice panicle blast, Jiangxi Province, China (photo: Bo Ming))

Rice orange leaf disease (ROLD; Ou 1987), caused by rice orange leaf phytoplasma (ROLP), is an emerging disease in South China, which is transmitted by yet another leafhopper (*Nephotettix cincticeps*; Li et al 2015).

Emergences of other diseases have also been recorded. These are mostly fungal, flower and panicle diseases, such as the spikelet rot disease (Huang et al 2011) caused by a mix of fungi, some of which produce mycotoxins.

Ecosystem services, as affected by plant disease

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

As indicated in earlier sections, the [Rice x East Asia] system has been performing a major role in the nutrition of over 2 billion humans. As population increased, the system has been able to increase regularly its performances (Fig. 1) so as to provide enough staple to the populations of East Asia. This is a major achievement of agricultural sciences in East Asia. It is foreseen that rice will remain the most important food crop in East Asia even in a distant future.

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

Progress of the [Rice x East Asia] PlantSystem in generating food has overcome, but is still now facing, many challenges (Peng et al 2009). These challenges are: (1) the narrow rice genetic background, (2) the overuse of chemical fertilizers and pesticides, (3) difficulties in maintenance of irrigation infrastructure, (4) oversimplified crop management, (5) a weak extension system, and (6) the overall increasing population of East Asia. All these difficulties have direct or indirect links with plant health. They take place, are related with, or are generated by

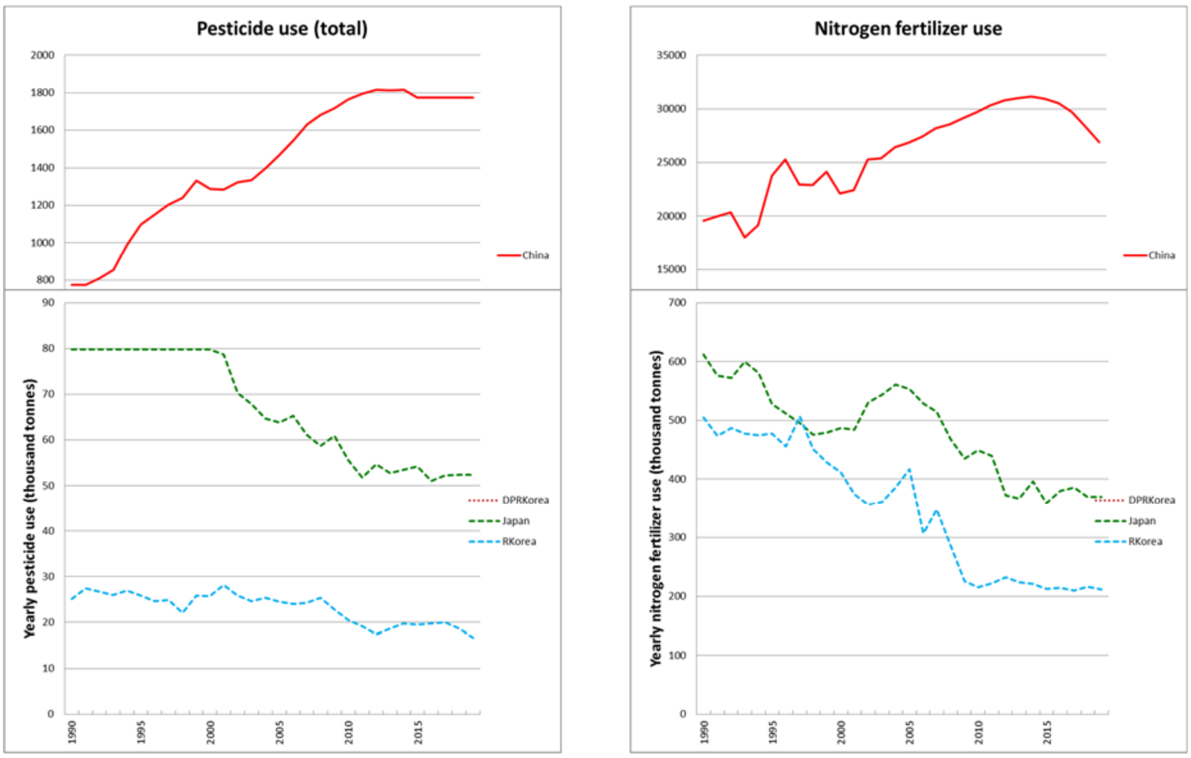


Figure 2. Pesticide and nitrogen fertilizer yearly use by country

current trends: the decline in arable land in China, the increasing water scarcity, global climate change, and labour shortages.

Better mineral fertiliser application practices have been extensively studied (Peng et al 2010), especially in China. Better fertiliser practices (especially nitrogen) are one angle to manage plant disease, especially sheath blight (Savary et al 1995). However, as Fig. 2 suggests, research has had limited impact in China, except for a limited decline in fertilizer use after 2015. Mineral fertilizer use is still extremely high in China. Nitrogen fertilizer use in Korea and Japan has been on a steady decline since 2000 (FAOSTAT 2021).

Pesticide use is extremely high in China, although a stabilisation has taken place since 2012. Japan's use of pesticides in weight is on a steady decline since 2000. This contrasts with Korea, where pesticide use is high although showing a declining trend (FAOSTAT 2021). Since 2015, the Chinese government has carried out research on the technology of "double reduction" of both pesticides and chemical fertilizers to control environmental pollution (Shuqin and Fang 2018). Plant pathogens and pests are now considered in China as a main obstacle to progress towards food security (Hu et al 2016). Addressing this obstacle will be long and difficult, because it will entail a progressive process where several entry points will need simultaneous consideration in order to reduce disease and pest losses while reducing agricultural effluents (pesticides, fertilizers) and maintaining rice yields to an acceptable level. This will require strengthen scientific research. As the international propagation of disease and disease emergences show, international research will have a critical role to play; this will necessarily imply international collaboration in plant breeding.

Note: data are for total national yearly use, and cover all crops in each country. Data are therefore not for rice cultivation only. Data source: FAOSTAT (2021).

Complementary information

Own assessment of the findings of the present report: reasonably confident: a number of studies, publications, support our views. There are gaps in the literature.

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Rice-Wheat system in South Asia

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Background information

The Rice-Wheat System (RWS) of South Asia is one of the critical granaries and food production hotspots in the world. The system expands across the Indo-Gangetic plains from Northern Pakistan, to India, to Nepal and to Bangladesh. Overall, this swath of cultivated land is home to about 20% of the world population (Chauhan et al 2012) and includes a number of the world's megacities, including Delhi, Kolkata, Dhaka, and Lahore (approx. 30.3, 16.8, 20.2, 13.0 Million inhabitants, respectively; Wikipedia 2021).

Agriculture has been in existence in various forms for several centuries in the Indo-Gangetic plains, probably a partial emanation of the much older agriculture and civilization centre established along the Indus River (Thapar 2002). The Indo-Gangetic Plains may be seen as one of the major cradles of agricultural emergence, comparable to the much older Neolithic cultures of the Middle-East (the 'Fertile Crescent') and of the Indus Civilizations, but roughly contemporaneous with the Chinese cradles of the Yangtze-Yellow River Basin, of Central Mexico, and of Central America. History suggests that most of the Indo-Gangetic plains were initially heavily forested, giving rise, along with river alluvium brought by frequent floods, to highly fertile soils (Thapar 2002). It also seems that rice (and barley) was by far the most frequent cereal first grown in the Indo-Gangetic plains, wheat being a comparatively newcomer (Thapar 2002). This explains why today the region is considered a major source of rice genetic diversity (Singh et al 2013; 2014).

The RWS of today's South Asia is an extremely diverse agro-ecosystem (Chauhan et al 2012; Erenstein and Thorpe 2011), where rice and wheat are omnipresent, but are spatially and temporally combined with sugarcane, potato, mustard, maize, and a wide diversity of field legumes and a host of vegetables, generating the

Rice transplanting, Northern India (photo: S Savary)

Wheat fields harvested, Northern India (photo: S Savary) essential protein, vitamins and fibre sources to the large vegetarian fraction of the population.

Fertile land and widespread availability of water, contrasted seasons, along with an extensive labour force, all conspired in the growing importance of agriculture in the Indo-Gangetic plains, and then of the RWS of South Asia. This is also why declining soil fertility, increasing water scarcity, and population and labour challenges, combined with increasing pollution and climate change effects are today threatening the very existence of the system, potentially with major consequences at the regional and global scales.

This report focuses on the provisioning services, especially food, generated in the RWS.

PlantSystem considered in this report

This report focuses on the production of rice and wheat in the RWS, and the health of these two crops. The actual yields of both rice and wheat vary across the Indo-Gangetic plains.

Table 1 shows that despite differences in the two cereal productions and differences in actual yield estimates among authors (Timsina and Connor 2001), the rice and wheat production in the Indo - Gangetic plains contribute to a substantial fraction of the national food security of four countries (from 71% in Nepal to 100% in Bangladesh).

The RWS of the Indo-Gangetic plains therefore plays a key role in the level of food security in South Asia. The development of the system and its current performances constitute one of the key achievements of the Green Revolution (Evenson and Gollin 2003), which enabled massive progress in the production of the two main world staples in one critical ecoregion of the world, through the deployment of high-yielding, short-straw varieties of rice and wheat.

Over the years, concerns have been growing for both the performances and the sustainability of the system. The yield performances of the system have stagnated during the last decades (Erenstein and Thrope 2011); and sustainability issues have mounted with respect to (1) water supply (Chauhan et al 2012) with water tables steadily deeper, (2) decreasing soil fertility (Chauhan et al 2012), (3) irrigation water and soil salinization (Chauhan et al 2012), environmental and pollution issues associated with crop residue management (Chauhan et al 2012), (4) greenhouse-gas emissions, (5) nutrient imbalances in soils and (6) grave concerns about drinking water quality associated with arsenic and selenium contamination (Nawaz et al 2019; Timsina and Connor 2001). These problems are overlaid on (i) a very diverse, heterogeneous system (Erenstein and Thorpe 2011) where the impacts of these problems, their perceptions, and

Country	Area (Mha)	Contri-bution (%)	Yield (t/ha)				Production (M tons)			
			Rmin	Rmax	Wmin	Wmax	Rmin	Rmax	Wmin	Wmax
India	10.3	85	2.9	5.8	2.6	2.8	29.9	59.7	26.8	28.8
Pakistan	2.2	92	2.9	3.7	2	2.1	6.4	8.1	4.4	4.6
Bangladesh	0.5	100	2.8	4.3	2.2	3.1	1.4	2.2	1.1	1.6
Nepal	0.6	71	2.4	3.8	1.6	2.7	1.4	2.3	1.0	1.6

Table 1. Areas under Rice (R)-Wheat (W), national contribution to cereal consumption, actual yields (minimum and maximum for rice – R and wheat – W) and actual national productions (minimum and maximum for rice – R and wheat – W) in the Indo-Gangetic plains (from Timsina and Connor 2001, modified).

the available options will vary, (ii) the unfolding consequences of climate change, with heat waves, floods, and melting glaciers, and (iii) rapid societal changes among rural and urban populations (Erenstein and Thorpe 2011).

Wheat and rice health in South Asia

F

State of wheat and rice health in the past 30 years

The literature broadly indicates that the primary wheat diseases in South Asia during the past 30 years (1990-2020) are: leaf rust (*Puccinia triticina*), stripe rust (*P. striiformis*), and leaf blight, which involve a complex dominated by the spot blotch pathogen (*Bipolaris sorokoniana*), along with the tan spot pathogen (*Pyrenophora tritici-repentis*) and *Alternaria triticina* (Duveiller et al 1997). As in most wheat-producing regions in the world, the leaf and stripe rusts have been persistent and major threats, however generally controlled by the efficient deployment of host plant resistances (Duveiller et al 2007). But the case of leaf blight is different, because the breeding of host plant resistance has been difficult (several different pathogens involved with very similar symptoms, resistance genes mostly in the form of quantative trait loci (QTL), and yet a strong genetic flexibility of the main pathogen, *B. sorokoniana*; Duveiller et al 1997). There is an overall agreement among experts in considering that the expansion of the rice-wheat rotations has been associated with an increase in the importance of these blight diseases, for a number of possible reasons, some of which are not yet fully understood (for example, an increase of organic matter as rice stubbles on which the pathogens may multiply; soil characteristics; the presence of alternate weed hosts; Duveiller et al 1997).

Wheat loose smut, Northern India (photo: M Singh)

With respect to rice, the same 1990-2020 period may be considered a stabilisation of progress made during and rapidly after the Green Revolution. Major diseases such as rice blast and bacterial blight have been generally under reasonable control, mainly because of suitable resistance genes deployed in rice varieties (Nagarajan 1994). The importance of bacterial blight, however, is consistently reported in the literature, especially from India (Gnanamanickam et al 1999), where a minimum level of resistance to bacterial blight is now required for any new variety registration (Darshan Brar Comm. Pers.). Rice tungro disease epidemics, sometimes considered a major threat to rice health in the Indo-Gangetic plains in the 1990s (Nagarajan 1989) did not materialise. Brown spot (caused by *Bipolaris oryzae*) occupies in rice a status analogous to the blight diseases of wheat. Both occupy similar ecological niches: brown spot is also associated with unfavourable soil characteristics (low phosphorus and nitrogen); with water shortages; with survival in soil and crop residues; and it also is seed-transmitted (Barnwal et al 2013). As is the case of wheat blights, plant breeding for brown spot resistance in rice has been difficult and generally unsuccessful so far, for similar reasons (partial resistance governed by several QTL; pathogen flexibility; and the selection and breeding rendered much harder by the interaction of genetic plant resistance with soil and climate physical factors; Barnwal et al 2013). As is the case of wheat blights, rice brown spot causes important yield losses, especially in less-favoured environmental (and technical) contexts (Singh et al 2003). And, similar to wheat blights, the importance of brown spot of rice has been on the rise (Barnwal et al 2013).

Brown spot on rice (photo: S Savary)

Evolution of wheat and rice health over the recent 10 years

The recent history of wheat health has been very eventful globally. The emergence of new strains of stem rust in East Africa has been a major concern in the 2000s (Singh et al 2008), globally and in South Asia in particular. However, as discussed by Nagarajan (2012), the Indo-Gangetic plains have been spared from the epidemic. In 2016, an epidemic of wheat blast (caused by *Pyricularia graminis-tritici*) occured in Bangladesh after the accidental introduction of the pathogen from Brazil (Ceresini et al 2018). The following years saw anxious monitoring of the disease in South Asia (Ceresini et al 2018), along with a flurry of publications. The 2016 epidemic did lead to a series of aftershocks that appear to have been limited to Bangladesh. There seems to have been a first geographical expansion of the disease in prevalence; but this was combined with a decline in severity. This would suggest that the epidemic of wheat blast in South Asia is going extinct. If true, this would support the view that the pathogen is a new species, and that it requires environmental conditions (including, especially, a host on which to overwinter and massively multiply; Ceresini et al 2018), which are not found in Bangladesh and surrounding countries.

In South Asia, and the Indo-Gangetic plains, the wheat blight diseases remain a major concern, with strong indication that this type of disease, spot blotch in particular, is strongly associated with climate change and increasing temperatures during the growing season (Sharma et al 2007).

The overall state of rice plant health is a source of concern in the Indo-Gangetic plains. Surveys conducted by the Directorate of Rice Research of India indicate both a decline in plant health and a shift in pathogen importance. Survey data of 2005, for instance, indicate that high levels of bacterial leaf blight epidemics are frequently observed (Reddy et al 2011). The same data also indicate the emergence of false smut (*Ustilaginoidea virens;* teleomorph: *Villosiclava virens;* Fan et al 2016) in the Indo-Gangetic plains, and a significant statistical link existing between false smut epidemics and the deployment of hybrid rice (Reddy et al 2011). False smut is partly a concern because of yield reduction, but is a serious concern because of the mycotoxins associated with the disease and their toxicity to humans (Fan et al 2016). While the management of bacterial leaf blight through host plant resistance is an achievable goal even in the very susceptible high-quality rice varieties, the development of resistant rice varieties against false smut, despite recent progress towards mapping of QTL for partial resistance (Han et al 2020), is difficult. This opens the door towards worrisome use of fungicides, with serious consequences for poor farmers, the environment and consumers.

Ecosystem services, as affected by plant disease

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

Despite disease problems, the overall performances of the RWS in terms of food production may be considered as adequate (Chauhan et al 2012).

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

Despite increasing disease problems, the overall performances of the RWS in terms of stability of food production may be considered as adequate (Erenstein and Thorpe 2011; Timsina and Connor 2001).

Complementary information

The sustainability of the RWS of the Indo-Gangetic plains is a research topic of its own, and many scientists are concerned about its performances over the coming decades (Chauhan et al 2012; Erenstein and Thorpe 2011; Timsina and Connor 2001).

Plant diseases have been overlooked in the overall assessment of the sustainability of the system. Yet, there are clear indications that some specific diseases of wheat (Spot blotch; Sharma et al 2007) and of rice (Brown spot; Barnwal et al 2013), are clearly contributing to a decline in performances, especially under changing climate conditions.

Assessment of the findings of the present report: reasonably confident: a number of studies and publications support our views, but there are gaps in the literature.

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Wheat in East Asia

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Background Information

East Asia is the eastern region of Asia, bordering north with North Asia, south with Southeast Asia, southwest with Southwest Asia, west with Central Asia, and east with the Pacific Ocean https://en.wikipedia.org/wiki/East_Asia). East Asia occupies 11,839,074 km^2 and consists of China, Japan, Mongolia, North Korea, and South Korea. The population of East Asia was estimated as 1,666,471,330 in 2018, that is, about 22% of the world total population, ranking as the second most populated region of the world. The mean population density is about 140 people per square kilometre.

Wheat is a major staple food crop in East Asia. With 134.3 million metric tons (i.e., 17.4% of the world production) of wheat produced in 2017, China is the largest wheat-producing country in this region, and also in the world. (https://en.wikipedia.org/wiki/International_wheat_production_statistics). Because the other countries of East Asia only produce a limited amount of wheat (0.925 million metric tons in 2014; https://en.actualitix.com/country/asie/east-asia-wheat-production.php) and mainly import wheat to meet their consumption needs, this report focuses on wheat production and wheat health in China. The present report mainly concerns the Provisioning Service group in the Ecosystem Services.

In some areas of China, wheat is grown from valleys to top of mountains (photo: Xianming Chen)

PlantSystem considered in this report

Bread wheat is the second most grown grain crop in China, on 21.6 to 26.7 million hectares in the period 2000-2019 (http://data.stats.gov.cn/easyquery.htm?cn=C01&zb=A0D0F&sj=2019; https://ipad.fas.usda.gov/highlights/2014/12/China/index.htm; http://www.fao.org/giews/countrybrief/country.jsp?code=CHN&lang=en). Durum wheat is not grown in China. The wheat-cultivated area represents about 13% of the total cultivated agricultural area of China (Cock et al 2016). The wheat-cultivated area increased by 1.5 million hectares between 2005-06 and 2009-10, but was

Wheat crop starts maturing in fields, China (photo: Xianming Chen)

relatively stable afterwards, over the past 10 years. Wheat is grown in 30 of the 31 provinces of China, but especially in the North China Plain and Yellow and Huai River valleys. Winter wheat, representing 95% of the total wheat area, is mostly grown throughout the country while spring wheat, which accounts for only 5% of the total wheat area, is grown in the north-eastern and north-western regions of China. The area under spring wheat has been reduced from 6 million hectares to 1.5 million ha since late 1990s (http://wheatatlas.org/country/environment/CHN/0?AspxAutoDetectCookieSupport=1). In the Yellow River and Huai River valleys of China, wheat is mostly rotated with maize, and along the Yangtze River Valley, wheat is more commonly rotated with rice. The top ten wheat-producing provinces of China are Henan (36.03 million metric tons), Shandong (24.72), Anhui (16.07), Hebei (14.51), Jiangsu (12.89), Xinjiang (5.72), Hubei (4.10), Shaanxi (4.01), Gansu (2.81), and Sichuan (2.47) based on the 2018 production statistics (https://www.statista.com/statistics/242630/wheat-production-in-china-by-province/).

Wheat yield in China has steadily increased over the past decade despite periodic droughts and diseases. The total wheat production in China has increased from 98.23 million metric tons in 1990 to 133.59 million metric tons in 2019 (https://www.indexmundi.com/agriculture/?country=cn&commodity=wheat&graph=production). This represents an average yearly increase of 1.45% over the past 30 years. China's average wheat yield (about 5.23 $t.ha^{-1}$) is among the highest in the world. Such high yields have been achieved through widespread irrigation, the development of high-yielding varieties, adequate supply of inputs, and strong government financial support (USDA FAS 2014).

Wheat is a major staple source for the population of 1.4 billion in China (about 22% of the world population), accounting for 40% of the grain consumption in the country (https://en.wikipedia.org/wiki/International_wheat_production_statistics). Although China is the first wheat producing country worldwide, the country needs to import a small fraction of wheat from other countries to meet its national consumption. From 1990 to 2019, China imported over 3.86 million metric tons of wheat on average each year (https://www.indexmundi.com/agriculture/?country=cn&commodity=wheat&graph=imports). The import quantity decreased from 15.9 million metric tons in 1991 to 0.5 in 2007 but varied greatly from year to year. Such large variation is partly attributed abiotic and biotic stresses, including diseases.

Wheat health in East Asia

State of wheat health in the past 30 years

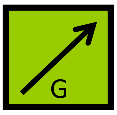
Wheat can suffer damage caused by numerous diseases in China. Major diseases include stripe rust (yellow rust) caused by *Puccinia striiformis*, powdery mildew caused by *Blumeria graminis*, Fusarium head blight (scab) caused by *Fusarium graminearum* (teleomorph *Gibberella zeae*), leaf rust caused by *Puccinia triticina*, root and foot rot caused by *Cochliobolus sativus*, sharp-eye spot caused by *Rhizoctonia cerealis*, flag smut caused by *Urocystis agropyri*, wheat spindle streak mosaic caused by the *Wheat Spindle Streak Mosaic Virus* (WSSMV), take-all caused by *Gaeumannomyces graminis* var. *tritici*, and common bunt caused by *Tilletia caries* (Cock et al 2016). Other viral pathogens such as the *Soil-Borne Wheat Mosaic Virus* (SBMWV) and *Chinese Wheat Mosaic Virus* (CWMV) are also considered as long-term threat to wheat production in China (Guo et al 2019). Viral diseases alone can lead to yield losses varying between 10–30% in diseased wheat fields (Guo et al 2019). Wheat aphids are also very serious in many wheat production areas, because they transmit several viruses, in addition to the direct damage they cause.

Stripe rust is one of the most important wheat diseases in East Asia, especially China (photo: Xianming Chen)

Evolution of wheat health over the recent 10 years

China has made considerable progress in wheat disease management over the recent 10 years. A nation-wide system for wheat disease and pest research and control has been established, including scientists and extension specialists at universities and institutes at the regional, provincial, and national levels. These constitute a national network for research, monitoring, and management implementation. Funding for research and management of major diseases of wheat has increased over the years, an increase probably larger than in many other countries. Forecasting and early warning are made every year for possible disease and pest outbreaks. Specific prevention and control measures are recommended by expert scientists and implemented by farmers and/or plant protection corporations through guidance from various levels of governmental agencies. Wheat disease and pest management has become increasingly science-based, effective, and efficient. To control the main diseases of wheat such as stripe rust, powdery mildew, and Fusarium head blight, the development of wheat cultivars that carry durable resistances has been recognized by the scientific community and adopted as a primary target of breeding programs. However, chemical control is still currently the most common approach for disease management. Since a majority of the wheat production is still achieved by individual farms with very small landholdings, and because a very large fraction of the workforce moves to cities, timely application of chemicals is an important challenge for disease and pest management. To address this problem, various sizes of plant protection companies have been established, which apply chemicals for managing diseases and pests. To prevent major disease epidemics and yield losses, and also to reduce the number of chemical applications, the approach of "One Application to Prevent Three Problems" (insects, diseases, and inadequate crop growth), involving a mixture of insecticides, fungicides, and plant growth regulators, has been used in wheat production in recent years. New technologies have also been used to improve disease management. For example, use of unmanned aerial vehicles (UAV) has become popular in disease monitoring and chemical application. Plant protection companies and use of new technologies have at least partly solved the problem of workforce shortage in disease management.

Ecosystem services, as affected by plant disease



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

Over the past 30 years, i.e., since the early 1990s, Chinese agriculture changed from collective-based to individual family-based. Although at relatively small scales, co-operative production has emerged to solve the labour shortage issue, since young and middle-aged farmers go to cities for work. Agricultural land has been declining with urban expansion (Güneralp et al 2020; Jiang et al 2013). Growing other crops instead of wheat in some regions has been practiced to avoid damage by diseases, especially stripe rust (Li and Zeng 2002). However, wheat production and protection are generally effective, as the national yield has been increased by average 1.45% on a yearly basis over the past 30 years (https://www.indexmundi.com/agriculture/?country=cn&commodity=wheat&graph=production). This increase mainly results from high-yielding cultivars, expanding irrigation, and high input of fertilizer and chemicals for control of diseases and pests. Reduction of wheat and other crop cultivation in some mountain and hill slopes for reforestation purposes has had favourable effects to the country's overall ecosystem.

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

Over the recent 10 years, plant health achieved by the prevention and control of major diseases has enabled the Chinese national wheat production to regularly increase despite the challenge of land reduction. This has contributed to food security, both in China and in the world. Prevention and control of stripe rust would save more than 2 million metric tons of wheat grain every year (Chen et al 2014). As mentioned above, reduction wheat land in mountain slopes for reforestation has significantly contributed to improve the overall ecosystem in China. The increase of wheat production under the reduction of land by developing high yield cultivars, and to some extent, through the development of disease resistant cultivars, and increasing irrigation, fertilizer and chemicals for control of diseases and pests, has enabled land use diversification, leading to the cultivation of other crops, especially fruits and vegetables (Li 1998; Textor 2020; USDA-FAS 2019). This has improved overall living standard in China (DCCC 2017). However, challenges still remain to make wheat production more profitable for farmers by reducing inputs while sustaining yield increase. This especially concerns the reduction of fertilizer and pesticides to improve the environment and ecosystem.

Complementary information

Three elements in the recent years require specific attention.

- First, the rational use of pesticides and fertilizers has been promoted and has started to be practiced to protect the environment.
- Second, the "One vote vetoes release" system, which leads to rejection of a given variety if it lacks resistance to one of the main diseases of wheat, has been used in many provinces. This system has promoted the development of wheat varieties with resistances to the main diseases such as stripe rust. This system, however may leave other diseases un-addressed in breeding programs. This system may also encourage the use of major genes for disease resistance that

may be overcome by new pathogen races or strains. Nevertheless, breeding and growing disease-resistant varieties is receiving more attention in China today and breeders have started to pay more attention to the development of wheat varieties with durable resistance to major diseases.

- However, many problems remain to be addressed in wheat resistance breeding. For instance, focusing on only one pathogen or pest is not adequate for addressing multiple disease and pest issues, which may lead to minor diseases or pests becoming major problems. Research is needed to study the damage of various diseases and pests and the effects of various methods, such as development and appropriate deployment of resistant cultivars with various resistance genes versus the use of chemicals or the combination of resistances and chemicals, the use of fertilization regimes on diseases, for achieving plant health and improving environments. As high yield has been the top priority for wheat production and many other crops in China, full tillage still is the main practice. No-till and reduced tillage require more investigations. Developing more effective, efficient, and environmentally favourable approaches for plant health, especially for wheat production in China and other countries in East Asia, is an on-going challenge for scientists.

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Wheat in Western Europe

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Background information

Wheat is the most important cereal crop in Western Europe both in terms of production (80-90 million tons) and of total area planted (about 12 million hectares) (EUROSTAT 2020; FAOSTAT 2020). Wheat is included in crop rotations of a large portion of agricultural land in this Ecoregion. Wheat in Western Europe is in general grown under intensive conditions, with high inputs of synthetic fertilisers and pesticides (Savary et al 2017; Singh et al 2016), resulting in high yields ranging from 5 to 10 t/ha (EUROSTAT 2020; FAOSTAT 2020). Soft winter wheat represents the majority of wheat grown in this region, whereas durum wheat and spring wheat only account for 10% and less than 3% of the total wheat acreage, respectively. This report focuses, therefore, on soft winter wheat.

Wheat harvested in Western Europe is important both for regional and global food security: three quarters of the wheat produced is consumed in Western Europe and the remaining is exported (about 20-25 million tons; FAOSTAT 2020). The agri-food industry associated with wheat, from crop production inputs (seed, fertilisers, pesticides) to food processing, is an important economic sector, employing many people.

Wheat has been grown in Western Europe for several millennia. This crop had and still retains a high cultural value. This is illustrated for example in paintings and poems representing wheat fields

Wheat field in Northern France (photo: L Willocquet) or landscapes. Wheat fields are part of the familiar landscapes of Western Europe. The cultural value of wheat also resides in its use for specific human food items that are culturally associated with specific geographical regions, such as bread (from soft wheat) and pasta (from durum wheat). Because of the overwhelming importance of wheat in terms of food provisioning for Western Europe, this report focuses on this ecosystem service.

Wheat field in South of France (photo: L Willocquet)

Wheat health in Western Europe

State of wheat health in the past 30 years

Wheat in Western Europe has been exposed to a range of diseases (CABI 2020; Figueroa et al 2018; Jørgensen et al 2014; Savary et al 2017; 2019; Singh et al 2016; Willocquet et al 2021). Several of them mainly damage the leaves: powdery mildew (*Blumeria graminis* f. sp. *tritici*), brown (leaf) rust (*Puccinia triticina*), yellow (stripe) rust (*Puccinia striiformis*), septoria tritici blotch (*Zymoseptoria tritici*), tan spot (*Pyrenophora tritici-repentis*), and stagonospora nodorum blotch (*Parastagonospora nodorum*). Collectively, these foliar diseases represent the main yield-reducing factors for wheat in Western Europe. The main disease on ears is fusarium head blight (*Fusarium* and *Microdochium* spp.), which not only reduces yields but also affects the grain quality because of the production of mycotoxins by some *Fusarium* species (Singh et al 2016). Other wheat diseases which impact production in parts of Western Europe include: systemic diseases mainly caused by viruses such as barley yellow dwarf virus (BYDV) and soilborne wheat mosaic virus (SBWMV); stem diseases such as eyespot (*Oculimacula yallundae*), and sharp eyespot (*Rhizoctonia cerealis*); root and basal stem diseases, mainly represented by take-all (*Gaeumannomyces tritici*) and common root rot (*Cochliobolus sativus* and *Bipolaris sorokiniana*) (CABI 2020); and snow moulds (*Microdochium* spp. and *Typhula* spp.), which may have serious impact in the northern parts of the region where winter wheat can be grown.

Leaf rust (photo: L Willocquet)

These diseases have been reasonably well controlled by the use of fungicides and resistant cultivars, together with cultural practices such as crop rotation, tillage, and residue management. The resulting overall wheat health status has been good, although varying over regions and years because of outbreaks of specific diseases. For example, leaf rust outbreaks occurred when widely used major resistance genes broke down, and FHB outbreaks occurred when weather conditions were favourable to infection (Singh et al 2016; Willocquet et al 2021).

Evolution of wheat health over the recent 10 years

Several wheat diseases have re-emerged or have gained importance over the past 10 years, resulting in declining wheat health in Western Europe. New strains of *P. striiformis* (yellow rust) overcame resistances in wheat cultivars, causing severe epidemics over the last years in large areas of Western Europe (Hovmøller et al 2016). Stem rust (*Puccinia graminis* f. sp. *tritici*) has been observed in different parts of the region over the past years, and is now established in Italy (Saunders et al 2019). Brown rust is increasing in importance in autumn in winter wheat, because of increased temperatures as climate change unfolds. Extreme weather events can trigger disease outbreaks and result in considerable crop losses, such as the fusarium head blight outbreak in Northern France in 2016 which was associated with heavy rainfalls at the time of flowering. Septoria tritici blotch has progressively become the main chronic yield reducing factor in many parts of Western Europe (Fones and Gurr 2015). This increased importance is partly due to the adaptation of the pathogen population to fungicides.

Stripe rust (photo: L Willocquet)

The decline in wheat health is a result of evolutions in wheat disease and crop management, which make wheat crops more vulnerable to disease. With respect to disease management, the efficacy of fungicides used has decreased, because of (i) adaptation of pathogen populations becoming less sensitive to fungicides (especially in the case of septoria tritici blotch); (ii) a decreased availability of protectant fungicides (which are less prone to pathogen population adaptation) because of legislation shifts; and (iii) reduced number of new chemicals with different modes of action. A decrease in the level of cultivar resistance is also observed in parts of Europe, associated with (i) the emergence of new strains overcoming the resistance genes deployed in cultivars (e.g., yellow rust), and (ii) a reduced priority level given to disease resistance in plant breeding programmes. With respect to crop management, the evolution of cropping practices has generated conditions which are more favourable to pathogen survival: (i) a decrease in diversity in crop rotation in many parts of Europe, except in the UK where crop rotations were already poor; and (ii) an increase in practices related to conservation agriculture, associated with reduced tillage, which favours the survival of pathogen inoculum in soils and on plant debris (e.g., fusarium head blight and septoria tritici blotch).

Ecosystem services, as affected by plant disease

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

Wheat yields in the past 30 years in Western Europe have been high, with a steady increase from 5 to 8 t/ha between 1980 and 2000, followed by a 20-year period of yield stagnation (Brisson et al 2010) between 8 and 9 t/ha, and associated with larger inter-annual variation. These yield trends have translated into an increasing, and then plateauing production (FAOSTAT 2020). This good level of production has been achieved in spite of the presence of diseases, which cause about 24% yield loss in the region according to a recent expert-based assessment (Savary et al 2019).

This provisioning service has been meeting demands from Western Europe, and worldwide through exports. The global demand of wheat has increased over the last 30 years, mainly as a result of population growth and changes in diets (Shiferaw et al 2013).

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

Despite the decline of wheat health over the past 10 years, wheat yield and production have remained high and achieved the primary aim of provisioning service in Western Europe, despite an overall stagnating yield over time with considerable inter-annual variation (EUROSTAT 2020; FAOSTAT 2020). The inter-annual variation in production over the last 10 years is partly associated with lower crop performance in years where diseases affected large wheat production areas (e.g., break-down of resistance genes against yellow rust in 2011, 2012, and 2016; favourable weather conditions for fusarium head blight in 2016). This provisioning service has been maintained through intensive fungicide use and deployment of resistance genes.

Complementary information

We wish to outline aspects related to the physical (climatic) and biological environments of wheat crops in Western Europe which may have important consequences on wheat health and its impact on wheat provisioning in the near future.

Climate change in Western Europe is associated with an increase in mean temperature and climatic variability, and more frequent occurrences of extreme weather events (Kahiluoto et al 2019). These conditions (1) may trigger disease outbreaks, as experienced in 2016; and (2) may render the environment favourable to the establishment of pathogens that develop under warmer conditions, such as wheat stem rust. It would also be relevant to ascertain the risks on wheat production caused by invasive pathogens, e.g. *Pyricularia graminis-tritici* causing wheat blast.

The positive influence of arbuscular mycorrhizal fungi is lower in modern wheat cultivars as compared to landraces (Zhang et al 2019). This trend may result from breeding strategies which have mainly focused on traits localised in the aerial parts of plants. This decline of phytobiome (e.g., mycorrhizal fungi) in modern cultivars may increase the risk of soilborne pathogens and reduce the resource use efficiency of wheat crops.

Wheat health and future provisioning is currently highly dependent on the availability of efficient fungicides. The intensive fungicide use in large wheat production areas is not sustainable. Furthermore, stricter regulations on the use of fungicides, increase of fungicide resistance in pathogen populations, and the increasing difficulties to develop new products (cost, regulations, market) render the production system vulnerable. There is an urgent need to develop alternative disease management strategies. This necessarily entails breeding for wheat cultivars with (1) durable resistance to multiple pathogens, and (2) proper phytobiome adaptation to farmers' soils and environments.

Level of confidence in the assessment: Very confident. A large body of recent references were used to develop this report.

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Wheat in South America

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Background information

The main wheat producing countries in South America (SA) are: Argentina (68%), Brazil (20%), Chile (5.4%) and others (6.3%, Paraguay, Uruguay). These countries collectively produced a total of 18.51 (63% for export) million tons in 2018 (FAOSTAT 2018). The flat and temperate climate of the Pampas region of Argentina (AR) accounts for most of the SA wheat production (Soriano et al 1991; Matteucci 2012). There are two distinct wheat production regions in Brazil (BR): (1) the traditional, subtropical climate, regions of south BR (PR, SC and RS states); and (2) the more recent ones (< 20 years) in the Cerrado biome (Goianas and Mato Grosso States; Cunha et al 2006).

In the Pampas (AR and South BR), wheat is grown during winter-spring season, with harvests from August to January. Rainfall is generally well distributed throughout the year. The wheat season in these regions is strongly influenced by ENSO, with warmer and wetter El Niño years and drier and cooler La Niña years (Anderson et al 2017).

In the BR Cerrado, wheat is grown during the winter (dry) season (March to September) with or without irrigation. The non-irrigated crops are grown in March when the soils are sufficiently wet to produce yields close to those obtained in the South (~3,000 kg/ha). Irrigated wheat is sown from April to May on (highly fertile) soils after vegetable crops, with yields that are much higher (~7,000 kg/ka).

PlantSystem considered in this report

Wheat is the most important cereal crop in SA. In AR, the leading wheat-producing country, the cultivated area was 6.8 million hectares with a total production of 16.3 million tons and with yields averaging 2,990 kg/ha in the 2019/20 season (Secretaría de Agroindustria, Argentina, 2020).

The area sown to wheat in BR was 17% higher in 2021 with 2.7 million hectares. Total production was 7.7 million tons with yields averaging 2,800 kg/ha (CONAB, 2021). The main wheat-growing areas are in the Southern region of Brazil, but a significant expansion of wheat cultivation in the Cerrado has occurred in the last five years. Expert opinion predicts an expansion potential to up to 3 million ha of wheat in the tropics.

Wheat health in South America

State of wheat health in the past 30 years

Wheat is affected by several diseases which vary in importance among regions of South America, mainly due to spatial distribution of the diseases which is likely shaped by climatic differences. Overall, most of the economically significant diseases can be successfully managed, however at significant economic costs.

In the Pampas (temperate climate) the most important diseases include stripe rust (*Puccinia striiformis* f. sp. *tritici*), leaf rust (*Puccinia triticina*), tan spot (*Drechslera tritici-repentis*), stem rust (*Puccinia graminis* f. sp. *tritici*) and leaf blotch (*Parastagonospora nodorum*). Among these, leaf blotch decreased in importance during the last 30 years, usually not requiring a specific control. In contrast, tan spot replaced leaf blotch in importance, probably as a result of the expansion of no-till practices and the use of infected seeds (Carmona 2006; Carmona et al 1999). Leaf rust has historically been more prevalent than stem rust (Carmona et al 2000; Germán et al 2007; Moschini and Perez, 1999), but the latter has appeared in susceptible cultivars (Campos 2019). Fusarium head blight (FHB, *Fusarium graminearum*) is of sporadic occurrence in the Pampas occasionally causing serious losses, ranging from 10 to 30% in 1978, and 24 to 50% in 1993 (Reis and Carmona 2013).

In BR, disease importance and ranking also depend on the region. In the Cerrado, the most important diseases are: wheat blast (*Pyricularia oryzae* Triticum pathotype), spot blotch (*Bipolaris sorokiniana*), bacterial leaf blight (*Xanthomonas translucens* pv *undulosa*), tan spot and powdery mildew (*Blumeria graminis* f. sp. *tritici*). In Southern BR, the main diseases of wheat are: FHB, powdery mildew, tan spot, the newly identified virus soil-borne wheat mosaic disease-(SBWMD; Stempkowski et al 2020; Valente et al 2019), BYDV (barley yellow dwarf virus), and leaf rust. Spot blotch has declined in importance over the last 30 years, being replaced by tan spot.

Bacterial leaf blight (photo: Paulo Kuhnem)

Soil borne wheat mosaic virus (photo: Paulo Kuhnem)

Localized losses have occurred due to extreme (climatic) events and/or failures in fungicide applications. The increasing use of modern, improved, cultivars, crop rotation, seed treatments and fungicides have been effective to protect yield from losses due to plant diseases. Two to four fungicide applications are usually performed. In the Pampas, fields are planted without rotation with one or two fungicide applications.

Evolution of wheat health over the recent 10 years

Recent shifts in importance and re-emergence of diseases have been observed in SA, leading to year-to-year variation of plant health. In the Pampas, the major emergent disease is stripe rust, while leaf rust and tan spot remain endemic. Stripe rust was first observed in Argentina in 1929 attacking almost 80% of the total wheat grown area (Humphey and Crowell 1930). The following year the disease caused severe epidemics causing losses estimated at 2 million tons, representing 30% of the total production of that year (Carmona et al 2020b; Fernández Valiela 1979; Lindquist, 1982).

Tan spot (photo: Paulo Kuhnem)

Argentina wheat farmers faced the worst stripe rust epidemics since the late 1920s in the last decade: three million hectares were affected, with reports of severe losses (Global Rust Reference Center, 2018). Yield loss estimates of 70% were recorded in some fields due to newly introduced exotic races of *Pst* (Carmona et al 2019).

These epidemics led farmers to apply an additional fungicide application (Carmona et al 2020a). A major shift in leaf spot diseases was the replacement of *Zymoseptoria tritici* (septoria tritici blotch) by *D. tritici-repentis* (tan spot). The efficacy of fungicides decreased, particularly to control leaf rust and tan spot (Sautua and Carmona, 2021). Recently, two diseases caught the attention of the wheat sector: leaf blotch and bacterial leaf streak (*Xanthomonas translucens*, Erreguerena et al 2019). Powdery mildew, usually a secondary disease, has increased in importance since 2018. Among the rusts, leaf rust is endemic and affects susceptible cultivars. FHB is relatively stable, with the last severe epidemic in 2012/2013 season due to atypically favourable climatic conditions (Moschini et al 2001; 2004).

In Southern BR, stem rust has been controlled successfully through host plant resistance. Unlike the (Argentina's) Pampas, stripe rust is sporadic (presumably limited by warmer springs) and occasionally appears when spring is cooler and when inoculum is blown into the country from

Field damaged by wheat blast in Cerrado (photo: Paulo Kuhnem)

Argentina (Embrapa 2020). Potential adaptation to warmer temperature, which has been reported in other growing regions in the world (Mboup et al 2012), remains to be investigated in Brazil. Wheat blast is rare in Southern BR, but sporadically appears in regions at the transition to the tropical production areas of Northern PR state. FHB occurs every year in Southern BR, but with variable impact according to variation in seasonal weather (Duffeck et al 2020). There are currently no cultivars available with good levels of resistance to FHB and against accumulation of mycotoxins, which are currently under regulation (Anvisa 2011). Spot blotch is more important than tan spot in the Cerrado. However, wheat (head) blast is a major limitation to the expansion of wheat in the area. The disease occurs almost every year, but with variable intensity across years depending on the late summer rainfalls and window of sowing (Ceresini et al 2018).

Ecosystem services, as affected by plant disease

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

AR is the main wheat producer in SA. Historically, the release of high-yield cultivars together with disease management was a successful strategy in to improve yields. However, despite the intensity of the different diseases that affect wheat in Argentina, grain production remained at high levels, reflecting the different disease management tactics that have been implemented (resistant or tolerant cultivars, fungicides, etc.).

The wheat acreage in BR in the 1980s was about 4 million hectares, but was reduced by approximately 1 million hectares during the 1990s with yields averaging were around 1000 kg/ha. Thirty years later, wheat acreage was further reduced by another 1 million hectares. However, the national average yield increased to 2,900 kg/ha in half of the original area, leading to a national production that doubled to 6.8 million tons in 30 years. It is clear that use of improved management, cultivars and fungicides have contributed to decrease losses to plant diseases.

An important aspect to long-term production is the durability of genetic resistance against leaf rust and its impact on the increase in the prevalence and intensity of this disease. The genetic basis for resistance in AR cultivars is based on a few specific resistance genes against specific leaf rust races. As a result, the resistance is not stable and durable over time. For this reason, resistance has been overcome in several cultivars in recent decades within just a few years after their release (Germán et al 2004). Improved wheat cultivars of French origin (e.g., Baguette10) were introduced to the AR market but showed high susceptibility to foliar pathogens (Simon et al 2013), especially to leaf rust (Carmona et al 2004) which thus contributed to an increase in fungicide applications (Carmona et al 2004; Germán et al 2011).

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

In the Pampas, the emergence of diseases suggests that plant health could be reducing the (field) yield potential. A clear example was the new and atypical stripe rust epidemics in the entire Pampas region (Global Rust Reference Center 2018). The size of the wheat area remained stable in the last decade in BR, with regional variations. Yet the total production increased by 1 million tons, as a result of an average yield increase of around 200 kg/ha. The use of improved, high yielding cultivars contributed to this yield gain. The use of 2NS-based cultivars with resistance against wheat blast (Cruppe et al 2020; Cruz et al 2016) in the Cerrado and the improved resistances to FHB and tan spot in Southern BR have been the key advance in breeding for disease resistance. Fungicides have been applied more frequently in the Cerrado, mainly against wheat (head) blast, but the efficacy of fungicides varies with the cultivar, weather, and the application technology (Indicações 2020). In 2011, a cooperative fungicide network was established to evaluate and monitor the efficacy of several fungicides for the control of FHB and wheat blast (Machado et al 2017). The efficacy of fungicides for controlling wheat blast is comparatively lower and delays in sowing dates in the Cerrado have been successfully used to escape the wet environments and warm temperatures (~26°C) during wheat heading stages, which favour this disease.

Complementary information

Little information is available on the responses of wheat pathogens to climate change. In Argentina, the agricultural policies implemented in the last 15 years have evolved, impacting the planted area, technological investments, incentives to invest in wheat breeding programs and wheat planting by farmers.

Level of confidence in the assessment: Very confident: many studies, publications, support your views. There are only few gaps in the literature.

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Wheat and maize in North America

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Maize health in North America

Maize ear rots (photo: F Dalla Lana)

State of maize health in the past 30 years

Maize is affected by multiple diseases such as grey leaf spot, northern corn leaf blight, eyespot common rust, southern rust, along with multiple types of ear rots and stalk rots (https://loss.cropprotectionnetwork.org/; https://phytopath.ca/publication/cpds/; Mueller et al. 2016). Furthermore, maize can also be negatively impacted by mycotoxins due to their close link with several of the ear rots. Nonetheless, for many of the primary diseases, there are good sources of genetic resistance incorporated into commercial hybrids. Foliar fungicide applications in maize prior to 2004-2005 were low. Since then, use has increased, but the focus has not always been on "disease management" (Mallowa et al 2015; Paul et al 2011), rather fungicides were also applied for perceived plant health benefits.

Within the past several years, diseases such as tar spot and bacterial leaf streak have occurred across a larger geographical area of the U.S. Corn Belt, raising concern about their potential impact. Nonetheless, given changes in production practices including the use of seed treatments (Hitaj et al 2020), there has been a decline in several other diseases, for example, Stewart's wilt and Goss's wilt.

Maize gray leaf spot (photo: Paul Esker)

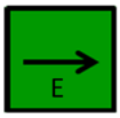
Evolution of maize health over the recent 10 years

For the most part, maize health is stable, although there are some indicators of a slight decline. The general profile for diseases has not dramatically changed over the past 10 years and management options do exist, especially with the use of genetic resistance. Nonetheless, both the prevalence and severity of several important diseases have increased across different corn producing regions. These include the ear rots, along with the corresponding risk for mycotoxin contamination of grain, as well as tar spot and bacterial leaf streak (https://loss.cropprotectionnetwork.org/; Rocco da Silva et al 2021). A main concern regarding these diseases is that they can negatively affect not only grain yield, but also post-harvest grain quality, and in the case of tar spot, silage yield and quality may also be affected. There is still not sufficient information on the potential impact of these diseases, especially tar spot, to improve knowledge of the biology and epidemiology.

Maize tar spot (photo: Paul Esker)

With climate change, increases in diseases like Northern corn leaf blight and Southern rust are occurring in areas where the disease was not commonly found. This concurs with some of the questions regarding how diseases may increase in importance in new regions (Garrett et al 2021) Furthermore, in some parts of the North American landscape, climate change is enabling early planting of row crops, under conditions where *Pythium* spp. can reduce productivity.

Ecosystem services, as affected by plant disease



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

Corn breeders generally consider diseases as a second priority after yield potential. However, commercially available materials generally have good resistance levels to the major maize diseases (Esker et al 2018). Yield trends are positive for maize, which is partly due to the fact that a major emphasis on maize production has been placed on planting maize crops with hybrids that are well-adapted to the local area of production, i.e., understanding the genotype x environment interaction, which includes disease management. Over the past 30 years, maize production has increased by approximately 27% in area, over 300% in production value, and 90% in production quantity (https://www.nass.usda.gov/). This reflects the increased demand for biofuels and higher yielding maize hybrids.

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

The incorporation of novel trails (Bt [*Bacillus thuringiensis*], for example) have contributed to reduce the impacts of plant pests and diseases. Chemical control is still not a major management component for this system where the use of adapted hybrids maintains stable maize yields. Ear rots and mycotoxins remain persistent concerns.

Wheat health in North America

State of wheat health in the past 30 years

Wheat disease impacts over the past 30 years have mainly been due to several different types of diseases, including Fusarium head blight (scab; vomitoxin), different rust species (leaf, stripe, and stem), the Septoria-Stagnospora leaf complex, tan spot, and viruses such as the wheat streak mosaic and barley yellow dwarf viruses (https://loss.cropprotectionnetwork.org/; https://phytopath.ca/publication/cpds/; Aboukhaddour et al 2020; Brar et al 2019; Chen 2005; McMullen et al 2012). Management of wheat diseases is well-developed in the USA and Canada. Fungicide use is often warranted against foliar diseases caused by fungi across most wheat market classes (Paul et al 2018a, 2018b; Willyerd et al 2015). Yet the efficacy of this tactic remains variable as applications need improvement in technology and timing.

Wheat field trial (photo: Paul Esker)

Evolution of wheat health over the recent 10 years

Wheat production is much more dependent on environmental factors than other row crops in North America. This reflects the succession of critical growth stages over time, which differs between winter and spring wheat. While much of the breeding effort for corn and soybean originates from the private sector, breeding, especially breeding for disease resistance in wheat is driven by the public sector. Fusarium head blight continues to challenge wheat production, as do concerns regarding the impact of major rust diseases, especially stripe and stem rust. The importance of diseases also varies in the challenge they constitute for farmers in different wheat classes and regions of North America. Wheat production has expanded into new areas and increases in Fusarium head blight have also been document. This may also be related with changing weather patterns driven associated with climate change (Garrett et al 2021).

Wheat fusarium head blight (photo: Paul Esker)

Ecosystem services, as affected by plant disease

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

Wheat yields are relatively stable. Knowledge of genotype x environment x management is much more critical across the different market classes for successful wheat production compared to other row crops such as corn and soybean. The area under wheat production has decreased by approximately 45% over the past several decades. Production has been widely variable from year to year, with an overall reduction of about 25-30% (https://www.nass.usda.gov/). While the economic value of wheat has increased by approximately 25-30%, the overall resources dedicated to wheat production are more limited compared to corn and soybean. Compared to corn and soybean, diseases have had a more consistent negative impact on wheat production year after year, which is why improving strategies for their management is critical. Many farmers still do not adequately control wheat diseases for lack of knowledge, thus hampering yield improvements.

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

There are many challenges in the management of wheat diseases and protect yield potential, because of their diversity and number, and because the major wheat diseases impact both wheat production quantity and quality. Despite the efforts on breeding for resistance against wheat diseases the impacts of many of the major diseases have not been consistently reduced. Unlike corn and soybean, wheat disease management is difficult; knowledge of genotype x environment x management is critical in wheat.

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Maize in Sub-Saharan Africa

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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

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).

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

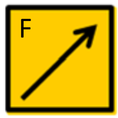
The adverse effects of common pests and diseases have been significantly reduced through advances in breeding maize for high levels of resistance to several foliar fungal diseases, MSV, *Striga*, and with advances in IPDM and biocontrol for reducing pre- and post-harvest losses from pests and mycotoxin 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

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

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



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.

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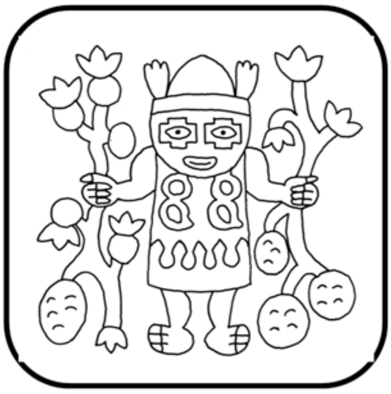
Roots, tubers, bananas & plantains

potato



cassava

banana
& plantain

Potato in South America

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Background information

Potato (*Solanum tuberosum*) in its area of origin, South America, is a key part of diets with a strong cultural history and wide range of cultivars and landraces producing white, gold, red, and blue tubers (CIP 2001). Some wild *Solanum* species are traditionally part of diets and also are important resources for potato breeding (Bonierbale et al 2020). With respect to ecosystem services, potato has an important provisioning role as a diet staple in the region and as a source of livelihood for smallholder farmers, especially in the Andes. Although sometimes consumed in less healthy forms such as potato chips, many potato varieties are highly nutritious (Burgos et al 2020). Potato was a key crop in Incan and pre-Incan cultures, and is currently widely grown in the Andes and in some regions of Brazil, Argentina and Chile. In the Chiloé Archipelago of Chile, *Solanum tuberosum* subsp. *tuberosum*, Chilotanum group, emerged as landraces, cultivated mainly by women, as an important food and genetic source.

Potatoes at a market in Puno, Peru (photo: J. Yuen)

PlantSystem considered in this report

Our focus is potato, which is clearly among the most important root or tuber crops in South America (Devaux et al 2020), especially in the Andes. Other important root and tuber crops in South America include cassava and sweet potato. South America harbours many other, less common crops, such as ulluco (*Ullucus tuberosus*), oca (*Oxalis tuberosa*), yacon (*Smallanthus sonchifolius*), mashua (*Tropaeolum tuberosum*), arracacha (*Arracacia xanthorrhiza*), achira (*Cana edulis*), and American yam bean (*Pachyrhizus* spp.), also important in the Andes. Wild potato species are also important for their role in traditional food systems and as genetic resources for crop breeding.

Potatoes processed into chuño at a market in Puno, Peru (photo: J. Yuen)

Potato health in South America

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State of potato health in the past 30 years

There are many important pathogens of potato in South America, as described below. Many of these obviously cause losses, but the lack of systematic monitoring of crop losses makes confident estimates of the state of potato health difficult.

Phytopathora infestans, the causal agent of potato late blight and a proximal cause of the Irish potato famine, continues to be an important cause for yield loss in potato. The disease drives frequent use of pesticides that may be difficult for smallholder farmers to afford. The A1 and A2 mating types have been present in the west and east, respectively, and their continued spread raised the issue of potential oospore production and sexual reproduction (Lindqvist-Kreuze et al 2020b). Today, new lineages and multilocus genotypes have been found in South America, mainly due to introductions from Europe or emergence from other solanaceous crops (e.g., Lindqvist et al 2020a).

Symptoms of late blight, caused by Phytophthora infestans (photo: J. Yuen)

Rhizoctonia solani, the causal pathogen of black scurf, can be important, particularly in southern South America, where the climate is colder with highly organic soil, such as in Chile. Farmers use seed treatments for its control and management.

Spongospora subterranea, the cause of powdery scab, is considered a re-emerging disease, due to climate conditions and management that favored it (Lees et al 2020).

Ralstonia solanacearum, causing bacterial wilt, has multiple biotypes in South America, but its importance in Peru has declined over the last 30 years, probably because of the use of improved seed and farmers learning how to manage the disease from extension training.

Potato blackleg, which is caused by several bacterial species, is an important disease. New bacterial pathogens may increase problems as they spread through the continent (Cardoza et al 2017).

Viruses constitute a continuous threat to potato production. Aside the most common viruses, including PVY, PVX, PVS, PVA and PLRV, which also affect potatoes elsewhere in the world, many other viruses infect potato in South America and particularly the Andean region. New viral diseases emerge periodically (Kreuze et al 2020).

Potato cyst nematodes (*Globoderra pallida*, *G. rostochiensis*) are highly diverse and can cause important losses (Thevenoux et al 2019).

More recently, '*Candidatus* phytoplasma aurantifolia' and '*Candidatus* Liberibacter solanacearum' have emerged as important threats to potato production, potentially as part of a disease complex with additional pathogens (Caicedo et al 2015, 2020; Castillo Carrillo et al 2018, 2019).

One challenge for potato health in South America is the risk of transmitting pathogens in vegetatively propagated plants such as potato when seed systems cannot reliably provide disease-free seed to most farmers (Forbes et al, 2020; Thomas-Sharma et al 2016). Use of "true" potato seed produced by flowers is still rare.

Many of the pathogens listed above may be spread through seed.

Potato breeding and multiplication is a slow, costly, and difficult process using vegetative reproduction. Potato breeding for disease resistance and combining resistance with all desired crop traits cannot therefore rapidly respond to new disease threats.

Evolution of potato health over the recent 10 years

The recent new problems are with '*Candidatus* phytoplasma aurantifolia' and '*Candidatus* Liberibacter solanacearum', potentially as part of a disease complex with additional pathogens (Caicedo et al 2015, 2020; Castillo Carrillo et al 2018, 2019). The purple top and zebra chip diseases caused by these pathogens have emerged as new threats and challenges for preventing their spread throughout the region.

Other diseases remain persistent challenges, mainly in the form of new variants as in the case of *Spongospora subterranea*, *Synchytrium endobioticum*, *Pectobacterium* spp. and PVY (associated with seed importation from North America & Europe).

Deciding whether potato health problems are increasing or decreasing overall in South America is challenging: some diseases are dealt with more effectively, while others emerge. New diseases develop, climate is changing, and the pressure over agricultural land increases steadily. A conservative estimate is that potato health is, at best, stable.

Ecosystem services, as affected by plant disease

Level of ecosystem services generated by potato, as affected by plant disease, in the past 30 years

The provisioning services generated by potato in terms of food production have been high compared to the many other possible crops that might be grown instead is South America. Comparing potato production in South America with that of, e.g., Europe, shows differences which depend on the production system: commercial production systems managed by large farmers in South America generate yields that are similar to those achieved in Europe; traditional production systems that are managed by small-scale farmers, on the other hand, produce much lower yields than in Europe (Devaux et al 2021). Probably 20% of this yield difference is attributable to plant disease losses, mainly viruses and late blight. Within South America, there are large differences in potato productivity between the Southern, Central and Northern regions; large differences occur even within countries, which primarily result from the variability in disease susceptibility, the production technologies used, and the availability of quality seed. Native potatoes grown throughout the Andes are generally lower yielding, but in some cases resistant to environmental stresses and able to grow where few other crops can, thus providing important food security and ecosystem services. This is achieved even though no or very little agrochemicals are used on such traditional systems.

Potato cultivation on terraces in Peru (photo: J. Yuen)

Evolution of the level of ecosystem services generated by potato, as affected by plant disease, over the recent 10 years

As a result of increasing temperatures, potato production in the Andes has moved to higher elevations in the past 10 years. This movement has led to agriculture encroaching of high-elevation vulnerable ecosystems. This movement has also been driven by new diseases, such as potato purple top, which farmers attempt to escape by growing potato at higher altitudes (I Navarrete, pers comm). Increasing insect pest populations with climate change have also increased pesticide use, likely increasing residues in the environment.

Complementary information

Climate change is becoming a challenge for potato production in the Andes. Potato seed could traditionally be produced at high elevations to escape disease-conducive environmental conditions. Under warming conditions, this strategy is compromised, while land at still higher elevations may not be available for production since this may result in destroying the remaining mountain wildlands.

There is uncertainty associated with the damage from purple top and zebra chip, as diagnostic difficulties have made tracking disease spread problematic.

While some diseases such as potato late blight continue to have clear effects on yield losses in the absence of management, losses due to other pathogens is less clear. The lack of systematic surveys of disease severity and yield losses makes difficult the assessment of potato health.

We are reasonably confident on the assessment: a number of studies, publications, support our views. There are gaps in the literature.

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Potato in East Asia

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Background information

Potato (*Solanum tuberosum* L.) is the fourth most important world food crop in weight, following wheat, maize and rice, with a global production area of 17.6 million hectares producing nearly 369 million tonnes of potato in 2018 (FAOSTAT 2020). Potatoes are grown in almost 200 countries, with around 50% of the production in Asia. Compared with other staple food crops, potato has the characteristics of possessing tolerance to cold, drought and unfertile soil as well as a high yield potential. Furthermore, potato supports long and diverse value chains, contributing to local employment. Thus, potato production has unsurprisingly dramatically increased in developing countries in the past two decades, concurrently with the increasing population. However, compared with grain crops, there is a lack of investment in research and technology in potato relative to its production scale. Thus, actual yield attained in East Asia is much lower than in developed countries. In 2018, the average yield in China was, for instance, only 18.7 tonnes/ha, compared to nearly 50 and 36 tonnes/ha in the USA and UK, respectively.

The top two potato producing countries, China and India, are both in Asia, accounting for 27.4% and 12.2% of the global production area. Potato production in both China and India suffers from a number of common diseases, such as early and late blight, Verticillium wilt, Fusarium wilt, black scurf, scab etc. Therefore, the present report focuses on potato production in China.

PlantSystem considered in this report

Potato was introduced to China about 400 years ago, but only recently has it been designated by the Chinese government as the fourth key national staple food crop after wheat, rice and maize. China is the world's largest consumer as well as the world's largest producers of potatoes since 1993. The potato plant is mainly self-incompatible, so potato tubers are usually used for propagation. As a result, 10% of the potato tubers produced annually is used for propagation rather than consumption (McKey et al 2010). In the region, although there are large co-operatives/companies who are specialised in potato production, most potato production is still achieved through small farm holders. Irrespective of production scales, potato is usually grown in monoculture. When intercropping or rotation is used, it is usually not by design or choice but by practicality to achieve maximum return per unit of land on a small farm holder.

In the developing countries, potato production is geared largely towards provision of food

Commercial potato crops at the flowering stage in Yulin, Shaanxi (photo: Xiaoping Hu) primarily intended to local populations. Furthermore, the agri-food industry associated with potato, from crop production to post-harvest food processing, is an important economic sector, employing many people. This report centres, therefore, on this provision service of the potato production.

Potato health in East Asia

State of potato health in the past 30 years

A number of pathogens can cause devastating crop losses in potato worldwide, including *Alternaria solani*, *Phytophthora infestans*, *Verticillium dahliae*, *Rhizoctonia solani*, *Fusarium solani*, *F. oxysporium* and several bacterial pathogens. In China, late blight (*P. infestans*) occurs in potato growing areas all year round, especially in areas with high humidity and cool climate (e.g. northern and southwest mountainous regions), with annual production area affected around 2 million ha and crop losses in the range of 10 to 30% in average (Huang and Liu 2016a). Early blight (*A. solani*) is the second most important disease in potato production in China; the average annual production area affected by this disease is around 0.9 million ha in China (Huang and Liu 2016b). Of the soil-borne pathogens, Verticillium wilt (*V. dahliae*), in addition to *R. solani*, has gradually become a serious threat to potato production in China, causing yield losses usually ranging from 10 to 15% but reaching up to 50% in severely affected fields (Jing et al 2018). Of the bacterial diseases, the black shank disease caused by *Pectobacterium carotovorum* subsp. *carotovorum* and *P. atrosepticum* is very serious in China.

Field investigation of potato diseases at Yulin, Shaanxi (photo: Wenjing Shang)

With the recently rapid expansion of potato planting area in China, the demand for high quality seed potatoes of cultivars with good resistance is difficult to meet. Pathogen inoculum thus may rapidly spread with infected seed potatoes to new production areas, generating an effective long-distance dispersal route. This is further aggravated by the absence of effective crop rotations, leading to a gradual erosion in soil quality where the primary inoculum builds up steadily.

The state of potato health in East Asia, particularly China, in the past 30 years was poor.

Early blight (photo: Xiaoping Hu)

Evolution of potato health over the recent 10 years

Although China has become the largest potato producer in the world, the average potato yield is below the global average and much lower than average yields of the USA or Europe (FAOSTAT 2020). Along with poor soils, cultivars and climatic factors, diseases contribute significantly to such low potato yields in China. The main yield reducers are early and late blight, and bacterial and fungal wilt. This situation is aggravated by the shortage of healthy seed potato propagation and an inadequate certification scheme. This is further compounded by the fragmented landscape of potato cultivation and a chronic under-investment in research and development on potato production compared to other major food crops. As a result, disease management currently relies on intensive fungicide applications. The backdrop of the current situation is that much of the potato production in China takes place in small farms of poor, often mountainous regions. Such an environmental and socio-economic context hampers knowledge dissemination and technology transfer.

Potato health state was declining over the recent 10 years.

Late blight (photo: Xiaoping Hu)

Ecosystem services, as affected by plant disease

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

Despite the low yield achieved, rapid expansion of potato production acreage in the last three decades has led to a nearly three-fold increase of the annual total potato production in China, from 31.6 million tonnes in 1988 to 90.3 million tonnes in 2018. Thus, from the strict perspective of (food) provisioning service, the provision service has largely been achieved. However, the delivery of this provision service is achieved at a much lower efficiency than desired, particularly in terms of excessive input of synthetic fertilizers and fungicides, and of gradual decline in soil health resulting from the mono-cropping of susceptible potato cultivars. For instance, the annual area affected by potato late blight can reach 40 to 50% of the total potato acreage in China with yield reduction in the range of 30 to 50% if climatic conditions are conducive to the disease (Huang and Liu 2016a). Despite the implemented disease management measures (usually fungicide applications), annual losses due to diseases in the range of 10-30% is not uncommon. In some cases, crop losses due to diseases may even be under-estimated. In fact, the low crop yield in the absence of severe visual disease symptoms, which is often attributed to "poor nutrient supply", may also be caused by potato pathogens.

The level of ecosystem services was fair.

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

The lack of effective disease management in China is one key factor contributing to low potato yields. Several factors may in turn explain of the absence of effective potato disease management in China. One element is that it is only recently that potato has been nationally recognised as one of the four key staple crops of China. Therefore, research and technology development for commercial potato production is lagging far behind its actual importance compared to grain crops. Another element is that effective knowledge transfer is hampered by the fact that much of the potato production is generated by small farm holders in poor and remote areas. Thirdly, continuous mono-cropping is extremely damaging for potato (far more than for grain crops) because of the very nature of soil-borne potato pathogens. A fourth element is that a seed potato propagation scheme at the national level, involving the highest possible standards of seed health, is required to ensure pathogen-free planting material. This should complement the use of resistant cultivars and the implementation of alternative control measures. Unfortunately, integrated disease management in potato has not yet received the attention that it deserves: much of the national agricultural research in China has only been focussing on breeding high yielding cultivars with resistance to key pathogens. On the other hand, China has recognised the problem which is associated with the fragmentation of research and technology in potato. As a result, a potato research institute has been established jointly with the International Potato Centre (CIP). Within the next 10 years, this new potato research institute is expected to contribute to sustainable management of potato diseases in China.

The generation of the provisioning service has been stable.

Complementary information

Although general biology and epidemiology of early and late blight diseases have been well studied in developed countries, fungal soil-borne pathogens and diseases are less well studied. Furthermore, soil-borne diseases are probably more influenced by local soil than by general climatic conditions. Much of the potato production of China takes place in small farms in poor and often mountainous areas, where soil physiochemical properties are expected to vary greatly. Furthermore, the effect of global warming (increasing average temperature and increasing frequency of extreme whether events) on potato production in these mountainous areas is hard to predict.

We are reasonably confident about the present report.

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Potato in Europe

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Background information

Potato production is a major economic activity in Europe that continues to play a key role in the region's food security. The EU is a net exporter of potatoes and its seed industry provides high-health certified seed potatoes to many countries throughout the world, a dynamic processing industry that contributes significantly to the global economy. Potato is also an important raw material for European starch production and biodegradable potato starch is routinely used in the chemical and textile industries. Potatoes became important in Europe in the 19th century after they had previously been brought from the Americas and easily adapted to the European climate. Since then, potatoes have slowly partly replaced cereals as a main staple crop. The potato crop supported Europe's explosive population growth and, thus, potatoes became one of this eco-region's popular food assets frequently playing a role in cultural values across the continent. Average yield in the 1850's was below 10 t/ha (Vos 1992). Today it is higher than 20 t/ha and in the north-west of the eco-region, average yields are higher than 40 t/ha (FAOSTAT 2018) with some farmers producing around 100 t/ha following strong investment in seed technologies, fertilizers and fungicides. Potato is also prevalent in Eastern Europe with the highest per capita consumption in the world, traditionally above 100 kg annually (FAOSTAT 2018). Although Eastern Europe constitutes the region with the highest use of potato as animal feed globally, in general, feed use of potato has strongly declined (European Commission 2007). This decline in feed use, together with a shift towards easy-to-prepare diets, has led to a significant decrease in demand for fresh potatoes since the 1960's. As a result, potato production in Europe has decreased with its demand (Eurostat 2019; FAOSTAT 2018). A growing reliance on pesticides to ensure a marketable yield, and consideration for environmental concerns, has led the European Commission and individual countries to implement pesticide use reduction policies. This report considers the importance of European potato production in terms of global food security, potato for processing and consumption and production of starch for industrial use.

Potato production fields and trials in Valthermond, Netherlands (Photo: Leo Bosman)

Roguing seed potato field (Photo: Peter Kromann)

PlantSystem considered in this report

The plant system considered is the *Solanum tuberosum* ssp. *tuberosum* potato cropping systems in Europe. Potato is ranked in the top three agricultural crops in Europe, second to wheat and comparable to sugar beet in terms of crop production value (Eurostat 2019; FAOSTAT 2018)

Potato health in Europe

State of potato health in the past 30 years

European climates suitable for the cultivation of potatoes are also favourable for a number of yield-reducing potato diseases of which late blight, caused by *Phytophthora infestans*, is the most important with the potential to cause total crop loss. With a polycyclic disease cycle, aerially dispersed sporangia can quickly spread in humid, disease favourable weather. If left unchecked, inoculum levels can rapidly increase, and the disease can progress to destroy potato crops in a matter of days. The devastating impact of potato late blight was first seen in Europe in the middle of the nineteenth century. In the 1840's, late blight epidemics in North-western Europe caused severe famines after *P. infestans* had been introduced from the Americas. Millions of underprivileged died or emigrated because of the potato disease (Bourke 1993). Over the last 30 years, potato farmers have become accustomed to applying fungicides 7 to 20 times on average per cropping season to avoid crop loss risks (Schepers et al 2018). Thus, late blight is one of the top drivers for chemical fungicide use and the costliest disease of any agricultural crop. Second to late blight disease, potato early blight, caused by *Alternaria* spp., is considered another major disease of potato, especially in the warmer and drier central parts of the eco-region. Insect vector-borne diseases, such as potato leaf-roll virus (PLRV), strains of potato virus Y (PVYO, PVYN) and potato stolbur phytoplasma disease are major constraints of potato production in Eastern and Southern Europe, as are potato nematodes (*Globodera* and *Meloidogyne* species) and plant pathogenic bacteria (*Pectobacterium* spp.). Phytosanitary measures such as restrictions on imports of seed potatoes reduces the risks of introduction of pathogens to European countries. Some of the potato diseases which have become established in Europe continue to spread within and from the eco-region, while others are partly controlled by quarantine measures. In the past 30 years, late blight has been contained in the European eco-region through support from the global pesticide industry and the development of DSS (decision support systems). Additionally, the breeding for host resistance supports the control of late blight (Andrivon et al 2006).

Late blight field trial at Wageningen University & Research (Photo: Peter Kromann)

Evolution of potato health over the recent 10 years

Throughout the 1990's, the European populations of *P. infestans* became highly diverse as a result of sexual reproduction. Soil-borne sexual oospores were shown to be important inoculum for early *P. infestans* epidemics in parts of North-Western Europe (Andersson et al 1998; Drenth et al 1995). The current pathogen population is dominated by aggressive clonal lineages that out-compete and displace older genotypes, thereby facilitating their spread across the eco-region according to their evolutionary fitness. There are a few locations in the eco-region, such as some parts of the Netherlands and Scandinavia, where highly diverse sexual populations dominate. The clonal lineage 13_A2 (Blue 13) became dominant in various countries after 2004 and a combination of its aggressiveness and resistance to metalaxyl fungicide meant that management strategies had to be adapted. Since then a clonal lineage 33_A2 (Green 33) with reduced sensitivity to the fluazinam fungicide has been identified but has been shown to be less fit than other lineages. Continued surveillance and genotyping has demonstrated rapid spread of another three lineages (37_A2 Dark Green 37, 36_A2 and 41_A2). The former has reduced sensitivity to fluazinam fungicide, which demonstrates the ability of the late blight pathogen population to evolve in response to fungicide use (Euroblight 2020). In recent years, early blight has also become increasingly widespread, especially in the inland, central and eastern parts of the eco-region. Warmer and drier summers have turned early blight into an economically significant disease in combination with *Altenaria* spp. populations rapidly adapting to new conditions of host resistance and patterns of fungicide use (Metz et al 2019; Odilbekov et al 2019). Despite more diverse, more aggressive and more fungicide resistant pathogen populations, European potato crops have remained fairly healthy. This, however, has come at a higher environmental and economic cost from enhanced disease management efforts with European potato farmers currently spending well above an estimated half billion euros on fungicide application annually based on the currently cultivated area (4,800,000 ha, FAO 2018) and an estimated average cost of control of 125 euros ha^{-1}.

Ecosystem services, as affected by plant disease

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

Comparing European potato production during 2014-2016 with 1988-1990, shows that the average annual growth rates of production tonnage and potato cultivated area were -1.3% and -2.4, respectively. The annual growth rate in yield per hectare was however 1.3%. The harvested production declined by 30% in Europe during this same period (FAOSTAT 2018). This steady decline was associated with a reduced use of potato as animal feed, urbanisation with changing diets and specialisation of agricultural production. Potato has increasingly become a highly specialized crop partly because of the increasing demands and investments required to manage potato diseases. Late blight has been the main production constraint and there is no doubt that potato production would not have declined in Europe in the same manner, were it not for this devastating and extremely costly plant disease. Haverkort et al (2008) considered a total annual loss of 15% of European potato production to late blight to be a conservative estimate.

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

Over the past 10 years, the phasing-out of chemical plant protection products, coupled with climate change and extreme climate events, has made potato production more challenging. Research has confirmed that European *P. infestans* populations evolve at an alarming rate and faster than ever before. Outbreaks of late blight continue to occur earlier in the season and farmers increasingly rely on the use of fungicide to produce a marketable crop. More aggressive lineages that are less sensitive to the previously popular metalaxyl and fluzinam fungicides are spreading across the eco-region, making late blight control ever more difficult and costly to manage, with a need for earlier and more frequent applications than before. In Eastern Europe, there is still a large percentage of small traditional farms where fungicides are not routinely used and yield loss to late blight is increasingly common. In western European countries, disease risk by the more aggressive *P. infestans* populations is mitigated through increased investment in fungicide applications with some farmers in North-Western Europe spraying on average 25 times with a series of multiple active ingredients. Production is maintained on industrial scale farms despite increasing disease pressure despite the significant input costs. Yet because of the increased demand for potato for processing in some countries, potato production is increasing. Thus, production of potato has increased in recent years in some European countries as in France, Belgium, The Netherlands and Denmark (Eurostat 2019).

Complementary information

Potato diseases have also intensified due to climate change and increased connectivity effects of international potato trade. Longer and warmer summers are conducive to multiplication of inoculum and shorter, milder winters have increased the rate of survival of pests. Extreme and erratic rainfall has also made application of fungicides more difficult. Early blight (Delgado-Baquerizo et al 2020) and insect vector-borne diseases are more prevalent as longer growing seasons at higher average temperatures have allowed more multiplication cycles to occur on water and nutrient stressed plants than before. Furthermore, governments are reducing the availability of approved chemical pesticides to reduce the negative environmental and human health effects of European agriculture. This in turn makes the control of this disease even harder. For a series of reasons mentioned in this report, potato production has become a highly demanding crop in terms of technology, which is shifting production from across the continent to fewer specialized countries in the north-west of the eco-region, which have developed highly specialized industries aiming to deal with production constraints including the increased potato disease pressure (Eurostat 2019).

As the team of authors of this report, we are very confident of the findings of the present report. Information on European potato systems is widely available with considerable scientific and sectorial literature describing the developments in this provision system.

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Cassava in Sub-Saharan Africa

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Background information

This report discusses the cassava plant system in Sub-Saharan Africa. Cassava was introduced to Africa in the 16th century from its origin in Latin America (Nweke 2005). Since that time, its cultivation has spread throughout the parts of the continent that are ecologically suitable for its cultivation. Cassava is cultivated on 18.7 million hectares in Africa, which makes up almost 75% of the global total (FAOSTAT, 2022). The [cassava x sub-Saharan Africa ecoregion] system is particularly important in view of the critical role that this crop plays for food production in Africa (Nweke 2005). Most of the production is undertaken by hundreds of millions of smallholder farmers who grow the crop primarily for its food security value. However, experience from other continents, most notably Asia, has shown that the crop also has a strong potential to drive economic growth, because cassava roots can be processed into a wide diversity of processed and higher value products. Many African governments are now looking at cassava as a means to achieve economic development through strengthening existing value chains, creating new value chains, as well as identifying new markets for cassava products, both within and outside of the continent.

PlantSystem considered in this report

This report considers cassava (*Manihot esculenta*), its cultivation and its plant health status in sub-Saharan Africa. Several wild relatives of cassava have however been used in breeding programmes to introduce sources of disease resistance that were not present in the cultivated species.

Cassava is a shrubby perennial dicot in the Euphorbiaceae family which is typically grown from vegetative propagules (stem cuttings). It is most commonly cultivated for a period of 8 to 18 months, after which the tuberous roots are harvested. Roots can be consumed fresh, boiled or processed into a wide range of products. The most common forms in which the roots are eaten are fresh boiled or processed into flour or roasted granules ("*gari*") which can be stored and subsequently used to make various forms of thick porridge. Processing through fermentation enables removing cyanogenic glucosides which occur in the tuberous roots of some varieties. This is frequently done as a first step in the preparation of flour, although flour may also be prepared without fermentation. In many regions where cassava is the primary food crop, the leaves are also consumed. Today, one of the strongest commercial opportunities that cassava

Healthy cassava crop, Tanzania (photo: J Legg) holds lies in its potential to partly replace wheat flour in bread and pastries. Another is its high quality starch that can be used in the food and beverage industry as a thickener, binder, expanding agent, stabilizer, and carrier of sweeteners.

Cassava grows best in loam or sandy-loam soils with adequate drainage in tropical humid or sub-humid environments (Cock and Howeler 1978). It may be grown and produces tuberous roots with rainfall as low as 400 mm annually, but yields are highest where rainfall exceeds 1,600 mm (FAO 2013). Modelling research has further shown that cassava is likely to be one of the few tropical crops that can perform better under forecast scenarios of future climate change (Jarvis et al 2012). However, cassava production has been severely affected over recent decades by several important plant health constraints.

Cassava health in Sub-Saharan Africa

P

State of cassava health in the past 30 years

Cassava in sub-Saharan Africa has been affected by several major biotic constraints over the past 30 years. The two most important arthropod pests have been the cassava mealybug (*Phenacoccus manihoti*) (CM) and the cassava green mite (*Mononychellus tanajoa*) (CGM). Both were introduced from South America in the 1970s but have been effectively controlled through classical biological control programmes (Bellotti at al 1994; Onzo et al 2005).

Currently, the most economically important diseases are the virus diseases – cassava mosaic disease (CMD) and cassava brown streak disease (CBSD). CMD is caused by cassava mosaic begomoviruses (CMBs) and CBSD by cassava brown streak ipomoviruses (CBSIs). Both types of viruses are transmitted by the whitefly vector, *Bemisia tabaci*. CMD has been reported throughout cassava-growing parts of Africa since the 1930s, and CBSD for a similar period, albeit restricted to coastal East Africa. A pandemic of unusually severe CMD spread through large parts of East and Central Africa from the 1990s onwards (Legg et al 2006). This was followed by pandemic spread of CBSD over that region of Africa from 2004 (Alicai et al 2007). Africa-wide losses in excess of US$ 1 billion annually have been attributed to CMD alone (IITA 2014). These two diseases continue to be the most important biotic constraints to cassava production in Africa.

Cassava brown streak (photo: J Legg)

Symptoms of cassava mosaic disease on leaf, Uganda (photo: J Legg)

Other widespread but less economically damaging diseases of cassava in Africa include cassava bacterial blight (CBB) (*Xanthomonas axonopodis* pv. *manihotis*), cassava anthracnose disease (CAD) (*Colletotrichum gloeosporioides* f.

sp. *manihotis*) and cassava brown leaf spot (*Cercosporidium henningsii*). CBB and CAD are known to cause significant yield losses in humid forest ecologies of central and West Africa (Legg 2012). The whitefly, *Bemisia tabaci*, is primarily important as the vector of cassava viruses. However, it has also been reported to cause damage to cassava plants in parts of the Great Lakes region in East Africa, where it occurs at very high levels of abundance (Legg et al 2011). The African Root and Tuber Scale (ARTS) *Stictococcus vayssierei* is a major pest of cassava in the forest zones of central Africa (Doumtsop et al 2019).

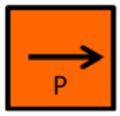
Yields of cassava in Africa are much lower than those in other continents where the crop is cultivated (FAOSTAT 2022), and a major reason for this is the greater prevalence of plant health constraints in Africa.

The overall state of cassava plant health in sub-Saharan Africa is poor.

Evolution of cassava health over the recent 10 years

Two major cassava pests – CM and CGM – were both brought under control through the deployment of biological control programmes from the 1980s through to the 2000s. CM is no longer an important production constraint, but biocontrol of CGM is incomplete and this pest continues to cause losses in areas favourable to the mite during periods of drought. The ecology and management options against ARTS, however, are poorly studied while the pest is increasingly affecting cassava production in West and Central Africa (Doumtsop et al 2019). Of the major diseases, CMD caused widespread and massive losses during the 1990s and 2000s. However, resistant varieties, introduced first in severely affected areas in the 1990s, were widely adopted by farmers (Dixon et al 2003). As a result, CMD has been less damaging over the last ten years than during the previous two decades. By contrast, CBSD continues to spread. The levels of host plant resistance that are currently available for breeding programmes for CBSD resistance are not as high as they are for CMD (Legg et al 2011). While CMD damage has declined, CBSD damage has become prominent. Overall, the plant health status of cassava in SSA is stable at a poor level of plant heath.

Ecosystem services, as affected by plant disease



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

Cassava mainly generates the provisioning form of ecosystem services: it is a major food crop in SSA. Annual production of cassava in sub-Saharan Africa has increased from 8.6 million tonnes in 1990 to 18.7 million tonnes in 2018 (117%) (FAOSTAT 2022). This compares with a population increase during the same period of 103%. The increase of cassava production has kept pace with population growth. However, most of this increase has come from an increased cultivation area. Over this period, yields have only increased by 11.0%, from 8.2 t/ha in 1990 to 9.1 t/ha in 2018. This contrasts strongly with Thailand, the largest cassava producer in Asia, where the cultivated area declined by 6.7% during 1990-2018, while yields increased by 64.2% over the same period. Annual yield in 2018 in Thailand was 22.9 t/ha, more than twice the average cassava yield in Africa. Pest and disease damage is one of the major reasons for low yields in Africa throughout the past 30 years. Africa-wide losses caused by CMD were estimated at 24% in 2006 (Legg et al 2006). Although these may have declined slightly, losses due to CBSD have increased. The combined losses due to diseases, pests, and nematodes in SSA are likely to be in the range of 30 to 40%. The near-complete lack of fertiliser application and inadequate soil moisture in many areas where the crop is grown are probably the two most important abiotic factors that limit cassava yields in Africa. Set against these negative impacts, however, are the environmentally positive approaches that have been taken in Africa to control diseases and pests. Major pests (CM and CGM) have been managed effectively with classical biological control approaches that have avoided pesticide use and protected the natural enemy fauna on cassava crops. Similarly, the host plant resistance focus for cassava disease management has ensured the preservation of communities of beneficial organisms.

The overall status of cassava's provisioning service over the last 30 years is poor.

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

The provisioning service of cassava in Africa, mostly in the form of food, over the last ten years has been increasing: the overall production has increased 49% while the population grew by 29% (FAOSTAT, 2022). However, this cassava production increase has come almost entirely through an expansion of cultivated areas. Indeed, the average yield declined by 5% during that period. Increases in cultivated area over this period were most marked in Nigeria, the world's largest cassava producer (with an 81% cultivated area expansion), and the Democratic Republic of Congo (99% area expansion). Pests and diseases are a major factor causing losses in cassava production in Africa, as described in the previous section.

This assessment, however, has noted that losses to pests and diseases have remained roughly stable over the period of the last ten years. This is because some diseases, such as CBSD, have spread and caused greater damage, whilst others, such as CMD, have been controlled through the increasing deployment and dissemination of resistant varieties. The modest reduction in yield recorded across the continent (5%) probably reflects a stable situation given the limited accuracy of FAO data for this crop in the SSA ecoregion.

We therefore conclude that the status of cassava provisioning over the last ten years, considering plant health effects, is stable.

Complementary information

The impacts of cassava plant health constraints differ greatly between regions within Africa as well as between countries. These effects are apparent from country-level production statistics. The most damaging plant health constraints over the last 30 years have been the two virus diseases – CMD and CBSD – and in both cases, new epidemics emerged from East Africa before spreading into central Africa (Legg et al 2011). Neither severe CMD nor CBSD, however, have been reported from West Africa. These regional variations are highlighted by data for total production change since 1990, where Nigeria in West Africa recorded an increase of 320% compared with 59% for DRC in central Africa, 79% for Zambia in southern Africa and just 50% for Tanzania in East Africa (FAOSTAT 2022). The overall impacts on provisioning services from cassava have, however, also been strongly influenced by government policies. Thus, while some countries such as Nigeria have placed a heavy focus on the expansion of cassava production, others (such as Tanzania) have placed a relatively low national priority in comparison with other major food staples such as maize.

Although there is evidence for climate change impacts across the African continent, no studies have generated clear field-based evidence of impacts on cassava production, or on its major pests and diseases. Models have been developed to analyse the effect of anticipated temperature increase on cassava virus vectors (Aregbesola et al 2019) and new studies are being initiated on the effects on the viruses that they transmit. High temperatures are known to impair the functioning of many plant viruses (Chellapan et al 2005). This means that even if increased temperatures result in greater virus vector populations, there may not be significant increases in virus epidemics. Sustained production of cassava in Africa depends heavily on the continued effectiveness of biological control of the two major pests– CGM and CM. It therefore is critically important to conduct research to analyse the effects of climate change on the sensitive balance in predator-prey-host relationships. Research will also be required to improve understanding of plant-vector-virus interactions so that effective measures can be developed to counter any anticipated deleterious effects of climate change. Finally, introductions of alien invasive species will pose an increasing threat to cassava production in Africa, particularly the large number of insect pests and viruses that are present in Latin America and witches broom-causing phytoplasma agents in East Asia, but which are absent in Africa.

We are confident about the main findings of this report.

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Banana and Plantain System in Sub-Saharan Africa

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Background information

Banana (*Musa* spp.), including plantain, is one of the major staple food crops grown in 40 countries in sub-Saharan Africa (SSA), with an annual production of 44 million tonnes on 6.4 million hectares of land that feeds over 70 million people (FAOSTAT 2018). Africa produces a third of the world's bananas, East Africa being the largest banana-growing region, accounting for about 40% of aggregate production in Africa. Banana provides 30-60% of the daily per capita calorie intake in some of the East African countries such as Burundi, Rwanda, and Uganda with the greatest consumption at 220-460 kg per person annually (Abele and Pillay 2007; Kilimo Trust 2012). Banana and plantain are mainly cultivated by smallholder farmers for household consumption and for local or regional markets; only about 15% of the banana production enters international markets. It is a valuable component of food security and is also a cash crop, widely traded within countries from regions of sufficiency to areas of deficiency. Banana has a strong potential to provide raw material to the emerging agro-industry in SSA. Banana and plantain can be cultivated in diverse environments and produces fruits throughout the year in favourable weather conditions.

This report mainly covers the Provisioning Services for banana and plantain in sub-Saharan Africa.

PlantSystem considered in this report

Banana and plantain are non-woody herbaceous, perennial plants of the genus *Musa* under the family *Musaceae*. They are mostly a tropical plants that grow well in a temperature range of 15°C – 35°C with relative humidity of 75-85%. All cultivated bananas are either diploid or triploid hybrids between sub-species of *Musa acuminata*, or between *M. acuminata* and *M. balbisiana*. Banana and plantain originated from Southeast Asia. West-Central Africa is considered a

A banana plantation in Uganda (photo: George Mahuku) secondary diversification hub for plantain, and East Africa is a secondary hub for East African Highland bananas (EAHB). Hundreds of banana cultivars are grown and consumed worldwide, but large-scale banana farmers mainly grow the Cavendish type of dessert bananas for local and international commercialization. Plantain, however, is frequently grown in Central and West Africa, while East African Highland bananas are cultivated in east Africa. Other dessert banana varieties such as Sukali Ndiizi and Gros Michel are also grown at small scale in Africa. Plantain and EAHB represent approximately 70% of all bananas grown in Africa. Banana and plantain are rich source of carbohydrates, fibre, potassium, vitamins (vitamin B6, vitamin C), and various antioxidants.

Banana and plantain health in sub-Saharan Africa

State of banana and plantain health in the past 30 years

Banana yields are only 9% of the potential 70 $t.ha^{-1}$ per year. A major cause for low yields are diseases and pests. The most important pest and disease constraints of banana are Fusarium wilt, bacterial wilt, nematodes, weevil, black Sigatoka and Banana Bunchy Top Disease (BBTD) (Hauser et al 2019). Banana Fusarium wilt, caused by *Fusarium oxysporum* f. sp. *cubense* (Foc), is most damaging to dessert varieties intended for fresh consumption, processing and export such as Gros Michel (AAA), Sukali Ndizi (Ney Poovan ABB), Kayinja (Pisang Awak ABB) and Cavendish bananas (AAA), as well as the cooking banana Bluggoe (AAB) (Blomme et al 2013). Foc race 1 is widely distributed in Africa on susceptible banana cultivars (Blomme et al 2013). A highly virulent Foc strain, called tropical race (TR4), was detected in Mozambique in 2013 (Viljoen et al 2020), and later in Mayotte Island off the east African coast (Aguayo et al 2020). Most bananas grown in SSA, such as the triploid EAHBs (called Matooke bananas) in East Africa, and the plantains and Cavendish bananas in West Africa, are not affected by Foc race 1. However, Cavendish bananas are severely affected by TR4 in northern Mozambique and by sub-tropical race (STR4) in South Africa.

Fusarium wilt symptoms on banana plants infected by Fusarium oxysporum f. sp. cubense (Foc), tropical race 4 (photo: George Mahuku)

Banana Xanthomonas wilt (BXW), caused by *Xanthomonas vasicola* pv. *musacearum,* is currently devastating banana production in East and Central Africa (Tripathi et al 2009). Yield losses can reach 100% in the infected fields, and its effects are worse during seasons of high rainfall. Losses to BXW have been estimated to be 2-8 billion US dollars (Abele and Pillay 2007). Because no highly resistant cultivars are available, the emphasis has been placed on cultural methods for containing the spread of the disease.

Yellow Sigatoka (caused by *Mycosphaerella musicola*) and Black Sigatoka (or Black Leaf Streak, caused by *Pseudocercospora fijiensis*) are widespread and maximum yield losses range between 33% and 80%. Yield losses from sigatoka have been increasing over the last few decades and are widespread. The adaptation range of *P. fijiensis* has been expanding into the cooler highlands, where the disease was previously absent (Kimunye et al 2020).

Important pests that may devastate banana plantations include weevils (*Cosmopolites sordidus*) and nematodes. Bananas are also affected by a combination of nematode species. The most damaging nematode species are *Radopholus similis* (burrowing nematodes), *Helicotylenchus multicinctus* (spiral nematodes) and *Pratylenchus* spp. (lesion nematodes). There is also evidence indicating that *Pratylenchus coffeae* is becoming more aggressive and widespread, replacing *R. similis* in importance. Maximum losses from nematodes range 25% to more than 80% (Jones 2009). The banana weevil (*Cosmopolites sordidus*) is the most important insect pest. Yield losses higher than 40% may occur in ratoon cycles (Gold et al 2004).

Four viruses have been reported on banana in SSA, the *Banana bunchy top virus* (BBTV), the *Banana streak virus* (BSV), the *Banana mild mosaic virus* (BanMMV) and the *Cucumber mosaic virus* (CMV) (Kumar et al 2015). With the exception of BBTV, all other three viruses are known to be widely distributed and are considered endemic. These three endemic viruses are not known to cause economically significant damage. No control efforts are implemented other than virus indexing for certification of planting material meant for domestic and international distribution. Of all these banana viruses, banana bunchy top disease (BBTD), caused by BBTV (genus *Babuvirus*), is the most critical and widespread viral disease of banana. Fruit production in infected plants are reduced by 70% to 100% within one season. All types of *Musa* cultivars grown in SSA are susceptible to BBTV. BBTV is transmitted by the banana aphid, *Pentalonia nigronervosa* and by vegetative propagation. BBTV disease is endemic in Central Africa since its appearance in the 1960s, contributing to production decline by 40% to 70% in the affected farms, and is emerging in West and Southern Africa. The banana bunchy top disease is considered invasive, which threatens the entire Eastern African sub-region. Over the last decade, BBTD has spread to at least eight countries (Benin, Cameroon, Mozambique, Nigeria, South Africa, Tanzania, Uganda and Zambia). The virus was also detected in Togo in 2018, but early detection and eradication prevented disease establishment.

Symptoms of banana plants infected by banana bunchy top virus (BBTV) (photo: Lava Kumar)

Reliable information on the general status of pathogens and pests in banana in the mainstream or informal literature is very limited. This hampers the understanding of changes in the banana health status during the past 30 years. However, the emergence of three major diseases (BXW, BBTD and Fusarium wilt TR4) in the various sub-regions of SSA has been documented to cause serious production losses in the past three decades. Empirical evidence suggests a decrease in production by up to 50% to 80% in the areas and farms affected by these diseases. Losses result from direct damage by the pathogens; indirect losses leading to decreased production results from farmers abandoning banana cultivation and shifting to other crops (e.g., to maize in BBTV affected central Malawi), an escape strategy which results from the lack of viable control measures to contain these diseases.

Evolution of banana and plantain health over the recent 10 years

Since the 2000s, the pest and disease levels and the damage they cause to the life-times of plantations and to banana yields have been increasing because (1) of the build-up in the population of endemic pathogens and pests, and (2) the emergence of pathogens, combined with (3) changes in climatic conditions, the increase of temperature, in particular (Erima et al 2017). Banana farming therefore faces multiple and increasing challenges in low altitude areas with weevils, nematodes, and Fusarium wilt (race 1). New diseases emerged as new threats since the 2000s, including the first report in Africa such as BXW in East Africa, BBTV in Eastern, Southern and Western Africa, and TR4 in Mozambique and Mayotte Island (Aguayo et al 2020).

Fusarium wilt can only be controlled by replacing susceptible with resistant banana varieties. A classical example is the replacement of Gros Michel (vulnerable to race 1) with Cavendish bananas in the mid-1900s. In the past decade, Sukali Ndizi, a popular and high-income dessert variety, is being replaced with Matooke bananas in East Africa when production is rendered impossible in small-grower fields. In northern Mozambique, TR4 susceptible Cavendish banana cultivars are also being replaced with Cavendish somaclones from Taiwan (Viljoen et al 2020). However, the response of cooking bananas and plantains against TR4 has not yet been extensively studied. TR4 may thus pose a significant threat to banana production on the entire continent. Where consumer preferences prevent the replacement of favoured susceptible varieties by less-favoured resistant ones, growers have no other choice than replace banana cultivation with less profitable crops. The threat of TR4 has caused panic among banana growers; its threat to smallholder farms in countries such as Tanzania is very real. TR4 was recently detected in a smallholder farmer's field in the Nampula province, —Mozambique. Given porous borders and the absence of effective quarantine systems, the threat of TR4 entering into smallholder production systems in East Africa is high.

The severity of sigatoka-like leaf spots have been on the increase. The pathogen (*P. fijiensis*) has expanded its range to new areas where it previously was not observed. A recent study revealed that the adaptation range of *P. fijiensis*, previously confined to elevation below 1350 m ASL, had expanded into the cooler highlands (at elevation higher than 1800 m ASL; Kimunye et al 2020). These highlands are the area where most of the susceptible EAHBs are grown by smallholder farmers. In addition, some of the previously sigatoka-resistant banana cultivars, such as Yangambi Km5 have been found susceptible, suggesting the emergence of new and virulent pathotypes of *P. fijiensis*.

Similarly, BBTV is spreading further in SSA. Its presence is confirmed in Southern Africa (Angola, Mozambique, South Africa, and Zambia) and West-Central Africa (Benin, Cameroon, and Nigeria). Presence of the virus is also confirmed in Tanzania and Uganda in 2020-21, which signifies incursion of the virus into East Africa. Within-countries expansion of BBTV has also been reported, as in Malawi, where it has reached both the banana-rich north and the southern regions, where it is a threat to banana diversity. Challenges in diagnosis, in containment, and in eradication efforts, resulted in unabated expansion of BBTV in SSA. BXW continues to cause large losses too. Complete losses and elimination of mats were reported recently in Burundi. BXW has however been brought under control, with incidence reduced from over 70% in 2005 to less than 5% today, in many bananas growing areas of Uganda using cultural control practices. Resurgences however have been recorded, and more may occur unless resistant varieties are developed and deployed.

Symptoms of Xanthomonas wilt (BXW) on banana plants (photo: Jaindra Tripathi)

Ecosystem services, as affected by plant disease

Provisioning **Regulating**

Level of ecosystem services generated by banana and plantain, as affected by plant disease, in the past 30 years

The overall increase in banana production since the 1960s in SSA has taken place despite a significant crop yield decline over the past 30 years. As indicated above, actual annual banana yields in farmer's fields are about 9% (range: 7.7 – 15.9 t.ha^{-1}) of the potential 60-70 t.ha^{-1} (Van Asten et al 2005). Low banana yields result from multiple factors, including poor soil, low water availability, losses from pests, and diseases. Shocks from pests and diseases, especially BBTV, BXW, black Sigatoka and Fusarium can lead to 100% yield losses. Fusarium wilt is one of many diseases that led to a decline in production of banana in Africa. Once introduced into a field, the fungus cannot be eradicated, and production will decline until further production is not possible. There were major geographical shifts of banana cultivation in Uganda over decades from lowlands to highlands and this is in part the result of the build-up of multiple pests and diseases in the lowlands. This then lead to a shift of the provisioning ecosystem services; food, fibre and others, to new areas of banana production. BXW was reported to have disrupted ecosystems as it massively cleared plantations, especially in hilly areas of Burundi.

This degradation of the situation has not, so far, led to an overall decline of production, and we can assess the overall level of provisioning service as "fair".

Evolution of the level of ecosystem services generated by banana and plantain, as affected by plant disease, over the recent 10 years

Overall, the production of banana has been congruent with the rapid population growth of SSA. With respect to the provisioning ecosystem service, we can assess the current status as "stable".

Maintaining the overall banana production to acceptable levels concurrently with population growth in SSA has come at a very large cost: forests and natural ecosystems have been cleared for agriculture, thus eliminating services (water, soil, climate) that these ecosystems provided. The displacements of banana cultivation has also come at environmental costs as well, because of the very ecosystem services (soil conservation, soil moisture) that banana plantations, with their long term cycles, ensure, especially in small farms and household and kitchen gardens.

Although all these impacts have not been specifically analysed in relation with banana cultivation, the ecosystem services other than provisioning have declined during the period.

Complementary information

Banana production is seriously affected by combined biotic factors (pathogens and pests), abiotic stresses (drought and low soil fertility), genetic challenges (narrow genetic diversity in germplasm), and socio-economic and market challenges (inadequate availability of clean planting material) for smallholder farmers. Changes in climate has a significant impact on banana yields where the crop is grown with minimal or no irrigation. Extreme weather events may further reduce the basal resistance of banana against pathogens. The evaluation of disease-resistant varieties of banana under sub-optimal environmental conditions (i.e., under the pressure of abiotic yield limiting factors such as drought, low soil fertility) is required. This will enable the breeding of improved banana varieties which will resist combinations of abiotic and biotic constraints.

We are very confident with own assessment of the findings of the present report as many studies and publications support our views.

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Perennial crops

grapevine

apple & pecan

coffee

citrus

Grapevine in Western Europe

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Background information

The cultivation and domestication of grapevine appears to have occurred between the seventh and the fourth millennia BC, between the Black Sea and Iran. From this area, cultivated forms would have been spread by humans in the Near East, Middle East and Central Europe. As a result, these areas may have constituted secondary domestication centres (Terral et al 2010). Greeks and the Romans developed its cultivation, spreading it all over the Roman Europe. Europe is, at present, the continent with the largest production, standing for 61 % of the world's total area under vines (OIV 2017). Vines were grown in the EU on 3.2 million hectares in 2015, accounting for 1.8 % of its total utilised agricultural area (Eurostat 2018). Spain, France and Italy were the main wine-grower countries in 2015, with 74 % of the total EU area under vines and 39% of the 2.5 millions of holdings. Vines for high quality wines dominated the EU vineyards, with 83% of the area dedicated to grapevine.

The area under grapevine in the EU has decreased over time, going from 3.4 million ha in 1999 to 3.2 million ha in 2009 and 2015. Grapevines in the EU are relatively old: 41% of the area was grown with at least 30-year-old vines and an additional 37% by vines between 10 and 29 years old (Eurostat 2018); this has an impact on the health status of vineyards.

Despite accounting for only 3.5% of the total EU agricultural area, grapes receive around 15% of the synthetic pesticides (active substances, a.s.) applied to major crops, a larger share than any other crop except cereals (PAN Europe 2020). The dose at which pesticides are applied to grapes amounts to 21.4 kg a.s./h. Much of this figure reflects the application of inorganic Sulphur; however, in addition to Sulphur-based fungicidal treatments, grapes receive substantial doses of synthetic fungicides averaging at 4.7 kg a.s./ha: a dose of synthetic fungicides higher than is received by any other crop, except potatoes.

This wide use of pesticide has generated increasing concerns on its side-effects for human health and the environment. Methods for disease control that are less dependent on chemicals have therefore been developed. These include Integrated Pest Management (IPM) and organic viticulture. IPM has become mandatory across

Vineyard in Northern Italy (photo: V Rossi) the EU following the Directive 2009/128/EC by 2014, while organic agriculture has been regulated through the Council Regulation 834/2007/EC. In Europe, almost 293,000 hectares (7.3% of the harvested grape area) were organic in 2015, which was almost 90% of the world's organic grape area. The countries with the largest organic grape areas were Spain, Italy, and France; each with more than 60000 hectares of organic grapes (FIBL 2017).

Grapevine health in Western Europe

State of grapevine health in the past 30 years

Grapevine in Western Europe has been exposed to a range of diseases caused by oomycetes and fungi, bacteria and phytoplasmas, viruses and viroids.

Several oomycete and fungal diseases mainly damage the canopy: leaves, shoots and clusters; these include downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), Botrytis bunch rot (*Botrytis cinerea*), black-rot (*Guignardia bidwelii*), Phomopsis cane and leaf spot (*Diaporthe ampelina*, syn. *Phomopsis viticola*), and other minor pathogens. Contamination of grapes and wines by mycotoxin OTA (ocratoxin A) produced by *Aspergillus* and *Penicillium* spp. has also been discovered in the mid-90's. These diseases have been reasonably well controlled by the use of fungicides and by cultural practices, make the plant canopy less dense, therefore make the microclimate less favourable for the pathogens, and thus reduce the pathogen inoculum.

Grapevine trunk diseases (GTDs) have re-emerged or have gained in importance in the past 25 years, resulting in a declining grapevine health in Western Europe. GTDs are caused by ascomyceteous fungi but some basidiomyceteous taxa also play an important role in the pathogen complex involved. In general, these fungi primarily infect grapes through pruning wounds, subsequently colonizing the internal wood tissues. Petri and Black foot diseases, Eutypa and Botryosphaeria diebacks, and Esca, have been reported as the major GTDs in Europe. These diseases cause significant economic losses because they reduced yields, increase crop management costs and shorten the life span of vineyards (De la Fuente 2016; Gramaje et al 2018).

Symptoms of downy mildew on leaf (photo: V Rossi)

Viruses and other infectious agents also constitute important threats (Maliogka et al 2015). *Bois noir* (BN) and *Flavescence dorée* (FD) are the most important Grapevine yellows (GYs, which are caused by phloem-limited bacteria) in Western Europe and cause serious yield losses (Tessitori et al 2018); the FD phytoplasma is a quarantine pest in Europe (EFSA PLH Panel 2016).

Symptoms of trunk diseases on foliage (photo: J Armengol)

Viruses are responsible for leaf-roll diseases (Closteroviridae), corky rugose wood-like syndrome (Betaflexiviridae), fan-leaf degeneration and leaf decline (Secoviridae), which often occur as multiple infection and cause reduction of berry production (Armijo et al 2016). Hop stunt viroid and Grapevine Yellow speckle viroid 1 are also widely distributed.

The resulting overall grapevine health status has been good, although variation over regions and years exist, with occurrences of outbreaks which can locally and punctually affect yield and/or quality of the product.

Evolution of grapevine health over the recent 10 years

The situation has worsened with respect to downy and powdery mildews, and to Botrytis bunch rot for three reasons: i) climate change increases the grapevine vulnerability to diseases (Bois et al 2017); ii) the reduced use of chemical fungicides in response to concerns over the side-effects on human health and the environment; and iii) the efficacy of chemical fungicides has decreased, first because of the build-up of fungicide resistances in pathogen populations, second, because of the decreasing availability of protectant fungicides (despite these being less prone to pathogen adaptation) as a result of legislation shifts, and third because of the reduced introduction of new chemical groups with different mechanisms of action. For the same reasons, some "minor" diseases such as black- rot, Phomopsis cane and leaf spot, sour rot, and other bunch rots are increasing in importance in some areas.

The situation concerning GTDs has also worsening, probably as a result of accumulated interactions among pathogen, host plants, environment (i.e., abiotic stresses) and cultural factors. This includes cultural practices that favour fungal infection in both nurseries and vineyards, such as the simplification of disinfection processes in nurseries, changes of grafting type, the cultivation of high-density spur-pruned trellised vineyards, which are often mechanically pruned (Mondello et al 2018). Similar causes apply for virus and phytoplasma diseases, which have probably accumulated in plants over the years, reducing fruit quality and plant vigour, and shortened the longevity of vines. Grapevine Leaf Mottling and Deformation syndrome has also become important (Buoso et al 2020). Further, grapevine yellow speckle viroid 2 and the Australian grapevine viroid have been detected in Western Europe recently (Gambino et al 2014). Removal and replacement of diseased vines, rather than leaving them in the vineyard where they could be for disease sources, result in the simultaneous presence of vines of different

Symptoms of flavescence dorée (photo: C Marzachi) age in the vineyards. This impacts on the feasibility and costs of agricultural practices, as well as on the production yield. Establishment of new vineyard as well as vine replacement after compulsory eradication, such is the case of FD-infected plants, favours further spread of these pathogens, favouring the emergence of complex diseases.

Ecosystem services, as affected by plant disease

Provisioning **Regulating** **Cultural**

Level of ecosystem services generated by grapevine, as affected by plant disease, in the past 30 years

Grape quality and wine-making technologies have constantly improved in the past 30 years in Western Europe, so that the production of high quality wine has steadily increased, as demonstrated by an increase in the export of wine. In 2017, the EU Member States exported € 21.9 billions (bn) of wine, € 11.3 bn of which outside the EU, mainly to the United States (32 % of extra-EU exports), followed by China (10 %), Switzerland (9 %), Canada (8 %), Japan and Hong Kong (both 7%) (Eurostat 2018). These good results have been achieved in spite of the presence of diseases, which have been therefore sufficiently well managed with regard to this provisioning service.

Management of the viticulture landscape generates regulating services, including climate regulation (in particular, the storage of CO_2 by grapevine in plant tissues and soil), water regulation and erosion (through a proper management of soil and soil cover), and biodiversity. Diseases, however, did not affect these services in a measurable amount at an ecoregional level; at a local level, however, the abandonment of vineyards due to high incidence of GTD and phytoplasma diseases is having a negative impact.

Vineyards also generate critically important cultural services, including recreation, heritage, aesthetic experience and landscape beauty. Diseases have both direct and indirect impacts, because of a decline in the aesthetic due to plant wilting and death (mainly due to GTDs), and because of the pollution generated by the use of chemical pesticides. These impacts, however, are difficult to quantify.

The overall assessment of ecosystem services provision is good, because improvement in provisioning services has in some extent offset the worsening for regulating and cultural services.

Evolution of the level of ecosystem services generated by grapevine, as affected by plant disease, over the recent 10 years

Even though grapevine health has declined over the past 10 years, grape and wine production and quality have remained high, as well as the global market share of the EU. The constant increase of public concern about the presence of fungicide residues in wine, however, represents a challenge. Regulating and cultural services have been decreasing due to a decline in the health status of vineyards. However, the improved management of the viticulture-dominated areas caused by a greater attention to multi-functionality (e.g., œno-tourism) and to environmental impacts (*via*, e.g., IPM and organic viticulture, precision agriculture, the use of digital technologies for vineyard monitoring and decision making in crop protection) had in some extend balanced the disease-related decrement.

Complementary information

There are reasons leading to consider grapevine health “in danger” for the future. The constant increase of public concern about i) the presence of fungicide residues in wine and ii) the loss of biodiversity due to fungicides represents a serious problem. The increase in organic and natural wines is a clear evidence of a change in the consumers' attitude; organic viticulture, however, is facing the problems related to the negative effects of copper-based fungicides on the biodiversity (La Torre et al 2018). This situation leads to a progressive reduction in the fungicide use, together with climate change and continuous erosion of fungicide efficacy (as previously mentioned), is worsening the health status of vineyards and this will be worsen in the future. Global change also represents a threat because of increased risk of introduction of alien harmful organisms such as, for instance, *Xylella fastidiosa* subsp. *fastidiosa* (the causal agent of Pierce's disease), which was officially detected on grapevine in Mallorca, Spain (Moralejo et al 2019). Alternatives to fungicides (biocontrol agents, botanical, etc.) for controlling oomycete and fungal diseases do not reach the level of efficacy of synthetic fungicides to date. There is an acute need to explore better the options for specifically-targeted pesticide and for biocontrol of vectors of grapevine vector-borne disease. The introduction of new varieties with resistance to mildews has not been a significant improvement so far at the European scale, mainly because of their limited use and their susceptibility to other diseases, such as black-rot. Plantations with resistant varieties, however, are increasing and recent studies show that consumers are willing to pay for the benefit that these varieties bring in terms of pesticide reduction (Fuentes Espinoza et al 2018).

Level of confidence in the assessment: reasonably confident.

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Perennial Fruit and Nut Crops in Eastern North America

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Background information

Eastern North America x Perennial Fruit and Nut Crops comprises a diverse environmental range from Mexico to Canada, and overlays the natural eastern temperate forests, northern forests, tropical wet forests, and great plains areas (Anonymous 2020). Perennial fruit and nut crops are grown throughout the ecoregion and represent many species including apple, avocado, blueberry, brambles, cherry, citrus, cranberries, grape, mango, maple, papaya, peach, pecan, plum and other minor perennial fruit and nut crops. Some crops are grown over broad areas of the ecoregion, while others are limited in cultivation. The primary purpose of these crops is provisioning services as specialty, supplementary foods (fresh and processed), but in some cases they may have cultural (landscape, native history, national foods, community activities, and art) services, and in a few cases, and to a limited degree, regulating service (erosion control, habitat health). The crops contribute to the local and national economies, with numerous people relying on them for employment and as a supplementary source of food; in many cases, they are valuable exports (USDA-NASS 2020).

We are reporting on:

1. Provisioning Services: food, etc.
2. Cultural Services: culture, spiritual, beauty, etc.

PlantSystems considered in this report

Two keystone species are considered: apple (*Malus* x *domestica*) and pecan (*Carya illinoinensis*). Apple is cultivated in the eastern regions of southern Canada from Ontario to Nova Scotia and in the US from the Canadian border to Georgia and as far west as Missouri and Minnesota. Pecan cultivation overlaps part of the apple range. It is cultivated throughout the south-eastern US from Florida to Texas and north to Illinois (USDA-NASS 2020). Both crops are important provisioning (supplementary, nutritious foods) and cultural (landscape [apple and pecan orchards], native history [pecans],

High density apple orchard in bloom (photo: Kerik (Denton) Cox)

A pecan orchard in Georgia, USA (photo: Clive Bock)

national foods [apple and pecan confections and baked goods] and beverages [apple], community activities [pick your own apples, cider tasting, agri-tourism] and art [e.g. apple and pecan featuring in fine and folk art, literature, wood working etc.] services (Pollan 2001; Robbins et al 2015; Wells 2017). Due to its native status, pecan additionally contributes a regulating service in areas where it grows naturally (Mississippi watershed area and through Texas and into Mexico). The apple was brought as seed to Massachusetts in 1632 by early European colonists. Both are important specialty crops in the region and represent the breadth of perennial fruit and nut production in eastern North America. Apple and pecan production (and associated industries) are important components of the rural economies where the crops are cultivated, and are both important sources of food and nutrition, for humans (and with apple, for livestock as pomace) with demonstrated health benefits.

Apple and pecan health in Eastern North America

State of apple and pecan health in the past 30 years

The health of the eastern apple has been stable over the last 30 years with horticultural advances being checked by disease and climatic changes, which present challenges for production in southern states. Following consumer preferences and financial needs of growers, breeding programs in this ecoregion have focused on varieties with traits to shorten time to establishment, and improve flavour, storage, and colour with disease resistance being of secondary importance (Dewdney et al 2003; Jurick and Cox 2017; Reig et al 2019). This in turn has led to widespread planting of varieties highly susceptible to fire blight (*Erwinia amylovora*) and apple scab (*Venturia inaequalis*). Rootstocks with fire blight resistance are available but are of limited use as the presence of scion tissue with active infections in commercial settings cannot be tolerated. Chemical management tools are highly effective against scab, but resistance to single-site chemistries presents a continual challenge as multi-site chemistries fall under public scrutiny (Cox 2015). Similarly, pecan health in the south-eastern region has been stable, although there remain recalcitrant disease-related health issues with widely grown cultivars susceptible to pecan scab (*V. effusa*; Bock et al 2017). The pathogen can reproduce rapidly (7-10-day cycle) through production of abundant conidia. Host resistance exists and in some cases is durable, but there are examples of host resistance failing due to pathogen adaptability - a particular problem with long-lived orchard crops. On susceptible cultivars the disease is effectively controlled by fungicides,

Apple scab (photo: Kerik (Denton) Cox) although tree size is an issue in achieving adequate fungicide coverage. As in the case of scab on apple, fungicide resistance is also a recurrent issue. No other disease is of major, or widespread concern on pecan. Overall, health of both crops can be considered good.

Evolution of apple and pecan health over the recent 10 years

Recently, apple and pecan health in relation to their respective scab diseases has been under greater threat due to development of fungicide resistance to several classes of fungicide used to manage the diseases (Bock et al 2017; Cox 2015; Standish et al 2021). Despite fungicide resistance, the registration of new, efficient fungicides against both scab species has helped mitigate their impact while broadening the range of chemicals to preserve efficacy. Advances in decision-aid support systems, biopesticides, new antibiotics, and improved growth regulator use practices have mitigated fire blight epidemics on apple (Dewdney et al. 2007; Norelli 2003; van der Zwet 2012). Thus, impacts of fire blight have been minimal. Although only characterised relatively recently, the pathogen *Xylella fastidiosa* (cause of pecan bacterial leaf scorch) is probably widespread (Bock et al 2018), but most indications are that its impact on the health of most cultivars is minimal. Climate change effects on the health of apple are felt more profoundly in the southern US where seasons begin several months earlier, propelling the plantings into an active state of growth at a time when climatic fluctuations are extreme, frequently leading to frost injury or susceptibility to newly emerging diseases. Although in southern areas of production, health of apple may be experiencing recent decline, in part due to disease (as driven by climate change), overall, both apple and pecan may be considered stable.

Symptoms of scab (caused by Venturia effusa) on pecan fruit (photo: Clive Bock)

Ecosystem services, as affected by plant disease

Provisioning

Cultural

Level of provisioning and cultural ecosystem services generated by apple and pecan, as affected by plant disease, in the past 30 years

Provisioning services

Overall, both the apple and pecan industries have performed well in the past 30 years in eastern North America, despite some disease issues. Cultivated area and total production in this region are steady to increasing, although yield is stable as might be expected with perennial crops. With apple, a consumer culture of premium pricing for new, fresh market varieties with desired traits of colour, flavour, and storability has resulted in planting systems more amenable to fresh market production, with little regard for disease resistance (Jurick and Cox 2017; Reig et al 2019). The new varieties are highly susceptible to fire blight, apple scab, and fruit rots. Nonetheless, these diseases have largely been controlled using pesticides, resulting in little impact on provisioning of apple due to disease. Apple production is variable in the ecoregion, and tends to be lower in the warmer production areas. Production of pecan in wet years is adversely affected by scab, with concomitant increased cost of chemical control measures (Bock et al 2017). Despite some issues with fungicide resistance, these remain mostly effective, so as for apple, provisioning has been stable. Due to climatic conditions, pecan yield in the humid Southeast is inherently lower compared to yield in the western US. Production fluctuates but this is primarily due to alternate fruit bearing; hurricanes also occasionally impact production in pecan. However, exports and the discovery of the health benefits of nut crops (Robbins et al 2015) have helped boost consumer demand internationally, benefitting growers through higher prices in recent years. As added value, recently pecan truffles have become sought after as an alternative to the European truffle (Grupe 2016). Overall, thanks to availability of effective pesticides, provisioning of neither apple nor pecan has been noticeably impacted by disease and may be considered good.

Cultural services

Diseases and environmental calamities have had limited impact on the cultural celebration of apple. Apples are consumed fresh or processed in the form of baked goods, dried slices, or increasingly pressed beverages to be seasonally consumed. Considerable fall agri-tourism, including apple festivals, is based on a central theme of picking of local fresh apples and consuming processed apple products. Apple orchards are an iconic part of the landscape in the eastern US and the apples themselves and apple pie, are symbolic of local culture in New York, many New England States, and Eastern Canadian provinces. Apple blossoms are state flowers in Michigan and Arkansas. Additionally, the apple can be found as literary subject and in popular folklore, as evidenced by the story of John Chapman (Johnny Appleseed; Pollan 2001). Moreover, there are associations between apples and sports and celebrations of national independence. Apple is a subject of folk artwork and apple wood, a premium medium for such art. Similarly, disease of pecan is not considered, or forecast to be, a threat to the cultural services of pecan (Wells 2017). Pecans (an Algonquian word) were a native American food and are a native North American species – and are thus long recognized of value culturally. Pecans are particularly important as part of the recognition of cultural events, specifically 'Thanksgiving' across the US. As part of the food culture, pecans are consumed fresh and in various processed forms, including as 'pecan pie', and are becoming more appreciated for their health benefits. It is the state tree of Texas, and in varying capacities is an official state symbol of Alabama, Arkansas, California and Oklahoma. As iconic components of landscapes of the Southeast, and as apple, as objects of fine art and folk art, pecan orchards and activities around pecans continue to be appreciated. Provision of cultural service by apple and pecan may be considered to be at very least, good.

Evolution of the level of provisioning and cultural ecosystem services generated by apple and pecan, as affected by plant disease, over the recent 10 years

Provisioning services

The area cultivated to apple has not increased recently but orchard renewal and replanting to more efficient systems with newer value-added varieties has increased yield (USDA-NASS 2020). The new apple cultivars remain susceptible to both scab and fire blight, but control of both diseases is achievable (Jurick and Cox 2017; Reig et al 2019). The fresh market production is the only remaining market, and the grower stakes in production are higher. Climatic changes have led to occasional catastrophic fire blight and apple scab epidemics, and in southern production areas newly emerging foliar diseases caused by *Glomerella* (*Colletotrichum* spp.) and *Marssonina* sp. Success of fresh market production fluctuates with erratic seasonal weather including spring freezes in some years and excessively wet or dry seasons in others with less seasonal consistency from year to year. As noted, pecan yield is stable, although acreages and production may show modest increases in recent years (USDA-NASS 2020). Fluctuations are attributable to alternate bearing, although disease (scab) or loss of fungicide efficacy can affect production in specific years, locales, or orchards. But pecan scab is manageable at a cost. A hurdle to resolving scab is time to develop new scab-resistant pecan cultivars (~25 years), and the risk that the cultivar may lose resistance through pathotype selection. Other concerns for pecan include water availability for irrigation and the competition from overseas producers (Wells 2017; Thompson 2020). Overall, the situation can be considered stable for both crops, although apple may be subject to greater disease pressure with climate change.

Cultural services

Plant health has not greatly influenced the importance of apple as a cultural icon in the eastern US recently. Apple picking and processed apple products are still an important component of the fall celebrations and agri-tourism as well as a symbol for the region's identity (Pollan 2001). There has been a recent interest in fermented apple cider and a burgeoning industry is developing in the north-eastern and mid-western US with year-on-year expansion. Cider production has a long history in eastern Canada and continues as a protected market. Such interest has led to expansion of orchards with cider varieties possessing traits that impart complexities of flavour to cider. As with the wine industries, tastings and tours are also a becoming a popular cultural phenomenon. Similar to apple, in the recent past diseases of pecan have not threatened the cultural services provided by the crop. As noted, the native status and health benefits are capitalised on, and are well-recognised, and may be intensifying (Wells 2017). There are iconic dishes that continue to be popular (e.g. pecan pie). Mail order pecans remain a popular gift. Particularly recently (the last 20 y) pecans (and associated pecan truffles; Grupe et al 2016) have been the subject of numerous recipes. Fine art and folk-art recognising apple and pecan in North American culture continue to be widely represented. Provision of cultural service by apple and pecan may be considered at least stable.

Complementary information

Due to its native status, pecan additionally contributes a regulating service in areas where it grows naturally (the Mississippi watershed area and through Texas and into Mexico). It can be a dominant species in some areas. The status of several other perennial tree fruit and nuts in Eastern North America are similarly good to excellent with stable to improving status (e.g. grapes, blueberries, cane fruit), while a few may be fair, with stable to declining servicing (peaches in the Southeast; USDA-NASS 2020). Per capita consumption due to consumer preference and disease may play a role in the decline of peach production in North America although there is minor expansion of peach production for local consumption in Florida (Crisoto et al 2006). Disease is an issue on both apple and pecan (particularly scab on pecan, but fire blight presents a greater risk to the apple industry as complete planting loss is possible). Pecan production and profitability are sensitive to price, and competition from other countries (pecan is being actively planted in Mexico, various countries in South America, South Africa, Australia and China (e.g., Duvenhage 2017; Wells 2017). Thus, export markets could shrink (or expand) depending on availability of pecans outside eastern North America or the US as a whole. Climate change in the ecoregion could also impact pecan production (but there is no information on this aspect pertaining to pecan). Apple production and profitability are similarly sensitive to price and competition from foreign markets such as China. As a result of such competition, processing is no longer a viable market for the eastern North American apple industry. In turn, the industry has turned to value-added fresh market products (particularly managed varieties with improved and unique flavour profiles). Cider production is the one exception to this trend.

We are reasonably to very confident on most points: there are several studies, publications, and other sources of information that support our views. In only a few cases are there gaps in the literature, precluding certainty.

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Coffee in Central America

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Background information

Central America has a tropical climate which is modulated by elevation. Climate change is expected to strongly affect Mesoamerica in the near future, because low latitudes are exposed to climate change several decades earlier than higher latitudes (Hawkins and Sutton 2012). Central America may therefore be seen as an observatory for early climate change impacts. The region is also under the influence of two oceans (Pacific, Atlantic-Caribbean sea), and its climate is strongly influenced by El Niño – La Niña Southern Oscillation. This results in large weather variability with dry and very rainy years.

Coffee is one of the most traded agricultural products in the world. About 100 million people depend on it. In 2014, it was estimated that 26 million farmers in 52 countries produced over 8.5 million tonnes of coffee, worth US$39 billion. The retail value of coffee is much higher. In the US alone, sales reached US$87 billion in 2019. Coffee is generally produced by smallholders, who own areas of less than 5 ha (Rhiney et al 2021).

Coffee used to be the most important export in value and a very important contributor to national GDPs 30 to 40 years ago in Central America (Avelino et al 2015). Since then, the contribution of coffee to GDPs has dropped below 7 % in the region, with a maximum of 6 % in Guatemala, and less than 1 % in Costa Rica and El Salvador (Espíndola Rafael and Trewick 2021). Yet 1.9 million people directly depend on coffee in the region, most of them smallholders and agricultural labourers (Avelino et al 2015). The social and economic importance of coffee has been highlighted by the coffee rust crisis (starting in 2012), when 16–32% of the total labour force, depending on the country, a total of around 375,000 people, lost their jobs because of the decrease in coffee production, with consequences in terms of migration from rural to urban areas and from Central America to North America (Avelino et al 2015).

This report focuses on Arabica coffee (*Coffea arabica*).

Landscape with pruned and free growth erythrinas (flowering) (photo: J Avelino)

PlantSystem considered in this report

Coffee is grown in agroforestry systems (AFSs), i.e., associations of Arabica coffee with shade trees, which generate a range of ecosystem services: provisioning, supporting, regulating, and cultural services (Avelino et al 2018). Ecosystems services generated by these AFs can be summarised as follows (Avelino et al 2018):

- AFSs provide habitat for a large number of species (e.g., birds, ants, and fungi) with potential for the regulation of pests and diseases;

- dampen microclimatic variations;

- intercept light, thus suppressing weeds;

- contribute to carbon sequestration in the perennial plant species associated with coffee and in the soil;

- reduce surface runoff and soil loss through erosion;

- improve water quality; and

- enable a regular supply of water for human consumption or hydropower generation.

In terms of provisioning services coffee-based AFSs produce coffee as well as food, fuelwood, and construction materials, resulting into a diversification of farmer's incomes. Through radiation interception, shade trees suppress excessively high yields and extend the maturation duration of berries with buffered temperature.

Fertiliser application (photo: J Avelino)

Shading thus results into: (1) stabilised yields over years; (2) improved coffee quality; and (3) prevent the risk of coffee tree exhaustion through excessive production.

Furthermore (Avelino et al 2018), coffee-based AFSs improve their own environment by (a) reducing soil acidity, through the organic matter that is incorporated into the soil; (b) generating nitrogen in the case of associations involving leguminous trees (litter fall and pruning residues can produce up to 340 kg N/ha/year); and (c) increasing soil biodiversity (e.g. earthworms).

AFSs also enable ecotourism that contributes to the protection of complex, traditional, and culturally established systems.

Coffee health in Central America

State of coffee health in the past 30 years

Coffea arabica originates from the highlands of East Africa. Many coffee pests and diseases are still not reported in Central America, particularly: the Coffee Berry Disease (CBD, *Colletotrichum kahawae*) and the Coffee Wilt Disease (CWD, *Fusarium xylarioides-Gibberella xylarioides*). Recent introductions of pathogens and pests in the region include *Xylella fastidiosa* in 1995 (Rodriguez et al 2001) and the Coffee Berry Borer (*Hypothenemus hampei* in 2000 in Costa Rica; Staver et al 2001).

The past 30 years can be divided into two periods, first 1990-2010 with epidemics at national or specific coffee zone scales, caused by two main diseases, the American Leaf Spot Disease (ALSD, *Mycena citricolor*) and the Coffee Leaf Rust (CLR, *Hemileia vastatrix*). Prior to 2010, ALSD mainly affected Costa Rica and Guatemala in specific years (i.e. during the very rainy La Niña years – J. Avelino, personal observation), where high elevation and cool temperatures favour development of the fungus. In 2010, a la Niña year, a regional ALSD epidemic occurred, also covering Honduras and Nicaragua, and even Colombia (Avelino et al 2018).

Three national CLR epidemics occurred in Costa Rica, Nicaragua, and El Salvador in 1989, 1995, and 2002, respectively. These epidemics mainly reflected farmers' economic difficulties, who could not afford purchasing fungicides to manage CLR. However, starting 2012, a regional CLR epidemic of a magnitude never seen before occurred, which affected the whole of Central America, along with Mexico and the Caribbean. That Coffee Leaf Rust regional epidemic actually had started in Colombia (2008-2011) and continued until 2013, when Equator and Peru were also impacted. Coffee leaf rust is the main threat on coffee in the entire region since 2012 (Avelino et al 2015; McCook and Vandermeer 2015).

These last epidemics have led the farmers to replant their farms with CLR-resistant varieties (Harvey et al 2021), which however are more susceptible to ALSD. Given the current climate change forecasts (elevation of temperatures), this large-scale variety replacement could lead to large ALSD epidemics in specific climatic years only. Moreover, this replacement of coffee varieties might not solve the CLR problem, because many new rust races have emerged that are able of overcoming resistance genes carried by the newly planted varieties. Some pathogen races seem entirely new. In Honduras alone, 11 new races of *Hemileia vastatrix* have for instance been identified since 2014 (Avelino and Anzueto 2020).

Leaf rust infected by Lecanicillium lecanii (photo: Isabelle Merle)

Evolution of coffee health over the recent 10 years

The Coffee Leaf Rust epidemics have been very serious, leading to variable production reductions with an average of 20% over several years at the region scale. Yield reductions in El Salvador have been in excess of 50% and the production of this country has not recovered yet. This is because much of the coffee area in El Salvador is planted to the highly susceptible tall Bourbon cultivar, with old plants and with limited disease management. Recovery of plantations in this country requires a gradual cultivar replacement, which will take several years (Avelino and Anzueto 2020).

The social impacts have been very large, with 375 000 workers losing their jobs, 130 000 households severely impacted and suffering various degrees of malnutrition (Avelino and Anzueto 2020; Avelino et al 2015).

It seems that the climatic variability in the region has increased, leading to the ALSD epidemics of 2010 and to the CLR epidemics since 2012. These two diseases have very different meteorological requirements. They used to only concern some specific coffee areas or countries at a time, but

Mycena citricolor on leaves – insert: propagules (photos: J Avelino) never be a concern for the region as a whole (J. Avelino personal observation).

Ecosystem services, as affected by plant disease

Provisioning services **Regulating services**

Level of provisioning and regulating ecosystem services generated by coffee, as affected by plant disease, in the past 30 years

Coffee is the main agroforestry system in Central America: it constitutes the main human-made forest in the region. Coffee areas therefore serve to connect protected areas and significantly contribute to the conservation of biodiversity (DeClerck et al 2010). The overall ecosystem services generated by AFSs have been high over many years. The emphasis on environmental conservation in agricultural systems has generated innovations in the form of payment for ecosystem services (DeClerck et al 2010).

Despite these economic innovations for environmental conservation, however, the evolution of these systems has been negative over the past 30 years, especially in the recent past years, because of a reduction of shade cover in coffee plantations (Harvey et al 2021; Jha et al 2014).

Evolution of provisioning and regulating ecosystem services generated by coffee, as affected by plant disease, over the recent 10 years

There is ground to consider that a degradation in the provision of ecosystem services is taking place (DeClerck et al 2010; Jha et al 2014), because the reduction in production caused by coffee leaf rust epidemics, and because of a reduction of shade cover in coffee plantations to take advantage of the high yield potential of new CLR-resistant varieties.

Harvey et al (2021) report fast and extreme biophysical changes in coffee-based systems mainly resulting from low coffee prices, changing climatic conditions, and severe plant disease epidemics. These authors report seven trends of concern: (1) the widespread varietal replacement with coffee leaf rust-resistant cultivars, (2) the intensification of coffee cultivation with higher planting densities, greater use of agrochemicals and reduced shading, (3) the substitution of the coffee crop with other agricultural uses, (4) the introduction of Robusta coffee (*Coffea canephora*) into areas where coffee was not previously grown, (5) the expansion of coffee into areas with forests, (6) the urbanization of coffee areas, and (7) the increase of voluntary sustainability standards.

Complementary information

- as in many other tropical export crops where much of the production is in the hands of small-holders, a main concern is the price paid to producers for their productions.

- in countries where financial agricultural support is weak or non-existent, farmers producing export commodities are especially vulnerable to global markets.

- lower prices on the global coffee market leads to lower farmers' financial resources. The reduction of lower farmers' financial resource has been demonstrated to be one cause for the development of coffee rust (Villarreyna et al 2020).

- Another issue is the level of farmers' training and their age, which constrain the prospects to learn or adopt new approaches.

We are very confident in this assessment: many studies, publications, support your views. There are only few gaps in the literature.

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Citrus in the world

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Background information

This report provides an assessment of citrus health globally. Citrus trees are a perennial crop grown for its fruits, which are one of the key sources of vitamin C in human diets (Liu et al 2012), a source of simple sugars, dietary fibre and secondary metabolites (Lv et al 2015), and a key ingredient in juices, jams, jellies and marmalades. Citrus fruits and by-products from juice production are also used to extract essential oils and citric acids used in the food, cosmetics and pharmaceutical industries (Kaur et al 2021; Panwar et al 2021). It is estimated that around 2/3 of citrus fruits produced worldwide are consumed as fresh fruit, and the remaining 1/3 is used mainly for juice production and some industrial purposes (Liu et al 2012).

Apart from the provisioning services associated with citrus that are mentioned in the previous paragraph, citrus trees also provide cultural services. They have a strong cultural value in many countries in Southeast Asia, where they are used in rituals, as well as for decorative and medicinal purposes (Vasudeva et al 2015). The first citrus trees were brought from its centre of origin in the Southeast foothills of the Himalaya's to the Mediterranean region around the fourth century BC as elite products (Talon et al 2020). Seeds and pollen remains of citron (*C. medica*) have been found in gardens owned by the affluent in Rome and the Vesuvius area (Langgut 2017), and citrus orchards have shaped the landscape of many agricultural areas along the Mediterranean Sea, while being present in the gardens of palaces and monasteries, city streets, orchards and private backyards for many centuries. During colonial times, citrus cultivation spread to Southern Africa, the American continents and Australia.

Citrus growing area, São Paulo State, Brazil (photo: L Willocquet)

PlantSystem considered in this report

The genus *Citrus* and related genera belong to the subfamily Aurantioideae within the Rutaceae family. Their centre of origin was located around the southeast foothills of the Himalayas, and their native habitat comprised the monsoon region, from west Pakistan to north-central China and south through Indonesia to New Guinea and the Bismarck Archipelago, northeastern Australia, New Caledonia, Melanesia and the Western Polynesian islands (Wu et al 2018).

The most cultivated citrus species are sweet oranges (*C. sinensis*), sour oranges (*C. aurantium*), lemons (*Citrus* x *limon*), mandarins (*C. reticulata*), grapefruits (*Citru*s x *paradisi*) and pummelos (*Citrus maxima*) (Wu et al 2018). Citrus fruits are the second most traded fruits globally by volume. Global citrus production reached approximately 143.5 million tons of fresh fruit in 2019, of which 55% were oranges, 25% were tangerines, mandarins, Clementines or satsumas, 14% were lemons or limes, and 6% were grapefruits or pummelos (FAOSTAT 2019).

Citrus species are grown in many tropical and subtropical areas, between the latitudes of 40°N and 40°S, up to 1,800 m of altitude in the tropics and up to 750 m in the subtropics (FAO 2021). The main citrus-growing areas around the world include the Asian continent (China, India, Indonesia, Pakistan), the Mediterranean region (Spain, Egypt, Morocco, Italy), North America (United States of America, Mexico), South America (Brazil, Argentina), South Africa and Australia (FAOSTAT 2019). This report focuses on six key citrus-producing areas around the world: China, Brazil, the US, the Mediterranean, Australia and South Africa.

In the Asian continent, China is the main citrus-producing country, providing 28% of global citrus production. Other key citrus-producing countries in Asia are India, Pakistan, and Indonesia. Due to the large population base of this region, citrus is mainly grown for domestic consumption (FAOSTAT 2019).

In Brazil, the total commercial citrus area is 700,000 ha, most of which (84%) is sweet orange, mainly for juice processing. Lemons, acid limes and mandarins make up the remaining (16%) cultivated area. São Paulo State is responsible for around 72% of all sweet orange produced in Brazil, followed by the States of Minas Gerais, Parana and Bahia. A well-established program for production of certified disease-free nursery citrus plants is present in São Paulo State since 2003. Nowadays most (>85%) citrus plants cultivated in that State come from certified nurseries.

Harvest in a citrus grove, São Paulo State, Brazil (photo: L Willocquet)

The USA grows around 270,000 ha of citrus, mainly in the states of California and Florida, but also in Texas and Arizona, for a total of 7.78 million tons in the 2019-2020 season. California accounted for 54% of total USA citrus production in that season, followed by Florida (42%), and Texas and Arizona (4%) (USDA-NASS 2020). Citrus production in California, Texas and Arizona is mainly for the fresh market, while Florida focuses on juice production.

In the Mediterranean region, citrus production is mainly for the fresh market, which defines its agronomic management and makes it more vulnerable to cosmetic damage by pests and diseases. Within the European Union (EU), Spain is the main citrus producer and a global exporter, followed by Italy and Greece (DG AGRI 2021a). Egypt, Morocco and Tunisia are also important citrus producers, with significant volumes exported to the EU (DG AGRI 2021b).

Australia grows citrus on 27,963 ha in various regions of the country, with its production increasing over time, according to the Australian citrus tree census (Citrus Australia 2020). The main citrus growing region is the Riverina, followed by the Murray Valley and the Riverland, which have a Mediterranean climate and mainly grow oranges and grapefruit. The other main production area is in subtropical Queensland with production heavily focused on mandarins, lemon and limes.

In South Africa, the industry comprises commercial plantings totalling 96,230 ha (CGA 2021), of which the majority is planted using certified disease-free propagation material and grown for export of fresh fruit.

Citrus health in the world

State of citrus health in the past 30 years

Citrus is grown around the world under different climatic and agronomic conditions. These influence the main pests and diseases and the state of citrus health, making generalisations difficult. Overall, the global state of citrus health in the past 30 years could be rated as fair, but big differences are apparent between regions. Even though citrus diseases have impacted the citrus industry in key areas like Brazil since the 1940s (Coletta-Filho et al 2020), most citrus pests worldwide were economically managed using biological control and selective insecticides until the emergence of several high impact plant diseases vectored by insects in the last 15 years (Urbaneja et al 2020).

Key citrus pests that require regular management across citrus-growing areas in Asia, the Mediterranean, North America, South America and Africa include: the Mediterranean fruit fly (*Ceratitis capitata*), the oriental fruit fly (*Bactrocera dorsalis*), the citrus leafminer (*Phyllocnistis citrella*), California red scale (*Aonidiella aurantii*), the citrus mealybug (*Planococcus citri*), the citrus red mite (*Panonychus citri*), the Asian citrus psyllid (*Diaphorina citri*) and the citrus fruit borer (*Gymnandrosoma aurantianum*) (Urbaneja et al 2020).

Emergent citrus diseases vectored by insects that pose a significant threat to global citrus health include: huanglongbing (HLB), associated with the phloem-limited bacteria '*Candidatus* Liberibacter asiaticus' (*C*Las) and '*Candidatus* Liberibacter africanus' (*C*Laf), which are transmitted by the Asian citrus psyllid (*Diaphorina citri*) and the African citrus psyllid (*Tryoza erytreae*), respectively (Gottwald 2010); citrus variegated chlorosis (CVC), caused by *Xylella fastidiosa* subsp. *pauca* and transmitted by sharpshooter leafhoppers and spittlebugs (Coletta-Filho et al 2020); citrus leprosis, a viral disease transmitted by mites in the genus *Brevipalpus* (Roy et al 2015); and citrus yellow vein clearing disease (CYVC), a viral disease mainly transmitted by the citrus whitefly (*Dialeurodes citri*) (Liu et al 2020). Other vectored diseases include citrus tristeza, which is the most economically important viral disease of citrus (Lee 2015). This disease, caused by *Citrus tristeza virus* (CTV) and transmitted by several aphid species, spread to all citrus growing regions in the early 20th century and caused a worldwide shift away from sour orange rootstocks, which had been chosen for their resistance to *Phytophthora* root rot, to other tolerant or resistant rootstocks such as Rangpur lemon (Dawson et al 2015).

Other emergent citrus diseases include citrus canker, caused by *Xanthomonas citri* subsp. *citri*, which spread from Southeast Asia to Africa, Oceania, South and North America, and has implications for import of fruit into the EU; and citrus black spot (CBS), caused by *Phyllocsticta citricarpa*, which is another invasive citrus disease that was first reported in Australia and is now present in Africa, South America, Asia and North America (Guarnaccia et al 2019).

China

In general, the status of citrus health in China for the last 30 years can be defined as fair to good. Although a citrus virus-free propagation program and integrated pest management (IPM) have been implemented since the early 1980s, the fast-developing citrus industry has created an imbalance between supply and demand for healthy nursery trees, especially for late-maturing citrus hybrids in recent decades. The inability to control certain pests to meet quarantine threshold requirements has led to the removal of the Chinese citrus fly [*Bactrocera* (*Tetradacus*) *minax* (Enderlein)], the oriental fruit fly and canker from the state quarantine list in 2009 and 2020, respectively. In addition, the outbreak of HLB in China is of major concern, especially for the fast-developing Guangxi citrus industry after the outbreak in the Ganzhou prefecture (Jiangxi province) in 2013, which led to the removal of over 50 million citrus trees.

Brazil

During the past 30 years, citrus health in Brazil can be rated as fair to good. The incidence of diseases varies among the different citrus-growing regions in Brazil. HLB, citrus canker and CBS are absent in Brazilian northwest states, but CVC is still a great threat for sweet orange production. In the Southern citrus-growing regions, specifically São Paulo, Minas Gerais and Paraná states, a high pressure from diseases such as CVC, citrus canker, CBS, leprosis and HLB has impacted the cost of citrus production. Nowadays, CVC has been efficiently controlled in São Paulo State as a long-term result of the certified citrus nursery program officially started in 2003. Currently, most (>85%) citrus plants cultivated in that state come from certified nurseries. Strategies based on pathogen exclusion and plant protection have supported the management of HLB (exclusively associated with *C*Las) for profitable citrus production.

United States

Overall, the state of citrus health in the US in the past 30 years could be rated as fair. Citrus production in Florida has been severely impacted by invasive plant diseases in the past 30 years, including citrus canker (Gochez et al 2020) and HLB (Graham et al 2020), while the citrus industry in California has remained free of major pest and disease problems (Grafton-Cardwell 2020).

Huanglongbing (HLB), blotchy mottle symptoms on leaves (photo: Helvécio Della Coletta-Filho)

Mediterranean

Spain is the main exporter of citrus fruits in the Mediterranean region, and the state of citrus health in this country has been good for the past 30 years, and could be considered excellent until the last 10 years. After some problems with citrus tristeza and other viral diseases in the 70s, Spain established a certified plant material program that dramatically improved the citrus health. The impact of citrus pathogens (*Alternaria spp.*, *Phytophthora spp.*) has been minimal, and IPM practices have been implemented since the early 2000s, with increasing adoption of biological control and a reduction in insecticide use. However, the impact of citrus pests has grown in the last 10 years, associated with the introduction of invasive pests, such as the mealybug *Delottococcus aberiae* (Martínez-Blay et al 2018). Citrus operations are often small, and growers have limited insecticide options to manage outbreaks. Italy and Greece lack a strong plant certification program and have been more affected by pests and diseases over the past 30 years. One example is the "mal secco", caused by the ascomycete *Plenodomus tracheiphilus,* that has impacted lemon production in Sicily. Egypt and Morocco have a strong citrus industry, they use certified plant material and have a wider range of insecticides authorised for citrus pests.

Alternaria brown spot (photo: Antonio Vicent)

Australia

Overall, the status of citrus health in Australia for the last 30 years can be rated as good. Most citrus pests and diseases are managed through a system of biosecurity, clean planting scheme, use of resistant rootstock, biological control and the use of fungicides and insecticides. Due to the differences between climatic regions and citrus species grown, some pests and diseases such as CBS are only present in the subtropical production region. Ongoing biosecurity efforts grant the absence of some major citrus diseases such as HLB, CVC and citrus canker. Two incursions of citrus canker have occurred in Australia in the last 30 years, one in 2004 and one in 2018. Extensive eradication campaigns have been successful and at present Australia is declared free of citrus canker.

South Africa

In general, citrus health in South Africa can be regarded as good to even excellent. The industry's Citrus Improvement Scheme (CIS) started in 1973, and since then has evolved based on world's best practices. The CIS is very well supported, and the very low incidence of graft transmissible diseases (caused by virus, viroid and bacterial pathogens) is testimony of this good agricultural practice. South Africa is still free from many of the feared citrus diseases, such as HLB, CVC, citrus canker, and leprosis. Citrus tristeza is effectively controlled by means of mandatory cross-protection of CIS-certified propagation material. African Greening, caused by *C*Laf and vectored by *T. erytreae*, is present in certain growing regions. Greening is not as severe as HLB, as *C*Laf and its vector are heat sensitive, and problematic in cooler growing regions. CBS is present in the summer rainfall growing regions (Carstens et al 2012), and is problematic largely because it limits market access to the EU. Citrus insect pests are effectively controlled to meet export quality and phytosanitary standards.

Evolution of citrus health over the recent 10 years

Citrus health has been negatively impacted by several invasive diseases that have been detected outside their native range in the last 10 years, including HLB, citrus leprosis, CVC, citrus canker, CYVC, and CBS. Citrus health is also under threat from climate change, which might exacerbate drought and high temperature problems in some of the subtropical areas where citrus is grown (Sato 2015).

HLB is considered the most destructive disease of citrus worldwide (Bové 2006). The Asian type of HLB has been a major threat to citrus production in Asia for the last 50 years (Zhou 2020), and it has now spread to the main citrus production areas in South, Central, and North America. All citrus varieties are susceptible to the disease, which causes blotchy mottle symptoms on leaves, premature fruit drop, irregular fruit maturation and the eventual death of trees. HLB was first detected in São Paulo (Brazil) in 2004, in Florida (USA) in 2005, in Yucatan (Mexico) in 2009, in Texas and California (USA) in 2012, and in Misiones (Argentina) in 2012 (Garcia-Figuera et al 2021). These areas have implemented costly control programs and are investing in the development of long-term solutions, such as genetically resistant or tolerant citrus varieties.

Citrus leprosis and CVC were first described in the USA in the 1860s and in Brazil in 1987, respectively, but they began spreading in the early 2000s and are now threatening citrus production in areas where they are present, apart from imposing trade restrictions on fruit exports to areas where they are not present. Citrus leprosis causes severe defoliation, girdled limbs, twig death, premature fruit drop, a reduction in both fruit quality and yield, and eventually the death of the tree in 3-5 years (Roy et al 2015). CVC causes leaf chlorosis, tree dieback, a reduction in fruit size and the fruits harden and ripen early (Coletta-Filho et al 2020). It is important to stress that CVC, which was a great threat for citrus production in São Paulo State, is nowadays effectively controlled.

Citrus yellow vein clearing disease was first found in Pakistan 1997, then India, Turkey, China and Iran, and is now causing epidemics in Pakistan, Turkey, and China (Liu et al 2020). Its fast spread via insects poses a threat to the citrus industry, particularly to the lemon, lime and sour orange industries in Asia.

China

Overall, citrus health in China has been stable over the last decade. Tatter-leaf, caused by Citrus tatter leaf virus, which is pathogenic on specific cultivars of pomelo, and severe stem-pitting of CTV on navel sweet orange in limited areas have caused some damage within recent years. The development of an early warning platform, promotion of healthy nursery trees, reduction of pesticide usage and promotion of biological and physical control, among other measures, have received much attention in recent decades and have been technically supported by key state projects for sustainable development. Furthermore, through the construction of a citrus quarantine pest-free zone and two HLB interception zones, the threat of further HLB spread is reduced at the moment. The threat of CYVC epidemics in the lemon industry is under control after much effort in recent years.

Brazil

As mentioned above, citrus production in Brazil is quite diverse, but mainly represented by São Paulo State. In the past 10 years the evolution of citrus health in São Paulo state could be considered stable in terms of one disease, but declining in terms of another. Vascular and graft-transmissible pathogens such as CLas, *X. fastidiosa*, viruses and viroids are absent from propagative material produced under the official certification program. Citrus mother plants were established in greenhouses by using buds from shoot-tip grafting material from basic (founder) plants, which were indexed for these pathogens and cross-protected by protective (weak) CTV isolates. Annually, founder and mother plants, as well as all nursery plants commercialised, are mandatorily tested for *C*Las and *X. fastidiosa* by qPCR. Despite these measures to maintain the health of propagative material, the incidence of citrus canker and HLB has increased slightly in the field in the past decade. Both diseases are under mitigation strategies in commercial groves, with no mandatory eradication of diseased trees.

United States

Because of the huge impact that HLB has had on the Florida citrus industry, overall citrus health in the USA has declined in the last 10 years. Since HLB was first detected in Florida in 2005, citrus cultivated area and yield have declined by 38% and 74% respectively, and HLB is now present in all citrus groves (Graham et al 2020). Even though citrus production has been kept at profitable levels, HLB is also widespread in Texas (Sétamou et al 2020). In California, the citrus industry has been funding a costly management program (McRoberts et al 2019) that has managed to keep HLB outside of commercial citrus groves to date (CPDPP 2021).

Mediterranean

The introduction of invasive pests from other areas has caused a decline in citrus health in the Mediterranean over the past 10 years. Apart from the mealybug *D. aberiae*, *T. erytreae* was introduced from Africa to Spain and Portugal (Ruíz-Rivero et al 2021), although it is still absent from commercial citrus production areas in those countries. Both HLB vectors and associated bacteria are priority pests for the EU, as well as *X. fastidiosa* and CBS. The latter is present in Tunisia and has caused production losses due to cosmetic damage to fruits and trade restrictions in exports to the EU.

Australia

Citrus health in Australia has been stable over the last 10 years. A recent invasion of citrus canker was eradicated and there is ongoing concern about HLB, which drives investment in biosecurity to ensure Australia remains free of these major pathogens.

South Africa

The status of citrus health over the past 10 years in South Africa can be regarded as stable and improving. Again, this is a result of the high rate of participation in the CIS. Moreover, advances in diagnostic tools led to improved ability to ensure that propagation material is pathogen-free, and the CIS systems were improved to include viruses and viroids that could previously not be detected using conventional diagnostic tools. South Africa has a mandatory post-entry quarantine system, which includes pathogen elimination by means of shoot-tip grafting. Strict adherence to this principle, and investment in biosecurity and awareness initiatives, has ensured that South Africa is still free from most feared diseases. Leprosis was recently detected in isolated growing areas (Cook et al 2019), but through the implementation of a rapid response plan, the disease is effectively being eradicated. South Africa's most imminent threat is the report of *C*Las and its vector in Kenya (Ajene et al 2020), and the required biosecurity plans were put in place.

Ecosystem services, as affected by plant disease

Level of provisioning and cultural ecosystem services generated by citrus, as affected by plant disease, in the past 30 years

Global citrus production has increased in the past 30 years, so the level of provisioning services generated could be considered as good. In terms of cultural services, the overall level could also be considered as good. Citrus trees are still commonly found in backyards, streets and small orchards in Southeast Asia, South America, North America and the Mediterranean region.

In China, the level of provisioning services over the past 30 years has been fair to good. China is the world largest producer of citrus, especially for mandarin and pomelo. It took around 20 years for citrus production in China to reach the first 10 million tons in 1997, but since then much less time was needed for every 10 million tons increase (FAOSTAT 2019). The introduction of industrial and commercial capital has facilitated the growth and productivity of the industry. HLB remains the most important threat to the survival of citrus production in China, but after a movement of the industry from the coastal provinces that were more historically affected by the disease to more northern provinces and the implementation of a strict control program, the industry has succeeded in keeping HLB epidemics under control for now (Zhou 2020).

The level of provisioning services associated with citrus **in Brazil** in the last 30 years could be considered as good. In Sao Paulo state (Brazil), the agricultural land occupied with citrus in the last 30 years has been reduced by 25% (from 600,000 to 450,000 ha), but the planting density has increased from 350 to 575 plants/ha, contributing to a productivity increase of 27% in this period. In the area where HLB was detected for the first time in 2004, citrus yield has increased from an average of 25 tons per ha (616 boxes of 40.8 kg) in the 2004/2005 season to 43 tons per ha (1051 boxes) in the 2019/2020 season, even though HLB incidence has been growing for the last 15 years (Bassanezi et al 2020). However, there was a significant cost increase to achieve this level of control, due to costs associated with inspection, removal of trees and higher density planting. The level of cultural services could be rated as poor due to the removal of HLB-symptomatic citrus trees as a part of the HLB management program since the first detection in 2004.

In the USA, the level of provisioning services associated with citrus over the past 30 years could be considered as fair, given the huge impact that HLB has had on citrus production in Florida since 2005, with a decline in citrus production by 74% and an increase in citrus production costs by 283% (Singerman et al 2018). In terms of cultural services, many citrus trees have been removed from residential areas in Florida, Texas and California as part of the eradication campaigns for HLB and even citrus canker in the case of Florida, so the level of citrus cultural services could be considered as poor.

In the Mediterranean, the level of provisioning services over the past 30 years has been good, despite some yield reductions due to pests such as *D. aberiae* in recent years, and more importantly, quality losses due to cosmetic damage caused by pests on fruit, which lowers the value of citrus in the high-quality export markets. The level of cultural services over the past 30 years has been good.

Australia's citrus production has increased over the last 30 years. The main challenges the industry faces are highly variable market prices at the domestic and international export markets and high labour and production costs. The level of provisioning services has been good over the past 30 years but is under threat from several major invasive diseases such as citrus canker and HLB.

The level of provisioning services provided by citrus in **South Africa** has been excellent. The industry has grown 65.6% from 58,101 to 96,230 ha in the past 10 years, on the back of excellent returns on exported fresh fruit. Fresh fruit exports have increased 33.9%, from 1.65 to 2.21 million tons, with many newly planted orchards coming into production (CGA 2011; 2021).

Evolution of the level of provisioning and cultural ecosystem services generated by citrus, as affected by plant disease, over the recent 10 years

Despite the negative impact of some invasive plant diseases, particularly HLB, on global citrus health in the last 10 years, the level of provisioning services and cultural services provided by citrus trees has not been as severely impacted on a global scale. In some important citrus-growing areas, such as the state of Florida in the USA, a marked decline in citrus health has triggered a decline in the generation of ecosystem services. That, together with the emergence of other citrus pests and diseases associated with an increase in global trade in the last 10 years, and the more frequent occurrence of extreme weather events linked to climate change, leads to an assessment of "declining" generation of services at the global scale over the recent 10 years.

In China, the level of provisioning services has been increasing, as the citrus industry has grown even faster in the past decade. For example, citrus production reached over 13.8 million tons in Guangxi province in 2020. Both labour and land costs are increasing, even though the area under citrus production has been gradually declining. In the near future, promotion of export and processing will be challenging.

In Brazil, citrus production is one of the activities that provide higher ecosystem services per cultivated area. In the last 10 years, the level of provisioning services has been stable and a total estimated 200,000 jobs are being provided, even though the cultivated area has decreased and the intensity and frequency of activities necessary to keep production profitable has increased.

The level of provisioning and cultural services associated with citrus has declined in the **USA** in the last 10 years, mainly due to HLB.

In the Mediterranean, the level of provisioning services has been declining in the past 10 years due to growing introductions of invasive pests that cause cosmetic damage on fruit and are increasingly difficult to manage with the limited number of insecticides available to growers.

In Australia, the health of citrus has not changed much in the last decade and as such the level of provisioning services has been stable over the last 10 years.

In South Africa, the effect of citrus health on the generation of provisioning services has been stable and the South African citrus industry has grown. The incursion of citrus leprosis was contained through rapid response and is being eradicated. No other debilitating pest incursions were detected.

Complementary information

In terms of the social and economic environment associated with global citrus health, it might be worth mentioning that orange juice consumption trends have changed over the last 20 years. In more developed countries (USA, Germany, France, United Kingdom), frozen concentrate orange juice (FCOJ) consumption has declined up to 45% between 2003 and 2018 due to a growing preference for healthier and more natural juices that are not from concentrate (NFC); while emerging countries (Brazil, Russia, China, South Africa, Morocco, Indonesia, Argentina, Turkey, Chile, Romania, Philippines) have seen an increase in FCOJ consumption (Neves et al 2020). This is likely to impact citrus production in countries like Brazil, that supplies 3/4 of the global orange juice exports (Neves et al 2020). In addition to phytosanitary challenges for citrus production in Brazil, climate change could also negatively impact production by increasing drought stress and by rising temperatures during the Spring and Summer in areas like São Paulo State.

In some areas like the Mediterranean or California, labour costs and water availability are major concerns for citrus growers.

Assessment of the findings of the present report: very confident, based on assessments made by six citrus experts in the major citrus-growing areas around the world.

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Peri-urban horticulture & household gardens

Peri-Urban Horticultural Systems and Household Gardens in Sub-Saharan Africa

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Background information

Sub-Saharan Africa (SSA) has diverse climatic zones, including arid, semi-arid, humid and semi-humid (Harvestchoice/IFPRI 2015). This broad range of climates allows a high diversity of plant species including many agriculturally important crops to grow in the region. Peri-urban horticultural systems are important as suppliers of vegetables to the growing urban populations. Their proximity to major markets makes it possible to produce perishable products such as vegetables. Such proximity is especially important in lower-income countries where the lack of good roads and cold chain options make it challenging to transport vegetables over longer distances.

Household gardens (or home gardens, kitchen gardens, backyard gardens) are an integral part of local food systems all over the world and make an essential, yet often little recognized, contribution to food and nutrition security. Gardening is an ancient practice and probably the oldest form of crop cultivation. Household gardens are typically mixed cropping systems that may include seasonal vegetables, fruit trees, herbs and spices and other useful plants and may be combined with livestock. Gardens are usually located close to dwellings for easy care and convenience and their main purpose is to supply the household with food, although excess production may be sold or shared.

The role of peri-urban horticultural systems is the provision of food whereas the role of household gardens includes cultural and regulatory services alongside food production. Cultural services include the conservation of plant species diversity and indigenous knowledge of plants, making living spaces more liveable and more beautiful (e.g. providing shade, reducing dust), a practice over which mostly women have control and the supply of inputs to the local food culture (Galhena et al 2013). Regulatory services include the recycling of organic household waste and grey water, and are mainly considered here according to water quality.

Women harvesting amaranth, near Dar es Salaam, Tanzania (photo: P Schreinemachers, World Vegetable Center)

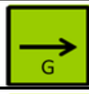
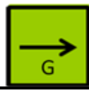
PlantSystems considered in this report

Under the peri-urban farming systems, several types of indigenous and commercial vegetables crops are cultivated to supply urban and peri-urban populations in the SSA. Vegetables, particularly tomato, okra, African eggplant, amaranth and African nightshade are among the main fruit and leafy vegetables cultivated in peri-urban areas throughout SSA (Mnzava et al 1999). These vegetables are also common in home gardens, although these generally also include many other vegetables alongside fruit trees, herbs, medicinal plants and other utility plants (Watson and Eyzaguirre 2002).

Tomato is among the main cash crops produced in peri-urban areas, but is affected by a large number of pests and diseases. African eggplant (edible fruits and greens) and okra (fruits) are also common in SSA. African nightshade and amaranth are traditional leafy vegetables that make an important contribution to nutrition security and livelihood of small-scale farmers. In general, these five vegetables are important components of the diets of most people in the region as well as sources of income and employment (provisioning) for people in peri-urban areas and improves soil health (physical, chemical and biological properties) in combination with other crops as they add soil organic matter and reduce erosion.

A man harvesting vegetables, Dar es Salaam, Tanzania (photo: P Schreinemachers, World Vegetable Center)

Vegetables health in Sub-Saharan Africa

Keystone species	Family	Health
Tomato	Solanaceae	
African eggplant	Solanaceae	
African nightshade	Solanaceae	
Amaranth	Amaranthaceae	
Okra	Malvaceae	
All species combined		

State of vegetables health in the past 30 years

Vegetable production practices in peri-urban areas of SSA are much more intensive than in field crops. Important plant health challenges have been observed over the last three decades, which vary with the vegetable type and season. For instance, smallholder tomato producers in peri-urban areas can suffer heavy losses when not investing in quality seed and good management practices.

The most important diseases in tomato production include tomato (yellow) leaf curl viruses and other Begomoviruses, bacterial wilt, Fusarium and Verticillium wilt. These diseases also affect other Solanaceous vegetables including African eggplant (Seck 2009) and African nightshade. Okra is less susceptible to diseases as compared to other vegetables. Some of the diseases of okra include vascular wilt caused by *Fusarium oxysporum*, damping-off, Cercospora blight, powdery mildew, bacterial wilt, okra leaf curl disease, Choaneophora fruit rot and root-knot nematodes (Ariyo and Olasatan 2009).

A tomato plant infected by (yellow) leaf curl viruses (photo: Wubetu Bihon Legesse)

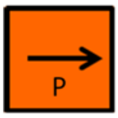
Leafy vegetables (amaranth, African nightshade and leafy type African eggplant) are relatively resistant to pathogens and pests. However, amaranth is affected by seedling damping off (*Pythium aphanidermatum*), stem decay caused by *Fusarium* sp., leaf and stem rot (*Choaneora cucurbitarum*) and necrotic lesions caused by *Alternaria* spp. (Blodgett et al 1998; Mnzava et al 1999). Bacterial wilt has been reported recently on amaranth (Sikirou et al 2019), and unidentified amaranth leaf blight diseases have been observed in Tanzania. Plant health challenges are much less important in home garden cultivation systems as it is a long-established tradition for SSA farmer's (Watson and Eyzaguirre 2002). In summary, the health of plants varies depending on crop type (poor in tomato, fair in African eggplant, and good in other vegetables). The overall assessment would therefore be "fair".

Evolution of vegetables health over the recent 10 years

Several vegetable diseases caused by viruses, fungi, bacteria or nematodes cause high yield losses under peri-urban cultivation systems in SSA, even under high pesticide use. The frequency and occurrence of these diseases vary depending on the host, pathogen type, disease management strategies, climate, and location. The frequency of major viruses such as Potato Virus Y and Potato Leaf Roll Virus is stable over time while frequency and damage by TYLCV has increased over the past years. Plant virus epidemics are likely to be greatly influenced by climate change, such as increased temperatures, leading to the increased abundance and activity of vectors (Jones 2009). Similarly, the frequency of occurrence, diversity and damage by bacterial wilt caused by *Ralstonia* sp. on tomato, African eggplant and African nightshade has increased and has become a challenge for smallholder farmers. The diversity of pathogen strains of viruses, bacteria and fungi has increased in recent years. Parasitic root-knot nematode is a common challenge in the sandy coastal regions and peri-urban areas where intensive farming is practiced (Coyne et al 2018). Leaf and fruit rot of amaranth and okra, caused by *Choanephora cucurbitarum*, was a major problem during the 1980s and 90s (Teri and Malsani 1994) but has not been a major issue in recent years, except for sporadic occurrences. Other diseases such as stem decay of amaranth caused by *Fusarium* spp. (Blodget et al 1998), damping off, leaf blight, mildew, fruit rot of okra, root-knot nematode, etc. are relatively stable except for an unidentified amaranth leaf disease which has been recently observed in Tanzania. On a 3-point scale, the state of plant health for the last 10 years has declined.

Amaranth stem canker caused by Fusarium oxysporum (photo: Wubetu Bihon Legesse)

Ecosystem services, as affected by plant disease



Keystone species	Family	Eco-S
Tomato	Solanaceae	
African eggplant	Solanaceae	
African nightshade	Solanaceae	
Amaranth	Amaranthaceae	
Okra	Malvaceae	
All species combined		

Level of ecosystem services generated by vegetables, as affected by plant disease, in the past 30 years

Vegetables are rich sources of vitamins, minerals, fibres and other bioactive compounds, which are critical to combat malnutrition. Vegetables also provide income, employment opportunities, and aesthetic value in the urban, peri-urban and home garden systems. Vegetables also improve the soil fauna in combination with other crops through different cultivation systems (rotation, mixed cropping, shifting cultivation). Consequently, peri-urban vegetable production strongly expanded over the last 30 years in SSA. However, farmers growing exotic vegetables (e.g., tomato) in the peri-urban areas frequently apply toxic and sometimes banned pesticides, often in excessive quantities (Levasseur et al 2007), while yield and quality remain very low.

Consumption of vegetables in SSA is far below the minimum intake guidelines set by the WHO (~240g/day/person) due to consumers' culture and poor yield and quality of produce (Kalmpourtzidou et al 2020; WHO/FAO 2003). The poor yield and quality of vegetables is due to losses from pests and diseases, lack of knowledge on disease management and lack of good farming practices. Peri-urban tomato production is strongly hindered by plant diseases. From the standpoint of (food) provisioning, the service rendered is therefore poor.

Evolution of the level of ecosystem services generated by vegetables, as affected by plant disease, over the recent 10 years

The scale of peri-urban vegetable production has expanded in response to rising urban demand as a result of rapid urbanisation. Farmers in SSA have seen a number of initiatives over the years to improve peri-urban vegetables production and productivity. Awareness of pest and disease (diagnosis), of disease management strategies and of cultivation practices are still low but are improved compared to 10 years ago. Research and development services are playing a role in enhancing awareness of growers of input suppliers and of policy makers on pest and disease management; they also contribute to improving safe and sustainable production of vegetables. However, according to FAOSTAT (2018), vegetable yields have stagnated at low levels for the last eight years while the total production of vegetables has significantly increased. This suggests that area expansion is the main source of such increased production.

Therefore, using a 3-point scale, the trend of the effect of plant health on the generation of provisioning services remained constant. With respect to the regulating and culture services, the effect of plant health has declined for tomato, while remaining stable for the other vegetables over the last ten years.

Complementary information

Published resources to understand the trend of plant health in SSA on peri-urban and especially for home garden vegetable production is very scarce. Observations therefore heavily rely on personal expert opinions and extrapolating from related literature on plant health reports in the region.

Despite the importance of vegetables in SSA, yields remain low at about 7 t/ha compared to 14 t/ha in Europe (FAOSTAT 2018). This is partly due to poor plant health resulting from biotic and abiotic constraints. Several new species and strains of viruses, bacteria, and fungal plant pathogens are being reported in several countries in SSA on different hosts. Climate change, globalization and increased urbanization have an effect in the introduction, evolution and spread of novel plant diseases. The introduction of new host plants also has increased the diversity of strains of many pathogens. Although farmers are becoming more aware of plant health and despite the intensive use pesticides, pest and disease problems of vegetables remain a major challenge in these systems.

Our confidence in this report is limited, because of gaps in studies that specifically address peri-urban and home garden farming systems.

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Peri-Urban Horticultural Systems and Household Gardens in South Asia

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Background information

The peri-urban horticultural systems of South Asia are key suppliers of vegetables to urban centres. Their proximity to major markets enables the perishable products to be sold after short distance transport. These systems are thus unaffected by inadequate infrastructure for perishable food transport (roads, cold chain, etc). Peri-urban agriculture is especially important and diverse in South Asia, with various forms: commercial gardening, home gardens, community gardens, community supported agriculture, vertical farming, rooftop gardening, etc. (Nicholls et al 2020). Peri-urban small-scale farms often grow a diversity of crops over space or time (i.e., in same growing season), which contributes to their overall output. Although peri-urban farms tend to be very small, their economic viability can be very good, and they can be equally or even more productive than commercial, monoculture farms.

PlantSystems considered in this report

Peri-urban vegetable production is characterized by year-round cultivation of crops, where vegetable crops are rotated according to seasons. In some cases, mixed cropping or inter-cropping is also practiced. Although production is mostly concentrated near the consumption centres (closest cities), surpluses are also transported to other urban areas within a country. These systems in South Asia produce and supply all kinds of vegetables, according to local demand. Leafy vegetables (predominantly spinach, mustard, amaranth and kangkong, and culinary herbs such as fenugreek and coriander), cauliflower, cabbage, radish, carrot, beans and peas, cucurbits, okra and tomato are commonly grown in the peri-urban systems of South Asia (Pushpakumara et al 2012; Sumangla et al 2013). Frequent irrigation is widespread, although involving very variable water quality. Most vegetable growers rely on organic manures, supplemented by inorganic chemical fertilizers.

Home gardens are commonplace in both urban and rural settings across South Asia. Many home gardens also have perennial vegetable trees, especially moringa and fruits such as bananas (including plantain). Leafy vegetables such as amaranth, sessile joyweed, Asian pennywort or culinary herbs grow wild under shade and among the planted trees in home gardens.

Tomato, fresh beans (French bean, lablab), cabbage, cauliflower, amaranth, and bitter gourd can be considered as keystone vegetables in South Asia in peri-urban vegetable production as well as home gardens. Chili pepper is also an important solanaceous vegetable, but is more commonly produced as a field crop grown at a larger scale and away from urban areas, although it is commonly found in home gardens as well.

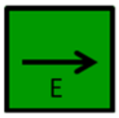
Field of tomatoes, Coimbatore, India (photo: P Schreinemachers, World Vegetable Center)

Woman in home garden, Sindhupalchok, Nepal (photo: P Schreinemachers, World Vegetable Center)

Keystone species	Family
Tomato	Solanaceae
Fresh beans	Fabaceae
Cabbage/cauliflower	Brassicaceae
Amaranth	Leafy vegetables
Bitter gourd	Cucurbitaceae

Vegetables health in South Asia

Home garden:



Peri-urban horticulture:

Assessment for keystone species in Peri-urban horticulture

Keystone species	State of plant health (30-years)	Evolution of plant health (10-years)	Health
Tomato	Pests and diseases and their management have been well studied and recommendations are available. Because of the development and adoption of technological innovations including disease resistant varieties to manage biotic constraints, the state of plant health has significantly improved. However, emerging diseases (especially viruses) and invasive pests remain a serious threat.	More research has been conducted on emerging plant diseases, shifts in plant pathogens, and disease management strategies including disease resistant varieties. The state of plant health has significantly improved.	
Fresh beans	Some research has addressed plant health in French bean (*Phaseolus vulgaris*) and hyacinth bean (*Lablab purpureus*). The state of plant health in French bean has improved, but remains a major concern in hyacinth bean.	More research has been conducted on emerging plant diseases, and the development of disease management strategies. The state of plant health has improved to some extent.	
Cabbage/ cauliflower	Pests and diseases and their management have been well studied and recommendations made available. The state of plant health has significantly improved, especially for the diseases, but the diamondback moth (*Plutella xylostella*) remains a major threat, especially in the lowlands.	More research has been conducted on the development of disease management strategies. The state of plant health has significantly improved.	
Amaranth	Although amaranth is a short-duration crop, plant health information is available to some extent. Plant health does not seem to be a major issue for the leafy types than the grain types.	Some research has been conducted on emerging plant diseases, especially viruses. The state of plant health has remained the same.	
Bitter Gourd	Plant disease management has been addressed to some extent for this species. Concerns on plant health are increasing despite varietal improvement, which primarily focuses on yield increase.	More research has been conducted on emerging plant diseases, and disease management strategies, with limited focus on disease resistant varieties. The state of plant health has improved to some extent.	
All species combined	Satisfactory knowledge on plant health is available on the considered crops. The state of plant health remains a major concern to smallholders in the region.	The state of plant health has been improving.	

State of vegetables health in the past 30 years

Year-round production is a common phenomenon in peri-urban vegetable production systems in South Asia. The use of irrigation and manure are high. The diversity of crops limits the build-up of pests and pathogens into severe outbreaks. Although the literature on plant health focused on peri-urban vegetable production systems is scanty (Chowdappa 2013), pests and diseases in these systems do not significantly differ from those of other (field) vegetable production systems. Literature on field vegetables thus can be useful.

Tomato: Damping off (caused by *Pythium* and *Rhizoctonia*), Alternaria leaf blights (*Alternaria alternata* and *A. solani*), gray mold (*Botrytis cinerea*), late blight (*Phytophthora infestans*), southern blight (*Sclerotium rolfsii*) and Fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici*) are major fungal diseases. Bacterial wilt (*Ralstonia solanacearum*), bacterial spot (*Xanthomonas vesicatoria*), tomato leaf curl (whitefly-transmitted Begomoviruses) and tospoviruses (thrips-transmitted peanut bud necrosis and tomato spotted wilt viruses) also cause severe yield losses (Nagendran et al 2019).

Fresh beans: Anthracnose (*Colletotrichum lindemuthianum*), gray mold (*Botrytis cinerea*), leaf spot (*Cercospora canescens*), powdery mildew (*Erysiphe polygoni*), leaf rust (*Uromyces* spp.) and wilts (especially *Fusarium solani*) are the most common fungal diseases (CABI 2019a; Chowdappa 2013; Mishra et al 2019). Severe economic losses can occur if pods are infected by powdery mildew. Common bacterial blight caused by *Xanthomonas campestris* pv. *phaseoli* and yellow mosaic virus also reduce production.

Cabbage and cauliflower: Damping off (caused by *Pythium* and *Rhizoctonia*), Alternaria leaf blights (*Alternaria brassicae* and *A. brassicicola*), downy mildew (*Peronospora parasitica*), powdery mildew (*Erysiphe cruciferarum*), and black rot (*Xanthomonas campestris* pv. *campestris*) are some of the major diseases (CABI 2019b; Chowdappa 2013), whereas club root of cabbage (*Plasmodiophora brassicae*) prevails locally in South Asia (Bhattacharya et al 2014).

Amaranth: Some knowledge exists on vegetable amaranth health. Capsicum chlorosis virus (CaCV) transmitted by thrips has been reported from India. Leaf blight (*Rhizoctonia solani*) is a major constraint for amaranth cultivation in the monsoon or under humid conditions (Uppala et al 2010). Damping-off, root rot and aphid transmitted *Cucumber mosaic virus* were also reported from vegetable amaranths (Raj et al 1997). The Papaya Leaf Curl Virus, transmitted by whitefly, and yellow vein net disease caused by the Ageratum Enation Virus have also been reported from grain amaranth.

Bitter gourd: Powdery mildew (caused by *Podosphaera xanthii*), downy mildew (*Pseudoperonospora cubensis*), mosaic (caused by three different viruses: Cucumber Mosaic Virus, Papaya Ringspot Virus and Bitter gourd Distortion Mosaic Virus), and leaf curl (caused by three different viruses: Bitter gourd Leaf Curl Betasatellite Virus, Tomato Leaf Curl Palampur Virus and Pepper Leaf Curl Virus) are some of the commonly reported diseases (Ali et al 2010; Raj et al 2010). The Indian Cassava Mosaic Virus associated with yellow mosaic disease of bitter gourd was also reported (Rajinimala and Rabindran 2007).

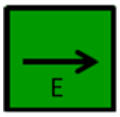
Evolution of vegetables health over the recent 10 years

Although many vegetables in peri-urban systems are produced year-round, the disease risk is relatively high, since vegetable crops are not usually rotated with plant groups that are widely different (such as, e.g., cereals). The incidence of some diseases, especially in the case of insect vector-transmitted virus diseases, will be altered due to climate change (Gautam et al 2013). Priority has been given to developing disease-resistant varieties of commercial crop species such as tomato and to some extent fresh beans and bitter gourd. Other disease management approaches include the use of antagonistic microbes, vegetable grafting, and fungicides.

However, some components in integrated pest management strategies have limited application in peri-urban production systems. For instance, crop rotation for a couple of years (2-3 years for rust disease, and 4-6 years for wilts) is required to reduce the level of inoculum. This is not always feasible in the intensively cultivated peri-urban vegetable production systems in South Asia. Plant health is not a major priority in home gardens for multiple reasons. First, home gardens in south Asia are usually managed at low levels of chemical (fertilizers, pesticides) inputs (but high levels of labour). Second, the agrobiodiversity is so rich in home gardens that it operates as an effective buffer against biotic and abiotic constraints (Kunhamu 2015).

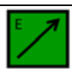
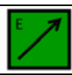
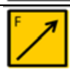
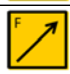
Ecosystem services, as affected by plant disease

Home garden, provisioning and cultural:



Peri-urban horticulture, provisioning and regulating:

Assessment for keystone species in Peri-urban horticulture

Keystone species in peri-urban horticulture	Provisioning services	Regulating services
Tomato		
Fresh beans		
Cabbage/cauliflower		
Amaranth		
Bitter Gourd		
All species combined		

Level of ecosystem services generated by vegetables, as affected by plant disease, in the past 30 years

Peri-urban horticulture: Over the last 30 years, disease resistant varieties have been introduced for tomato and French bean. Resistant varieties and root-stocks to overcome virus diseases, late blight, and bacterial wilt diseases limit the reliance on chemical pesticides in tomato. Similarly, resistant varieties against bean rust, wilt, and angular leaf spot reduced the dependence on pesticides in beans. However, the absence of insect-resistant varieties and the poor adoption of IPM practices have led to pesticide overuse, especially in tomato, cabbage and cauliflower, and bitter gourd. Resistant varieties and/or other disease management practices maintained or even increased the provisioning services. However, pesticide overuse adversely impacts regulating services (especially as a cause for declining pollinators and natural enemies of crop pests) in most of these crops. The very high cropping intensity of peri-urban production systems, compared with other (e.g., field) production systems, also adversely affects soil health, which further encourages the use of inorganic fertilizers. An important element is that peri-urban farms have limited access to organic manure (in the absence of farm animals) and are often located in river deltas characterized by heavy clay soils, both contributing to low soil organic matter. Continuous cropping in peri-urban farms also leads to inoculum build-up, and so increases in pathogens and disease incidences, favouring a progressive decline in provisioning services.

Home gardens contribute provisioning services in terms of food supply and cultural services including specific ingredients important to the South-Asian food culture (e.g. turmeric, cumin, chili, coriander, curry leaf, cardamom, and fenugreek). Home garden systems have a long cultural tradition in South Asia and there are no reports known to us that such systems are reducing in importance. Home gardens systems usually have a high diversity with many species grown mixed together in limited individual numbers (Gautam et al 2008). The literature on home gardens focuses on their role in biodiversity conservation, on food provision and their contribution to better nutrition. There are no known scientific studies for South Asia on plant diseases in home gardens, which may suggest that plant diseases are not a key concern in these systems. This may be explained by the small scale of cultivation in home gardens, the short duration of some crops such as leafy vegetables, and the fact that diseased plants can easily be removed with minimal effect on the overall productivity of a home garden. Therefore, on a 5-point scale, both provisioning and cultural services provision can be rated as "Excellent".

Evolution of the level of ecosystem services generated by vegetables, as affected by plant disease, over the recent 10 years

Peri-urban horticulture: The area under peri-urban vegetable production is increasing in South Asia, because of the growing population in cities that offer a steady market for the fresh produce. In addition, with growing health concerns and the raising awareness on the nutritional importance of vegetables, vegetable consumption is steadily increasing, stimulating the demand for vegetables. With the advent of innovative breeding tools and biotechnology, several disease resistant varieties are made available by the public and private sectors. The development of the bio-pesticide sector also has generated alternative options for pesticide-free, safer vegetable production. Protected cultivation is also increasing in peri-urban vegetable production. Thus, peri-urban vegetables farmers have adopted recent technological innovations to improve plant health in the recent decade. Hence, both the provisioning services and regulating services are improving in most of the crops.

For home gardens, the effect of plant health on ecosystem services is likely to be small for the same reasons as stated above. Therefore, on a 3-point scale, both provisioning and cultural services provision can be rated as "stable".

Complementary information

Peri-urban vegetable production is undergoing continuous changes in South Asia. In fact, peri-urban agriculture is highly flexible by nature, since the periphery of the cities keeps expanding. As a result, this production system faces land and water challenges. Mostly, only a few specialized crops are produced in peri-urban farms. Such lack of diversity and continuous cropping lead to increasing pests and diseases. The use of protective structures (which do not have environmental control) such as poly-net house, low tunnels, etc. in the hot and humid regions of South Asia increases the incidences of diseases. However, there is a lack of literature studying the evolution of pests and diseases and their management practices for different crops in peri-urban production systems systematically across South Asia. This prevents us from generalizing or extrapolating the available information at the ecoregional level. Hence, we are moderately confident that this assessment is accurate.

There is a lack of literature documenting plant health in home garden systems. Some of this may indicate a lack of serious problems; however, it also suggests a bias in agricultural research as home garden systems, despite their importance for food security, receive minimal attention in agricultural research and extension. Considering this lack of published studies, the degree of confidence is best rated as "uncertain".

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Peri-Urban Horticultural Systems and Household Gardens in Southeast Asia

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Background information

Peri-urban horticultural systems are mainly important as suppliers of vegetables to urban centres. Their proximity to markets makes it possible to produce vegetables that are perishable. Such proximity is especially important in lower-income countries where the lack of good roads and cold chain options make it challenging, if not impossible, to transport vegetables over longer distances.

Household gardens (or home gardens, kitchen gardens, backyard gardens) are an integral part of local food systems all over the world and make an essential, yet often little recognized, contribution to food and nutrition security. Gardening is an ancient practice and probably the oldest form of crop cultivation. Household gardens are typically mixed cropping systems that may include seasonal vegetables, fruit trees, herbs and spices and other useful plants and may be combined with livestock. Gardens are usually located close to a dwelling for easy care and convenience and their main purpose is to supply the household with food, although excess production may be sold or shared (Galhena et al 2013).

The role of peri-urban horticultural systems is the provision of food whereas the role of household gardens includes family needs, cultural and regulatory services alongside food production. Nutritional service towards the household includes the provision of much-needed vitamins and minerals (Schreinemachers et al 2018). Cultural services include the conservation of plant species diversity and indigenous knowledge of plants, making living spaces more liveable and more beautiful (e.g. providing shade, reducing dust), a place over which mostly women (and the elderly, and children) have control, and the

A woman harvesting ridge gourd from a garden in Nakhon Pathom Province, Thailand (photo: Sorawit Limsiriwat, World Vegetable Center) supply of inputs to the local food culture (Galhena et al 2013). Regulatory services would include the recycling of organic household waste and grey water, but are hard to quantify because of the small scale and diversity of household gardens. There is probably the greater tendency to recycle grey water in the home gardens in remote areas where water is scarcer and may have to be transported some distance to the homestead, though the perceptions and acceptability of using grey water vary greatly (Radingoana et al 2020). However, with climate change and pressure from urbanization, providing local greywater treatment facilities is becoming a higher priority for providing safe irrigation water for small-scale horticultural operations in peri-urban situations in SE Asia and other tropical and subtropical areas. The valuable habit of recycling organic waste through composting or simple surface mulching may be declining with the rural youth loosing interest in agriculture/horticulture and migrating to the cities and towns for work leaving ever aging parents and grandparents to tend the home gardens.

Home garden in Son La, Vietnam (photo: P Schreinemachers, World Vegetable Center)

PlantSystems considered in this report

Across SE Asia a great diversity of vegetable, fruit and herb/spice crops are grown in the smallholder peri-urban commercial horticulture systems for sale in local markets and in some cases for transport to and sale in the larger cities. Among the vegetables in these systems, generally the most valuable in terms of provisioning and income generation will be one or more Solanaceous species, bean species (Fabaceae) and fast-growing leafy vegetables such as some of the leafy brassicas. Leafy salad vegetables, such as lettuce, that are eaten uncooked, only have become more commonly grown in peri urban systems in recent years in response to the increased demand for more "Western style" cuisine, and as drinkable water and simple treatments to decontaminate from microbiological hazards have become more affordable and available (Cheung et al 2021). However, the most important vegetable species differ from country to country and even from region to region within a country depending on local preferences and growing conditions. For this assessment we chose tomato (*Solanum lycopersicum*), yard-long bean (*Vigna unguiculata* ssp. *sesquipedalis*) and the leafy brassicas pak choy (*Brassica rapa* subsp. *chinensis*), Chinese leaf mustard (*Brassica juncea*) and Chinese kale (Mandarin: "jie lan"; *Brassica oleracea*) as representative of some of the most important and ubiquitous for the peri-urban systems of SE Asia ecoregion (Jansen et al 1995). Tomato adds flavouring, colour and some nutrition to cooked dishes and sauces, and (particularly the cherry types) are increasingly being eaten raw as a salad vegetable/fruit. Yard-long beans are harvested at the almost full-grown, green-pod stage and eaten fresh and cooked for their relatively high protein (2.6%), vitamin, and fibre content. Similarly, the leafy brassicas are picked young when they are tender and require little cooking and so remain relatively nutrient dense.

Household gardens vary greatly in size and species diversity even within the same village so the species diversity they hold is huge considering the SE Asia ecoregion as a whole. Although most household gardens contain perennial trees and shrubs that are important both culturally and for their provisioning service, for this assessment we consider kang kong (*Ipomea aquatica*), chilli peppers (*Capsicum* spp.) and a Cucurbitaceous species (pumpkin, bitter gourd, luffa, cucumber etc.) as being common to most household gardens across the region (Minh et al 2015). Kang kong is a very fast growing (provided there is enough water) leafy vegetable that is highly nutritious and easy to grow. Chilli peppers add spice and colour to meals and are often grown as a semi perennial in the home garden situation since they can have a long fruiting season. Households only harvest what is needed on that day. Excess ripe fruits can be harvested and dried in small batches for the off season. The cucurbits are very diverse; some are highly nutritious while others are less nutritious and are eaten primarily for their texture or flavour, some have to be eaten or cooked while still young and green (e.g. cucumbers, bitter gourds), while others are left to mature and then can be stored for several months (pumpkins).

Peri-urban vegetables near Hanoi, Vietnam (photo: P Schreinemachers, World Vegetable Center)

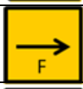
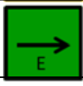
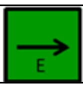
Although there is a great overlap in the vegetable species grown in the peri-urban commercial setting with those grown in the household garden, the cultivars grown are often very different. Since the commercial growers need to have more uniform crops growing more intensively and with synchronous harvesting, they are more likely to be purchasing seed of newer varieties and hybrids, whereas many household gardeners will save their own and exchange seeds of more traditional varieties and land races since these may be better adapted to their generally lower input/less intensive system where longer and less synchronous harvesting period is preferred.

Woman harvesting yardlong bean, near Hanoi, Vietnam (photo: P Schreinemachers, World Vegetable Center)

Keystone species	**Family**
Peri-urban commercial:	
Tomato (*Solanum lycopersicum*)	Solanaceae
Yard-long bean (*Vigna unguiculata* ssp. *sesquipedalis*)	Fabaceae
Leafy brassicas (pak choy (*Brassica rapa* subsp. *Chinensis;* Chinese leaf mustard (*Brassica juncea*); Chinese kale (Mandarin ”jie lan”; *Brassica oleracea*	Brassicaceae
Household gardens:	
Kang kong (*Ipomea aquatica*),	Convolvulaceae
Chilli peppers (*Capsicum* spp.)	Solanaceae
Cucurbitaceous species (pumpkin, bitter gourd, luffa, cucumber *etc.*)	Cucurbitaceae

Vegetables health in Southeast Asia

Assessment for keystone species:

Keystone species	Health
Peri-urban commercial:	
Tomato	
Yard-long bean	
Leafy brassicas	
Household gardens:	
Kang kong	
Chilli peppers	
Cucurbitaceous species	

State of vegetables health in the past 30 years

Peri-urban commercial systems, because of increased urbanization, generally have been squeezed into smaller plots and have had to intensify: closer spacing, year-round production, greater use of inorganic fertilizers or manure (where available), greater use of fungicides (almost absent 30 years ago), continuing use of excessive insecticide inputs, and use of higher yielding cultivars and F_1 hybrids. This in turn has probably lead to more favourable conditions for spread and increase in some pathogens - including the build-up of soil-borne pathogens and nematodes (Ali and Porciuncula 2001).

Commercial peri-urban tomatoes - Depending on the location, plant health has fluctuated as different pathogens have been introduced or emerged and new resistances or other control methods have been introduced;

Late blight (*Phytophthora infestans*) in cooler and wetter highland areas - emergence/introduction of new races/genotypes (including fungicide resistant races);

Tomato yellow leaf curl begomoviruses - increasingly rapid emergence of new species/genotypes perhaps associated with spread of more polyphagous and vectoring efficient *Bemisia* whiteflies - high disease level, mixed infections and recombinant types help virus to overcome plant disease resistance/tolerance (Kenyon et al 2014);

Tomato chlorosis virus (*Crinivirus*) - spreading across the region, no resistance commercialized yet though some genetic tolerance (stay green) genotypes have been identified;

Bacterial wilt (*Ralstonia solanacearum* species complex [RSSC]) - increasing importance especially where over intensification and lack of crop rotation is occurring. *Bwr6* and *Bwr12* starting to be commercialized more;

Other occasional or emerging problems: root-knot nematodes (*Meloidogyne* spp.), early blight (*Alternaria* spp), and bacterial spot (*Xanthomonas vesicatoria* species complex).

Commercial peri-urban yard-long-bean - Similar intensification of production as tomato has led to waves of disease and new resistance introductions; Anthracnose (*Colletotrichum lindemuthianum*), Rust (*Uromyces vignae*), mungbean yellow mosaic diseases (Begomoviruses), Cercospora leaf spot (*Pseudocercospora cruenta*), and aphid-transmitted potyviruses.

Commercial peri-urban leafy brassicas - Because of their very short production cycle these tend not to be affected by many pathogens except a few that are seed-borne and carry over from the seed crop (e.g., *Xanthomonas campestris*) or build up or are carried over in crop debris in the soil (*Pythium* spp.) and affect the germinating seeds or seedlings. Note that leafy brassicas are much more susceptible to attack by leaf-feeding insects.

Household gardens are generally very diverse, each with a range of cultivated plants, spice, medicinal and ornamental species planted in small blocks or as just a few plants. Although, to our knowledge, there are no formal reports and historical accounts of the plant diseases in HGs, it may be assumed that the high diversity of species and the less intensive systems might be less conducive to diseases. Rural HGs in most countries tend to be more reliant on self-saved or exchanged seeds, whereas HG in or closer to growing urban centres are generally smaller and given over to the less common plant species/varieties that are not so readily bought in the local market. Alternatively, peri-urban HGs may be more intensive with a smaller range of crop species, growing some for home consumption and the excess for informal exchange/sale (early stage commercialization). These are more likely to use commercial seed or seedlings of similar varieties to, and purchased from similar suppliers as, the peri-urban commercial growers.

HG Kang kong - Fast growing and easily propagated. Although there are commercial sources of seed, most HGs use self-saved and/or rooted cuttings shared by friends of diverse/mixed land races. Kang kong is infected by few diseases (e.g. White rust/White blister [*Albugo ipomoeae-panduratae*], leaf spot [*Cercospora ipomoeae*]) and these rarely cause significant loss, especially in the HG setting.

HG Chilli peppers - The most ubiquitous species in HGs, and generally grown as just a few plants of diverse and often local/family heritage land races/cultivars grown from self-saved or locally exchanged seeds. This type of seed system may support the inadvertent selection of *Capsicum* genotypes/landraces better adapted to the local conditions - including tolerance to locally endemic diseases; HG growers can put up with a fair level of disease on their chilli plants and if the disease becomes too extensive, they simply destroy the plant(s) and try growing new plants in a different part of the garden. A problem may arise however when the HG is close to commercial chilli production where disease epidemics, particularly of pathogen races novel to the region, readily can occur (e.g. Anthracnose [*Colletotrichum* spp.](Vos and Duriat 1995), pepper yellow leaf curl begomoviruses (Kenyon et al 2014), *Phytophthora* blight, Bacterial spot [*Xanthomonas* species complex]) and act as a potent source of 'exotic disease' inoculum for the HG.

Home garden chilli pepper infected with severe pepper yellow leaf curl begomovirus, West Java, Indonesia (photo: L Kenyon)

HG cucurbits - These are often trained or allowed to scramble along fences and over trellises, and often as much for their aesthetic appeal and the shade they provide as for their provision of food. They are usually grown from self-saved seed or locally exchanged seedlings of locally adapted cultivars/landraces that may show some tolerance to the local disease races. However, as with the chilli peppers described above, commercial/intensive production of a narrow range of cucurbit varieties can lead to the rapid build-up of pathogen populations (with selection for more virulent and aggressive strains/races) which generates more inoculum for the HG. Examples include the increasing occurrence of whitefly-transmitted squash leaf curl and other begomovirus diseases (especially in pumpkins, luffa, cucumber), aphid-borne poleroviruses (e.g. suakwa aphid-borne yellows virus in bitter gourd), whitefly-transmitted cucurbit yellows criniviruses, Fusarium wilt, Cercospora leaf spot, and Gummy stem blight (*Didymella* spp.)

Home Garden Bittergourd infected with a potyvirus and a littleleaf phytoplasma, Philippines (photo: L Kenyon)

Evolution of vegetables health over the recent 10 years

PU-Tomato - stable-declining; New species/strains of leaf curl begomovirus emerging which can overcome the current *Ty* resistance genes faster than new resistance can be identified and pyramided with older resistance. Tomato chlorosis virus (*Crinivirus*) is spreading rapidly across the region, perhaps because there are more vectoring-efficient whiteflies to transmit them, and there is no durable resistance identified. Thrips-transmitted tomato necrotic ringspot virus (*Orthotospovirus*) is an increasing problem in parts of Vietnam, Cambodia, Thailand, and China with no stable resistance identified yet. Bacterial wilt is an increasing problem in many areas and currently available resistances (*Bwr-6*, *Bwr-12*) do not provide complete control against all species/genotypes, especially where root knot nematode is also a problem (here grafting to resistant eggplant (*Solanum melongena*) rootstock may provide the most effective control but is also more expensive). New species/races of *Xanthomonas* bacterial spot are spreading across the region, some already resistant to copper-based bactericides, and able to overcome currently available host plant resistance.

PU-Yard-long bean - stable-improving; many commercial lines now carry Anthracnose and begomovirus resistance.

PU-Leafy brassicas - stable (good); short cropping cycle avoids disease build-up.

HG Kang kong - stable(good); still mainly locally adapted land races in most HGs.

HG Chilli peppers - stable-declining; spillover of new/more aggressive/virulent disease genotypes (e.g., leaf curl begomoviruses, Orthotospovirus (see tomato above) and bacterial spot from commercial plantings having a deleterious effect on HG where plants are kept for longer and there is little attention to virus-vector control or application of fungicides. No available resistance to many begomoviruses or criniviruses.

HG-Cucurbit spp. - stable-declining; spillover of pathogen inoculum from commercial production infecting HGs - whitefly-transmitted begomoviruses and aphid-transmitted poleroviruses.

Ecosystem services, as affected by plant disease

Provisioning

Peri-urban commercial

Provisioning

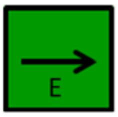
Household gardens

Regulating

Peri-urban commercial

Cultural

Household gardens



Level of ecosystem services generated by vegetables, as affected by plant disease, in the past 30 years

Peri-urban horticulture: The gradual introduction over the last 30 years of more disease resistance genes into commercial tomato and yard-long-bean cultivars, combined with greater use of a wider range of fungicides in the PU setting probably means that diseases now have less of a direct (negative) effect on the provisioning services that these crops provide. However, the higher planting densities of uniform stands of faster-growing and potentially higher yielding cultivars associated with intensification in PU areas means that the soils can be depleted/degraded much more quickly. There is a greater reliance on inorganic fertilizers, a demand for a more constant supply and more water for irrigation, and the crops are at greater risk from build-up of host resistance-adapting and/or pesticide resistant races of plant pathogens. Thus, diseases may have an indirect negative effect on ecosystem services *via* a greater use of pesticides (more pesticides in the environment, greater risk of pesticide residues on the produce, greater risk to the environment, to the growers and the consumers), diversion of water supplies from other uses and faster depletion of water reserves, and the faster depletion of fossil fuels for fertilizer production (Cheatham et al 2009). Some consumers might argue that intensively produced improved cultivars do not have as much flavour or nutrition ("goodness") to them as older, less intensively grown cultivars, and there is risk of higher pesticide residues on newer cultivars in intensive systems. As diseases have been relatively unimportant compared to insect pests in leafy brassica production in SE Asia, the diseases have had negligible effect on the ecosystem services, whereas hazardous insecticide residues above their MRLs frequently have been detected, for example in Chinese kale in Thailand (Wanwimolruk et al 2015).

Home gardens: Since most home gardens carry such a high diversity of plant species, poor health (disease) in a few species has minimal effect on the provisioning services provided by the garden and may be compensated for by growing more of another species, or including a new species not grown before. However, the different species/landraces in the home garden have different cultural significance (provide different levels of cultural service). Local land races of chilli and cucurbit have high cultural significance in some areas and so if a severe epidemic of an exotic strain/ disease of these crops is promoted by the local peri-urban or other agricultural system (e.g. Pepper yellow leaf curl), then few of the local land races of the crop may be resistant and there may be a significant decline in the provisioning service of home gardens, which may also affect its cultural service (e.g. inability to prepare culturally important meals [the right chillies and squashes], give culturally important food gifts [a large pumpkin, calabash], grow the most aesthetically pleasing and useful shade cover [luffa vines].

Evolution of the level of ecosystem services generated by vegetables, as affected by plant disease, over the recent 10 years

Peri-urban commercial: Faster plant breeding methods (e.g. marker assisted selection) means that new cultivars of tomato and yard-long-bean with different combinations of disease resistance have entered the market in recent years. However, because urban populations are perceived to seek clean, unblemished produce, many PU growers still apply pesticides prophylactically (Schreinemachers et al 2012). Thus, plant health has probably had a little positive or no effect on provisioning services, and no effect on cultural services.

Household gardens: In more rural and isolated areas where HGs are still very important, the level of disease is still relatively low and so the effect of plant health on provisioning and cultural services is minimal and stable. Nearer to large urban areas there is perhaps less interest and experience in maintaining HGs, and there may have been greater disease intensity, with spread from peri-urban commercial horticulture (though HGs could potentially also act as sources of infection for the PU systems). It seems likely that there is some loss in species diversity in these near-urban home gardens, including species with cultural/heritage importance (but it is difficult to attribute this directly to plant health problems).

Complementary information

Population growth, globalization (better communications and easier transport for travel and trade), urbanization, and climate change, have all been drivers of the changes in vegetable production systems in SE Asia over the last 50 years, including the rapid expansion in peri-urban commercial horticulture (and the decline in home gardens in the near-urban areas). These changes and the wide diversity of plant species, geographies/agroecologies and production systems encompassed by peri-urban horticulture and home gardens within SE Asia make it difficult to generalize about the changes (or not) in plant health and their effect on the associated ecosystem services over either the long or short term. Added to this, there has been considerable research and writing on the socioeconomic and other important aspects of different peri-urban horticulture settings. However, consideration of plant health has been restricted almost entirely to insects and the high rates of pesticides applied. Similarly, although there have been many studies about the nature and importance of home gardens in different parts of the world, remarkably little has been written about either the pests or diseases affecting them in SE Asia or elsewhere. However, the vegetable seed breeders and producers and the other input supply dealers to the peri-urban vegetable growers have much more intimate knowledge of the different pest and disease problems vegetable growers face in different locations. Thus, without empirical data, this assessment is based mainly on personal and expert opinions (in part built on interactions with vegetable seed and breeding companies) and extrapolation from knowledge of other crops and ecosystems in the region. As such, at best we can be only moderately confident that this is an accurate and reliable assessment.

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Urban vegetation

Urban Vegetation (Plane tree) in Southern Europe

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Background information

Urban vegetation, especially consisting of urban trees, has long been considered as a common good and a source of ecosystem services, for sociological, psychological, spiritual, political, and ethical reasons (Roy et al 2012). Since the 19th century, urban trees have played an important role in urban planning. Since at least the 1970s, they have been an essential part of urban ecology and are now given importance in terms of ecosystem services, both regulating and cultural (Konijnendijk et al 2005).

Urban trees play a major role in regulating services crucial to human wellbeing, especially with respect to climate and air pollution. They mitigate the effects of urban heat islands through evapotranspiration and shading of streets and buildings (Kleerekoper et al 2012). Urban trees improve air quality by absorbing pollutants such as ozone, nitrogen dioxide, ammonia and particulate matter (Livesley et al 2016). Urban trees also play a role in regulating rainwater because they absorb and store water through the canopy, and slow and filter runoff with their roots. Urban trees also contribute to some extent to reducing the ecological debt of cities through carbon sequestration (Nowak and Crane 2002). Finally, they promote the maintenance of biodiversity in highly artificialized environments, in providing support for numerous taxa (birds, bats, insects, epiphytic plants, mosses, lichens, fungi, etc.).

Urban trees are also crucial for amenity, social, spiritual and recreational functions (Turner-Skoff and Cavender 2019). They are an important element of parks, squares, riverbanks and outdoor places for relaxation, rest and fun; they are essential to the health, the mental and physical balance of city dwellers (Hanson and Frank 2016). They are associated with relaxation, games, art and nature, environmental education, health and quality of life. They have a soothing effect and are considered a positive element of the living environment (Nesbitt et al 2017).

Tree diseases can cause heavy losses in urban trees, such as did the Dutch Elm Disease, caused by the ascomycete fungus *Ophiostoma novo-ulmi*, which killed nearly all the elms of European cities in the 1980s.

PlantSystem considered in this report

The plane tree (*Platanus* sp., Platanaceae) was chosen as the Plant System for this assessment due to its importance as an urban tree in Europe. The oriental plane (*Platanus orientalis*, a native to southeastern Europe and the Middle East) was planted in gardens and cities during Egyptian, Greek and Roman antiquity and is still widely planted as an urban tree in its native range (Tsopelas et al 2017). The London plane (*Platanus ×acerifolia* (Aiton) Willd, syn. *Platanus ×hispanica* Mill. ex Münchh.) is an interspecific hybrid of the oriental plane and the American sycamore (*Platanus occidentalis*, native to eastern North America). It arose, probably in several locations, through natural hybridization of the parental species during the 17th century (Besnard et al 2002). It was then popularized during the 18th century and extensively planted in many cities, and along roads and canals in Europe. Plane trees are a major component of urban forests of many cities all over Europe. They account for instance for 40% of the urban trees in Paris and over 50% in London (Besnard et al 2002). They have also been widely planted in cities in North and South America, Asia and Australia.

Plane trees are large, reaching 30-50 m tall, and 3 m in trunk circumference, and are very long-lived (up to 2,000 years). They are particularly appreciated as urban trees, especially for their resistance to damage from pruning, air pollution, and compacted soil. One of the drawbacks of plane trees in cities is that they can cause respiratory allergies, due to pollen and hairs present on young leaves and on fruits. Furthermore, their frequent infestation by the sycamore lace bug (*Corythucha ciliata*) can cause a nuisance to people or amenities (human bites, honeydew deposits on parked vehicles and street furniture).

It is noteworthy that three out of the 14 outstanding trees selected for the "European Tree of the Year 2021" contest (winners of the national contest in 14 countries) are plane trees, including a 1,000-year-old oriental plane tree from southern Italy (European Tree of the Year 2021).

Two-century-old London plane trees along the Canal du Midi in Toulouse, southern France, classified as a UNESCO World Heritage site (photo: L Willocquet)

Plane tree health in Southern Europe

State of plane tree health in the past 30 years

The most severe disease of plane trees in Europe is the canker stain disease (also known as plane wilt), caused by the ascomycete fungus *Ceratocystis platani.* The disease affects the water-conducting vessels, causing wilting of the leaves and staining of the bark and wood. The disease is usually lethal, with young trees succumbing within 2-3 years after infection, and older trees within 4-5 years.

The pathogen is native to North America, where it has co-evolved with *P. occidentalis*, which is fairly resistant to the disease (Panconesi 1999). The fungus is thought to have been accidentally introduced by the US army in Italy (Naples, Livorno, Syracuse) and France (Marseille) on infected plane wood packaging during the Second World War. It was however officially first only reported in 1972 in Italy and 1974 in France (Ferrari and Pichenot 1974; Panconesi 1999). Over the decades, the pathogen has spread clonally all over Italy and south-eastern France, killing tens of thousands of London planes (Santini and Capretti 2000). It has also been found in Switzerland and Spain, and has spread to Greece, Albania and Turkey, where it kills oriental planes, both in urban areas and in wild stands (Lehtijärvi et al 2018; Tsopelas et al 2015, 2017).

Short and long distance dispersal of the pathogen is mainly due to contaminated pruning and cutting tools and road construction machinery. Fungal spores can also disperse in rivers and canals. The pathogen is classified as a quarantine pathogen and stringent and costly eradication measures are implemented in infected areas (EFSA PLH Panel 2016).

Several other diseases can affect plane trees, such as powdery mildew (caused by *Erysiphe platani*), anthracnose (caused by *Apiognomonia veneta*), Massaria disease (caused by *Splanchnonema platani*), and trunk canker (caused by *Fomitiporia* sp.), but these diseases are rarely lethal (Observatree 2016).

Since *C. platani* is an exotic invasive pathogen that has spread so far in a limited part of Europe (Italy, southern France, Greece, Albania and Turkey), the health status of plane trees in Europe is very heterogeneous. It can be considered poor in southern Europe. Other parts of Europe can be considered under threat of introduction of this invasive pathogen, since the climate is suitable to the pathogen in many regions. Therefore, even in central and northern Europe, the environmental conditions are not likely to be a limiting factor for the establishment of the pathogen (EFSA PLH Panel 2016).

Evolution of plane tree health over the recent 10 years

Over the last decade, canker stain disease has continued its inexorable progress into formerly disease-free areas in Italy, Greece and France. In Greece, the disease is devastating, as Oriental plane is an iconic tree in villages and cities. Some of these deceased trees were very old - sometimes several centuries of age - and were of great aesthetic value (Tsopelas et al 2017). In 2014, the pathogen was found in Albania, where it appears to have been present for many years on wild stands and on shade trees (Tsopelas et al 2015). The pathogen has further spread to the European part of Turkey, especially in Istanbul where many plane trees were found infected in city parks and along avenues (Lehtijärvi et al 2018).

In France, despite the strong eradication measures implemented in infected areas, the pathogen reached the Canal du Midi in 2006, probably via contaminated pruning tools. This 240 km-long canal, built in 1667 to connect the Atlantic Ocean to the Mediterranean Sea, was flanked by 42,000 London planes and has been designated a UNESCO World Heritage site since 1996. Between 2006 and 2022, the rapid spread of fungal spores in the water resulted in the infection of 30,000 trees, which were felled, and the remaining trees are also condemned (VNF 2020). Moreover, there were several very localized outbreaks of the disease in the northern half of France (Nantes and the Paris region) in 2019 and 2020 (DSF 2019).

In view of the recent expansion of infested areas, the health condition of plane trees in southern Europe is rated as declining.

Canal du Midi near Toulouse. Back: plane trees still standing; front: young Turkey oaks planted after diseased plane trees have been uprooted, as an eradication measure against the spread of the canker stain disease (photo: L Willocquet)

Ecosystem services, as affected by plant disease

Regulating

Cultural

Level of regulating and cultural ecosystem services generated by plane tree, as affected by plant disease, in the past 30 years

Regulating services

Similar to many other tree species used in urban forestry, with their great height and width and abundant foliage, plane trees play numerous roles in regulating services, such as shading, creating a cool microclimate, improving air quality, regulating rainwater runoff, sequestrating carbon and maintaining biodiversity (Kleerekoper et al 2012; Konijnendijk et al 2005; Livesley et al 2016). In areas where the canker stain disease has spread and killed tens of thousands of plane trees, these regulating services are lost, until new trees are planted in replacement of the dead planes. It takes many decades, if not centuries, to restore the level of ecosystem services that was provided by very old and tall plane trees.

Therefore, the level of regulating services generated by plane trees is considered as poor in southern Europe.

Cultural services

The Oriental plane is an iconic tree in south-eastern Europe and the Middle East. In ancient Egypt, Greece and Persia, it was planted in gardens, avenues and around tombs and it was considered a sacred tree (Tsopelas et al 2017). In Greece and Albania, the canker stain disease has killed many of these iconic trees of impressive size in the gardens, parks, squares and streets of villages and cities. Some of these iconic trees were more than 500 years old. Similarly, in Italy and south-eastern France, the loss of tens of thousands of London planes in villages and cities resulted in the loss of the associated cultural services, such as aesthetic and amenity values, as well as social and recreational functions (Turner-Skoff and Cavender 2019).

Therefore, the level of cultural services generated by plane trees is considered as poor in Southern Europe.

Evolution of regulating and cultural ecosystem services generated by plane tree, as affected by plant disease, over the recent 10 years

During the last decade, the canker stain disease has continued to colonize new, formerly disease-free areas in Europe, and killed both Oriental planes in Greece, Albania and Turkey and London planes in Italy and France (DSF 2019; Tsopelas et al 2017). Therefore, both the regulating services (shade, microclimate, air quality, etc.) and the cultural services (aesthetic and amenity values, social, spiritual, and recreational functions) provided by plane trees are totally lost in villages and cities where the pathogen has killed trees.

The inexorable loss of all of the 42,000 plane trees flanking the Canal du Midi, calls into question its classification as a UNESCO World Heritage Site (Le Point 2018).

In view of the recent expansion of infested areas, the trend of regulating services and cultural services provided by plane trees in southern Europe is rated as declining.

Complementary information

A breeding program for the selection of plane trees resistant to canker stain was developed at INRAE, France's National Research Institute for Agriculture, Food and Environment, in 1990-2000, based on controlled crosses between *P. occidentalis* genotypes from Mississippi and *P. orientalis* from Greece. Out of the 960 hybrids screened, one clone of London plane with quantitative resistance was released under the name Platanor® 'Vallis Clausa' (Vigouroux and Olivier 2004). To date, approximately 10,000 trees have been planted in southern France and Italy. Rare cases (0.3%) of canker stain symptoms and mortality have been detected on this variety, notably in the Canal du Midi alignments (ANSES 2019). Replanting of young Platanor® 'Vallis Clausa' trees in soil heavily contaminated by *C. platani* following the uprooting of dead plane trees seems to be the cause of the few cases of mortality observed (ANSES 2019). Replacement of infected soil by healthy soil in the planting pits would help to overcome this problem.

In addition, the dead plane trees along the Canal du Midi are gradually being replaced by other tree species (*Quercus cerris, Celtis australis, Acer platanoides, Tilia cordata, Tilia platyphyllos, Ostrya carpinifolia, Populus alba, Pinus pinea*).

The content of this report can be assessed as reasonably well documented, although it is quite difficult to rate the health status of plane trees and the level of the associated ecosystem services at the scale of the continent, since the canker stain disease, although very devastating, is present only in a restricted area of Europe. We are therefore reasonably confident in the assessment presented on this report.

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Forests

softwoods

oaks

eucalypts

amazon

Forests (Managed softwoods) in North America

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Background information

North American forests represent about 15.5% of the world's total forest cover (FAO and UNEP 2020) contributing to the global role forests play in influencing hydrological cycles and the physical, chemical and biological processes that affect planetary energetics (Bonan 2008). The Northern America Ecoregion referred to here is the actively managed forests of Canada and the continental United States. Although the North American managed forest plant system is geographically vast and climatically and ecologically diverse, it is primarily comprised of Pinaceae softwood tree species managed for structural timber and pulpwood. The forest products industry in the U.S. produces over $300 billion in timber and forest products annually (FAO 2019; Forest2Market 2016) while Canada's forest products exports contribute $17.1 billion in net trade (Government of Canada 2021). We have focused on the **Provisioning Ecosystem Services** of the North American Managed forest Plant System and the production of building materials and fibre but these forests are also significant in terms of their Regulating Services and Cultural Services to varying degrees. Some trade-offs may exist between commodity production of managed forests and the production of other ecosystem services depending on the extent of management interventions (Duncker et al 2012). The majority of managed forest land area in North America is managed for a variety of resource values including outdoor recreation which is itself a multi-billion-dollar industry contributing up to 5% of the US GDP (https://www.bea.gov/data/special-topics/outdoor-recreation).

Healthy eastern white pines (Pinus. strobus) in New Hampshire, illustrating examples of the multiple services forests provide: clean water, wildlife habitat, recreation (photo: Isabel Munck)

Enhancing the productivity of managed forests can allow for greater flexibility in the management of the remaining forest land-base for other ecosystem services (Sedjo and Botkin 1997).

PlantSystem considered in this report

Actively managed softwood forests in North America include both those intensively managed (US Southeast loblolly pine, US Pacific Northwest Douglas-fir) and those less intensively managed such as the US Northeast, Midwest, the majority of British Columbia (BC) and other Canadian provinces. The focus species include loblolly pine (*Pinus taeda*), the most extensively managed species of southern pines throughout the US Southeast (Coyle et al 2015), Douglas-fir (*Pseudotsuga menziesii*) of similar importance in the Pacific Northwest USA and southwest BC, lodgepole pine (*Pinus contorta* var *latifolia*) extensively managed throughout its wide range in western NA, eastern white pine (*Pinus strobus*) the most widely planted tree species in eastern NA (Wendel and Smith 1990), and red and white spruce (*Picea* spp.) the latter species having the broadest distribution across the northern half of the continent. The North American (Canada and USA) forest products sector, led by the species listed above, accounts for production of 25% of the world's industrial roundwood, 28% wood pellets, 27% sawn-wood, 33% pulp for paper, and 18% paper and paperboard (FAO 2019).

A young, healthy, mixed species stand (photo: Alex John Woods)

Managed softwood forests health in North America

State of managed softwood forests health in the past 30 years

The health of managed softwood forests in Northern America for the past 30 years is fair with each of the five major forest areas discussed having specific forest disease concerns. In the intensively managed southern pine plantations, root diseases including *Heterobasidion irregulare, Armillaria* spp., *Phytopthora cinnamomi*, and *Leptographium* spp. are all common though none have been implicated as the dominant factor in Southern Pine Decline (SPD) (Coyle et al 2015). These root pathogens and foliar diseases including brown spot needle blight (*Lecanosticta acicola*) are present in the region but have not significantly impeded the health of southern pines over the past 30 years.

In the intensively managed Douglas-fir forests of the Pacific Northwest laminated root rot (*Phellinus sulphurascens*) and Armillaria root disease (*Armillaria ostoyae*) are the two most damaging root diseases (Hansen and Goheen 2000), and although the impact of these pathogens has been comparable to losses to wildfire and timber harvesting (Healey et al 2016), losses to these diseases in the managed forests over the past three decades have been relatively stable. The foliar disease, Swiss needle cast, caused by the fungus *Nothophaeocryptopus gaeumannii* is a concern, primarily in terms of growth loss (Mildrexler et al 2019).

The most extensively managed tree species in BC, lodgepole pine, has the broadest suite of forest pathogens of any of the species managed in that forested region. Dothistroma needle blight caused by the fungus *Dothistroma septosporum* and hard pine rusts caused by *Cronartium* *harknessii, C. comandrae* and *C. coleosporoides* have been responsible for considerable losses (Woods et al 2005; 2017). These pathogens and others have challenged the health of lodgpole pine but clearly not to the extent of the unprecedented mountain pine beetle (*Dendroctonus ponderosae*) epidemic in that region (Kurz et al 2008). Combined, these biotic agents have reduced the health of this plant system over the past 30 years to fair.

The health of eastern white pine forests of the US Northeast for the past three decades could be considered good although a variety of diseases including brown spot needle disease (*Lecanosticta acicola*), Dothistroma needle blight, Caliciopsis canker caused by the fungus *Caliciopsi pinea* , Armillaria root disease (*Armillaria spp.*) and white pine blister rust (*Cronartium ribicola*) challenge the tree species (Costanza et al 2018; Wyka et al 2017). This latter pathogen, *C. ribicola*, continues to cause extensive mortality in five needle pines across North America illustrating the severity of risks to ecosystems associated with introduced pathogens (Geils et al 2010). In addition to the pathogen's impacts in eastern white pine forests, the introduced rust has caused serious losses in commercial western white pine (*Pinus monticola*) forests.

Armillaria root disease in a Douglas fir plantation (photo: Alex John Woods)

Most critically, *C. ribicola* has contributed to the decline of whitebark pine (*Pinus albicaulis*) and limber pine (*Pinus flexilis*) in the Rocky Mountains, leading to the listing of the former species as "Endangered" by the Committee on the Status of Endangered Wildlife in Canada (Schedule 1 of the Canadian Species at Risk Act (https://species-registry.canada.ca/index-en.html#/species/1086-748).

Lastly, over the past 30 years the health of managed spruce plantations across Canada and the US mid-west from a forest disease perspective could be considered good with some losses to root diseases (*Armillaria* spp.) and tomentosus root disease (*Onnia tomentosa*) (Price et al 2013).

Evolution of managed softwood forests health over the recent 10 years

Each of the five actively managed forest regions described in this report have experienced a deterioration in health for at least the past 10 years. In general, there has been an increase in pathogen impacts related to wider variation in precipitation, both excess (foliar diseases) and shortage (stress-initiated declines associated with root diseases and canker causing pathogens, as well as drought).

A suite of factors, including Heterobasidion root disease and drought appear to be exacerbating dieback in loblolly pine (Coyle et al 2019), while

Defoliated juvenile lodgepole pine trees, a result of Dothistroma needle blight. (photo: Alex John Woods) simultaneously brown spot needle cast activity has increased due to increased summer precipitation.

Similarly, eastern white pine in the US NE has experienced increased losses to foliar diseases including brown spot needle disease and Dothistroma needle blight as a result of increased precipitation in late spring/early summer while high summer temperatures have led to drought and increased tree stress. Caliciopsis canker and root diseases including Heterobasidion and Armillaria have taken advantage of the latter environmental conditions (Costanza et al 2018).

Intensively managed stands of Douglas-fir in the Pacific NW have experienced increased losses to Swiss needle cast as a result of a combination of increased temperature and precipitation and management actions that converted old growth and mature mixed-conifer forests to young monocultures of Douglas-fir on private forestlands (Mildrexler et al 2019). Forests in this region have experienced severe drought in recent years (van Mantgem et al 2009) likely triggering increased root disease activity (Agne et al 2018; Kliejunas et al 2009).

Lodgepole pine plantations throughout BC have suffered increased losses to forest pathogens including hard pine rusts (Heinemann et al 2010) and Dothistroma needle blight (Woods et al 2005) for the past 15- 20 years, due to increasingly favourable climatic conditions (Woods et al 2017). The volume impacts of forest diseases in Canada overall are not well documented (Price et al 2013) but root disease pathogens, in particular, are of similar importance as wildfire, insects and wind in the creation of canopy gaps (McCarthy 2001) and their impacts appear to be increasing.

Ecosystem services, as affected by plant disease

Level of provisioning ecosystem services generated by managed softwood forests, as affected by plant disease, in the past 30 years

Despite the influence of forest pathogens and other biotic and abiotic disturbances, actively managed softwood forests across North America have continued to produce the wide range of products described earlier (3) contributing close to $320 billion to the economies of the two countries combined (FAO 2019). Losses of timber values to plant disease have been relatively small thus far as have losses to atmospheric and water regulation functions, though adequate monitoring of terrestrial disturbances needed to confirm these assumptions remains a global information gap (McDowell et al 2015).

Evolution of provisioning ecosystem services generated by managed softwood forests, as affected by plant disease, over the recent 10 years

There is a trend to less provisioning of services over the last 10 years due to losses to timber volume and value and the fact that there are less healthy trees fixing C and regulating water levels across managed forests of North America. In each of the five managed forest areas described there is documented evidence of a deterioration in plant health. Given the relatively long rotation periods of even the fastest growing managed forests and the lack of consistent monitoring of biotic disturbances (McDowell et al 2015) there is likely a lag between losses of timber due to disease and the recognition of that loss. The ability of forest growth-and-yield models to accurately depict stand and tree growth responses in areas with insect and disease outbreaks is lacking (Russell et al 2015). It is possible that the recent deterioration of plant health is yet to be felt in terms of timber supply reductions due to management decisions reliance on growth and yield models that are not designed with forest pathogens in mind.

Complementary information

Climate change has already begun to disrupt the host/pathogen balance in forests of North America and elsewhere, often in favour of native pathogens. In addition, increased global trade has significantly raised the probability of the introduction of invasive, non-native pathogens. The threats to forests associated with other biotic (insects) and abiotic (fire, drought, flooding) disturbances are also on the rise and we are confident that these trends will continue. Given the challenges forests face, proactive forest management interventions are clearly needed and many of these can be most effectively practiced on young managed stands where species selection and stand density manipulations are possible. Most forests will have to adapt to climate change autonomously (Spittlehouse and Stewart 2003), thus, on the actively managed forest areas, decisions should be both wise and bold. Recognition of the rapid rate of environmental change has prompted the use of assisted migration to establish tree species better suited to future climatic conditions in parts of North America (Aitken et al 2008). The inherent risks associated with taking such chances, moving species while the environment itself is in flux, clearly demand increased monitoring (Metsaranta et al 2011). Distributed monitoring systems that observe changes on multiple scales of forest health including forest pathogens are essential (Millar and Stephenson 2015).

One of the greatest challenges in sustainable forest management is the accurate estimation of the impacts of disturbances including forest diseases. Growth and yield models help guide forest management decisions but the roles of abiotic and biotic disturbance agents including pathogens are often overlooked (Woods and Watts 2019). In managed forests no single factor, not site index, species composition nor growth rates, has a greater influence on modelled stand productivity than unexpected loss of crop trees (Flewelling and Monserud, 2002) such as that caused by forest diseases. Accurate estimation of losses to forest diseases must be validated as model outputs inform critical management decisions. It is possible that harvest rates in some managed forests have been set at overly optimistic levels as a result of overlooking the role of forest diseases (Woods and Watts 2019).

Some of the greatest uncertainty with predictions of future forest disease conditions is associated with the dominant role of precipitation patterns as they control both the behaviour of the pathogens and the stress trees suffer. Extreme drought, particularly hot droughts, are leading to fundamental changes in forests globally (Allen et al 2010) while the weakening of the jet-stream and the implications that has for precipitation patterns across North America are just starting to be realized (Francis and Vavrus 2015).

Level of confidence in the assessment: Reasonably confident. Forest disease conditions in managed forests of North America are going to get worse.

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Forests (Oaks) in North America

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Background information

In North America, oaks (*Quercus,* Fagaceae*)* are the most abundant and diverse woody plants and one of the most highly valued, important forest trees as measured by provision of ecosystem services and economic value. Oaks dominate ecosystems throughout much of North America from Pacific Coast evergreen forests, to Eastern temperate deciduous forests, and southwestern oak-piñon-juniper woodlands (Johnson et al 2019). Many oak species are majestic, overstory trees but others are shrubs or small trees, particularly in drier habitats (e.g., chaparral), and higher elevation forests. Oaks grow in well-developed soils but also thrive in serpentine soils, sandy barrens, and swamps (Nixon 2006).

Oaks provide numerous ecosystem services that support human well-being: provisioning shelter, regulating the environment, and enhancing culture and aesthetics. Oaks are economically important as sources of high-quality lumber (Burns and Honkala 1990). Ecologically, oaks provide forage, nesting and other habitat for birds, mammals, and fungi. They are foundational species that control wildlife populations and community dynamics, as well as modulate ecosystem processes (e.g., carbon balance and water supply) (Cavender-Bares 2016; Ellison et al 2005).

Oaks were designated by the U.S. Congress as America's national tree in 2004 and are a symbol of strength and longevity (International Oak Society 2001). The cultural and aesthetic values of oaks include stately shade trees along boulevards and in recreation areas and spectacular foliage color in fall. For indigenous peoples, acorns are an important food source and oak fibers are used in basketry, regalia, and structures (Anderson 2007).

Ecosystem Services: North American oak forests provide many benefits: 1. **Provisioning Services**: food, fiber, materials; 2. **Regulating Services**: climate, soils, water and 3. **Cultural Services**: culture, spiritual, beauty.

PlantSystem considered in this report

The Plant System assessed in this section is primarily the genus *Quercus* (oaks, Fagaceae). Taxonomically, within North American *Quercus* three groups are recognized, the white oaks (section Quercus, also called section Leucobalanus or Lepidobalanus), the red or black oaks (section Lobatae or Erythrobalanus), and the intermediate or golden oaks (section Protobalanus) (Nixon 2006).

In North America, oaks are widely distributed, found across the East through to the West Coast with species richness highest in the southern U.S. Oaks are abundant, with an estimated 43 billion stems in the U.S., representing 11 percent of the total U.S. tree population. White oak, *Quercus* *alba*, is most common representing 19 percent of all oak biomass (Oswalt 2019). Also, prominent and valued as a select wood producer is northern red oak, *Q. rubra,* the tallest and most rapidly growing eastern oak. The native ranges of white oak (*Q. alba*) and northern red oak (*Q. rubra*) extend from the mid-west and eastern U.S. states into southeastern Canada (Burns and Honkala 1990).

In the western U.S., coast live oak, *Q. agrifolia,* dominates Pacific evergreen forests where it is an important host of the invasive pathogen, *Phytophthora ramorum*, cause of sudden oak death. In the California landscape, this tree species is prized for its broad spreading canopy, which is often wider than the tree's height. Tanoak, *Notholithocarpus densiflorus* (Fagaceae)*,* another common host to *P. ramorum,* is considered an evolutionary link between oaks and chestnuts.

Historically, the major disease problems of *Quercus* species in eastern states and Texas are oak wilt and oak decline (Billings 2000). Numerous oak species are naturally infected by the oak wilt pathogen, *Bretziella fagacearum*. In general, members of the red oak group are highly susceptible to oak wilt compared to species of the white oak group that are moderate to high in disease tolerance (Juzwik et al 2011). Multiple species of both red and white oak groups are significantly affected by oak decline but differ by the suite of biotic agents responsible. Multiple occurrences of episodic decline and mortality of oaks, particularly red oak species, have been observed in northeastern, mid-Atlantic, Midwestern, and southern oak-hickory forests (Oak et al 2016).

Oak forests health in North America

State of oak forests health in the past 30 years

Over the past several decades, North American oaks, while still abundant, have become less dominant, particularly in the eastern U.S. (Fei et al 2011). Population declines vary geographically and by species. Despite the prevalence of oaks across the northern U.S., multiple studies indicate that oak sapling mortality and lack of regeneration present a doubtful future for oak forests (Woodall et al 2010).

Invasive pathogens are damaging oaks, and the continued introduction of new invasive pathogens poses a significant challenge to oak populations in the U.S. and Canada (Aukema et al 2010; Conrad et al 2020). Sudden oak death, caused by *Phytophthora ramorum*, was first recognized in the mid-1990s in coastal evergreen forests in the San Francisco Bay Area. The invasive pathogen was introduced on ornamental nursery stock, and despite quarantines and eradication efforts, has killed an estimated 50 million oak and tanoak (*Notholithocarpus densiflorus*) along the Pacific Coast in California and southern Oregon (Cobb et al 2020).

Oak wilt epidemics, caused by *Bretziella fagacearum* (formerly called *Ceratocystis fagacearum*), are on-going in Texas and north central states, resulting in the death of tens of thousands of oak trees each year (Billings 2000, Juzwik et al 2011).

Sudden oak death, caused by Phytophthora ramorum, on coast live oak (Quercus agrifolia) in coastal California – top view (photo courtesy of Susan Frankel)

Severe, multiple year *Tubakia iowenensis* foliar infections on bur oak (*Q. macrocarpa*) has led to crown dieback and tree mortality in Iowa and Minnesota (Harrington et al 2012). Change in severity of this disease has been attributed to increased spring precipitation resulting from climate change.

Oak decline and climate change were identified as critical current and future threats for oaks in the eastern U.S. (Conrad et al 2020) and are also a significant concern in the central and southern U.S. Accelerated oak mortality and progressive crown dieback of dominant and codominant oaks is common particularly for red oaks, in stands with lower site quality, older age classes (> 70 years), and relatively dry site conditions (i.e., shallow or excessively drained soils) (Oak et al 1996). Oak decline associated with drought, red oak borer and Armillaria root disease caused significant mortality of oaks in Missouri and Arkansas (approximately 2002 through 2012; Fan et al 2012).

Evolution of oak forests health over the recent 10 years

Over the past 10 years, invasive pathogens continue to kill trees and expand into new areas. For sudden oak death, *Phytophthora ramorum*, in 2015, a new aggressive strain damaging trees in Europe (EU1), was detected killing tanoak in Oregon near a nursery where the EU1 strain was first detected in 2012 (Grünwald et al 2019). The pathogen is under mandatory eradication but continues to expand its range (Navarro et al 2020). Oak mortality increases when wet springs are followed by hot, dry summers. In California, *P. ramorum* has killed, on average for 2018 and 2019, over a million trees per year along the Pacific Coast (COMTF 2020). The pathogen has become well-established throughout many coastal forests and continues to spread via windblown rain expanding the area of infestation and loss of oaks.

Sudden oak death on coast live oak in coastal California – dead standing tree (photo courtesy of Susan Frankel)

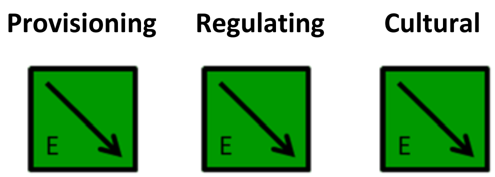
A significant expansion of the oak wilt disease range has occurred with new detections of *B. fagacearum* and red oak mortality in New York State since 2008 (Jensen-Tracy et al 2009; NY Cons 2020). Introduction of the pathogen to new geographic areas in the state is attributed to movement of diseased firewood and logs.

Conditions conducive to oak declines are increasing due to changing environmental conditions and anthropogenic influences that make hardwood forests vulnerable to disturbance. In response to changes in climate, novel decline etiologies, in particular high temperatures followed by secondary agents, appear more aggressive than in the past (Haavik et al 2015). Vegetation models indicate oaks in the southern-most part of their range may undergo extinctions in the future due to increases in temperature and drought (Rodríguez-

Sudden oak death on coast live oak in coastal California – dead grounded tree (photo courtesy of Susan Frankel)

Calcerrada et al 2017). Drought–pathogen (*Biscogniauxia)* interactions in the Ozarks, Missouri caused 10.0% mortality of white oak (*Quercus alba*) and 26.5% mortality of black oak (*Q. velutina*) in a single year, 2012-2013 (Wood et al 2018). Significant white oak (*Q. alba*) mortality associated with *Phytophthora* species has been reported in Ohio, Missouri, and Iowa (Nagle et al 2010; Reed et al 2019).

Ecosystem services, as affected by plant disease



Level of provisioning, regulating, and cultural ecosystem services generated by oak forests, as affected by plant disease, in the past 30 years

Commonly oaks are foundational species, dominating ecosystems and responsible for the services they provide for ecological function, wildlife habitat and human well-being. Oak forests contribute a wealth of provisioning, regulating and cultural services. Because of their longevity, threats to their health are of particular economic importance to commercial forest landowners, because long-term investment may be degraded and replacement of a damaged or destroyed forest takes multiple decades (Boyd et al 2013). Similarly, losses of ecological or cultural benefits due to pathogens can take a long time to return or may never be restored.

Provisioning services. In the U.S., oak species accounted for 41 percent of the eastern hardwood lumber production in 2010 and is used for wood flooring, household furniture, kitchen cabinets, and millwork (e.g., doors, windows, molding). Lower grade wood is used for pallets and railroad ties. Oak specialty products include whiskey and wine barrels, gun stocks, and guitar bodies (Luppold and Bumgardner 2016). As a food source for humans, acorns are important to indigenous peoples. Oak forests also support hunted or gathered food by providing habitat for wild game, berries, mushrooms, and honey (Miller and Lamb 1984).

Oaks support a vast array of wildlife including deer, birds, bats, amphibians, reptiles, and other animals. Mast is relied on for food. For nesting, animals utilize trunk cavities, coarse woody debris, and leafy canopies (McShea and Healy 2002).

Oak wilt has led to loss of habitat for the golden-cheeked warbler in Texas (Camilli et al 2009). Oak mortality in large disease foci may cover multiple hectares (Appel et al 1989) and leads to changes in stand structure. In addition, disease suppression programs to manage oak wilt in forest stands has led to cutting of numerous large areas (up to several hectares) of oak forests in states with epidemics (Bruhn and Heyd 1992; Lampereur and Walker 2018). In some situations, the subsequent regeneration in treated sites has led to a change in species composition, such as maple (*Acer* spp)-dominated stands.

Regulating services. Oak forests regulate numerous ecological processes including biomass production, carbon sequestration, biodiversity, pollination, decomposition, nutrient fluxes, and energy flow. They control water dynamics regulating flood control and water purification (Cavender-Bares 2019). Oak and hickory are of major importance in maintaining biodiversity (Fralish 2004). Loss of these species would have cascading effects on insect and bird populations, understory woody and herbaceous plants, as well as potential to cause increased soil erosion and loss of nutrients.

Cultural services. Oaks may live for hundreds of years. Majestic oaks in plazas, parks, and forests are symbols of longevity and strength. Oak trees are of enormous importance to humans who cherish particular oak landscapes, species, cityscapes, or individual trees (Boyd et al 2013).

Many North American societies and religions use representations of oaks in traditional rites and celebrations (Leroy et al 2020). Because of these associations, plant pathogen threats to oaks carry strong emotional meaning for many people.

Evolution of provisioning, regulating, and cultural ecosystem services generated by oak forests, as affected by plant disease, over the recent 10 years

As oak stands decline or experience accelerated mortality due to invasive species and climate change, many of the ecosystem services they provide decrease. New openings in stands may revegetate to shrubs, herbaceous plants or other tree species changing the landscape character and threatening numerous ecological processes. Oak mortality is of particular concern for the loss of mast which cascades through the ecological food web (McShea et al 2007).

Provisioning wood. According to Luppold (2019), since 1992, *Quercus* species have accounted for a third of the eastern hardwood growing stock volume, but oak poletimber [12.7 to 27.7 cm diameter at breast height (dbh)] volume has declined from 27 percent of total hardwood poletimber volume in 1992 to 23 percent in 2012 with most of this change occurring since 2002. This decline in poletimber volume of oak species is a precursor to reduced oak saw timber volume in the coming decades. For hardwood timber markets, other species may be suitable replacements, but the aesthetic attributes of oak wood are lost.

Complementary information

In this assessment we focused on the effects of pathogens and included climate as an abiotic disease when it disrupts plant health. In forests, pathogens interact with fire, insects, and other disturbance agents to influence tree survival, growth, stand composition and successional patterns. The extent of disease outbreaks is altered by other disturbances such as stand destroying fire, large-scale wind events, or large-scale insect outbreaks (e.g., spongy moth [*Lymantria dispar*]). Land use patterns, fire history and drought influence oak health and distribution (Abrams 1992). In California and many parts of North America, development including subdivisions, vineyards and other agricultural uses are causing oaks to disappear from landscapes (Gaman and Firman 2006).

Declines are increasing due to climate change, due to more frequent and intense periods of excessive heat and drought. While the effects on North American oaks varies depending on the local and regional environmental conditions, climate change is altering survival and growth (Haavik et al 2015).

Trees are long-lived organisms and tree populations may gradually shift their ranges over hundreds or thousands of years. Ecosystem composition fluctuates over eons, while humans tend to focus on observed changes in their local areas over a few years. Humans also tend to be most concerned over changes that directly affect them (i.e., lost timber revenue, a lack of shade canopy in their community) while loss of vital ecological ecosystem services (nutrient and hydrological cycling) may be less apparent and overlooked.

We are reasonably confident in this assessment. There are adequate studies to support this assessment, but North America is a large geographic area and forest conditions vary greatly from location to location. Some areas are exposed to invasive species, declining, or stressed due to climate change while other areas are thriving.

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Semi-natural Forests (Oaks) in Europe

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Background information

European forests cover 215 million ha, i.e. one third of Europe's total land area, and forest area continues to increase. 45% of European forests are predominantly coniferous, 36% are predominantly broadleaved, and the rest are mixed (Forest Europe 2015). European forests have a great socio-economic value due to their provisioning (timber) role. They also play an important role in environmental functions crucial for human wellbeing, such as mitigating climate change, conserving biological diversity, protecting soils and preserving water resources and providing recreation and amenity spaces.

European forests have provided fuel, timber and food to human populations for millennia and human intervention and management has progressively increased during the Holocene (Mc Grath et al 2015). Today, forests undisturbed by humans in Europe only represent around three percent (7.3 million ha) of the total forest area. Most European forests (>80%) are under management plans, but 90% of forests offer recreational functions, demonstrating their multi-functionality. Only a small percentage (<5%) of European forests are intensively managed plantations (FAO 2020; Forest Europe 2015). Most forests, especially broadleaved, are classified as semi-natural and are composed predominantly of naturally regenerated native trees and shrub species. These broadleaved forests are generally not intensively managed planted forests (included in semi-natural forests depending on sources, FAO 2020; Forest Science 2015).

PlantSystem considered in this report

Oaks (*Quercus* genus, Fagaceae) were chosen as the Plant System for this assessment due to their importance in European forests. Oaks are widely distributed across Europe, and are a major component of forests in many regions. Pedunculate oak (*Q. robur*) and sessile oak (*Q. petraea*) occur in all temperate regions from the Atlantic Coast to the Ural mountains and from northern Portugal to southern Scandinavia (Eaton et al 2016). They are frequently a dominant component of deciduous and mixed forests (with

Cork oaks in the Var region, France (photo: ML Desprez-Loustau) other species such as hornbeam, ash, maple or lime). For example, broadleaved oaks are the dominant species in one third of French forests (5.3 M Ha) while *Q. pubescens* (downy oak) and *Q. cerris* (Turkey oak) are more thermophilic and have a more restricted range in the southern part of Europe. Evergreen oaks such as *Q. ilex* (holm oak) and *Q. suber* (cork oak) dominate in the Mediterranean region, in forests or wood-pasture systems ("montados" in Portugal and "dehesas" in Spain). Altogether, Europe is home to 25 to 35 oak species among the more than 500 species worldwide (Hipp et al 2020).

Oak trees can grow to over 40 m tall and live for over 1,000 years. As a major tree species in Europe, oaks have important ecological roles. In particular, they support a wide biodiversity made up of thousands of species (Mitchell et al 2019). Since the earliest times, sessile and pedunculate oak have had a special place in European culture (Leroy et al 2020). Acorns were a source of food for the first modern humans and are still used for feeding animals in some regions. Oaks also provide cork and various non-timber products such as tannins. Their high quality hardwood timber value made them the preferred material

Old oak tree in a park in Italy (photo: ML Desprez-Loustau)

to build ships in the Royal Navies of France and England, wooden roofs of cathedrals, and is still used to make barrels for maturation of the most famous wines. Oaks have a strong symbolic image and many European countries have chosen oak as their national tree.

Semi-natural forests (oaks) health in Europe

State of semi-natural forests (oaks) health in the past 30 years

The general health status of forest trees, including oaks, is often assessed through crown condition. Poor crown condition can be a first symptom of what is called "tree decline", a syndrome generally considered as resulting from multiple stresses of both abiotic and biotic origin and frequently ending in tree mortality (Manion and Lachance 1992). The last report of ICP (International Co-operative Programme) Forests (Michel et al 2018), a large-scale representative monitoring network across Europe, indicated that among the main tree species, evergreen oaks and deciduous temperate oaks displayed the highest mean defoliation in 2017 (28.1% and 23.9% respectively). In many cases, oak declines were shown to involve severe drought stress interacting with biotic agents, especially pathogens, that may serve as predisposing or weakening factors (Delatour 1983). The root pathogens *Armillaria spp.* and *Gymnopus* (*Collybia*) *fusipes*, and the leaf pathogen *Erysiphe alphitoides*, causal agent of powdery mildew, were often reported as predisposing or contributing factors in pedunculate oak decline (Marçais and Desprez-Loustau 2014). In some cases, specific roles of pathogens in oak decline was emphasized, e.g. *Phytophthora spp (P. cinnamomi* in Mediterranean oak decline and *P. quercina* in Central Europe oak decline, Jung et al

2018), or bacteria interacting with the bark beetles *Agrilus biguttatus* in acute oak decline (AOD) in the UK (Denman et al 2014). Oaks can be affected by other pathogens locally, but they are not currently impacted by severe and widespread epidemics such as those affecting other European broadleaved trees caused by newly introduced invasive pathogens (e.g., ash dieback caused by *Hymenoscyphus fraxineus* and alder decline caused by *Phytophthora alni*). Based on these elements, and despite spatial heterogeneity and differences between species, the health status of oaks in Europe is rated as fair.

Evolution of semi-natural forests (oaks) health over the recent 10 years

According to the European large-scale systematic monitoring (Michel et al 2018) evergreen oaks showed a highly significant increase of 3.3% per decade in mean defoliation over the past 20 years. Causes of damage were not systematically investigated and were mainly attributed to abiotic factors. However, *P. cinnamomi* may play a role in deterioration of the state of health of oaks in Mediterranean areas (Camilho-Alves et al 2013). Moreover, an increasing impact of bark pathogens, such as *Biscognauxia mediterranea* and *Diplodia spp* (*D. corticola* and *D. quercivora*) has been reported (Moricca et al 2016). These pathogens are typical opportunistic pathogens that develop in stressed trees (usually following drought) while they live as harmless endophytes in non-stressed trees (Desprez-Loustau et al 2006).

Powdery mildew on oak leaves (photo: ML Desprez-Loustau)

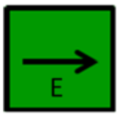
In contrast, no significant over-all trend in mean defoliation was observed for deciduous oaks (Michel et al 2018). Powdery mildew, which is the most common disease of deciduous oaks, shows high inter-year variation in incidence and severity but no over-all trend of increasing or decreasing incidence and/or impact has been reported. Also no change in incidence or effect of root diseases was reported.

The only emerging pathogens on oaks in Europe are newly described bacterial species in the Pectobacteriaceae, Yersiniaceae and Enterobacteriaceae families, such as *Brenneria goodwinii, Lonsdalea quercina* and *Gibbsiella quercinecans*, associated with Acute oak Decline (Brady et al 2017). Some of these pathogenic species have now been reported in England, Spain and Portugal.

In view of increasing levels of crown decline in evergreen Mediterranean oaks and the new bacterial diseases reported on oaks, the heath conditions of oaks in Europe is rated as declining.

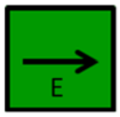
Ecosystem services, as affected by plant disease

Provisioning



Regulating

Cultural



European oak forests are highly valued both by forest managers and by nature conservationists, since they provide high quality timber products and host a rich range of biodiversity. More generally, as an extensively distributed and often dominant tree species, they provide a multiplicity of high level ecosystems services.

Level of ecosystem services generated by semi-natural forests (oaks), as affected by plant disease, in the past 30 years

Provisioning services. Oaks provide a wide range of valuable products, from high quality timber from *Q. robur* and *Q. petraea* where in France alone more than 12 million m^3 per year has been produced in the recent period (IGN 2018), to southern Europe cork oak forests (France, Italy, Portugal and Spain) which account for 90 percent of the world's cork oak production. In Spain, holm oak woodlands generate over 500 million € per year in Iberian ham production from approximately 2 million black pigs and big game hunting is yet another significant oak forest dependent resource in the Spanish dehesas (Bugalho et al 2018).

Regulating services. Oak forests have important environmental roles in water and carbon fluxes, providing a critical climate regulating service. Long-term carbon storage is an important regulating service of these long-lived trees, both in temperate and Mediterranean environments (Bugalho et al 2018). In France, oak trees represent a stock of more than 400 Mt C, approximately one third of the forest national stock (IGN 2018). Oak forests host a multiplicity of other plants, animals and fungi. Mitchell et al (2019) reported 2,300 species associated with oaks in the UK alone, including 38 bird species, 229 bryophytes, 108 fungi, 1,178 invertebrates, 716 lichens and 31 mammals. Among those, 326, mostly fungi, invertebrates and lichens, have an obligate association with oaks. Montados and dehesas, with predominantly Mediterranean oaks as tree species, have high conservation value and are part of the Natura 2000 network; they host a high number of birds, and several threatened and endemic vertebrates, such as the endangered Iberian lynx (Bugalho et al 2018).

Cultural services. Oak trees and forests belong to the cultural and historical heritage of European societies. They are a symbol of longevity, stability, strength and are appreciated for their aesthetic and spiritual value (Leroy et al 2020). Oak forests provide significant recreational and tourism services, and are associated with gastronomy through high quality Iberian ham and wines produced with their acorns and wood (barrels).

Evolution of ecosystem services generated by semi-natural forests (oaks), as affected by plant disease, over the recent 10 years

As oak forests are affected by decline in some regions, partially caused by pathogens and often in conjunction with climate (drought), it is expected that at least some of the ecosystem services they provide will decrease. Such negative impacts could be especially problematic on evergreen oak forests in Mediterranean regions (Moricca et al 2016). For example, significant impacts of cork oak decline caused by *Phytopthora cinnamomi* in Spain were reported on the structure and composition of soil food webs, with possible cascading consequences on soil biogeochemical processes (Dominguez-Begines et al 2019). No negative impacts of pathogens have been reported on provisioning services (especially timber by broadleaved oaks) or cultural services (for example recreational functions).

Complementary information

Contrary to several other native tree species in Europe, broadleaved oaks have not been affected by exotic invasive pathogens leading to high mortality in the last decades, such as *Hymenoscyphus fraxineus* causing ash dieback or *Phytophthora alni* causing alder decline. It is worth mentioning that the sudden oak death pathogen that is damaging oaks in the USA has been detected in Europe damaging Japanese larch but is not known to significantly damage oaks (Anses 2018). Two major threats for oaks, both of American origin, are quarantine organisms for Europe: the bacterium *Xylella fastidiosa* and the fungus *Bretziella fagacearum*. Both pathogens are agents of oak mortality in Northern America and their introduction into

Europe could be a disaster given the importance of oaks (Desprez-Loustau et al 2021). Recent epidemics in forest trees have often been caused by species which were not known to be pathogens, or which were even undescribed before they caused damage in an area where they had been introduced. Strict measures limiting the risk of introduction of pathogens potentially affecting oaks, not only through quarantine regulations but more generally through pathway (import) regulations is therefore a priority.

Among European oaks, the state of health of Mediterranean oaks is currently of greatest concern due to severe declines, in which *P. cinnamomi*, a pathogen of exotic origin, plays a significant role, in conjunction with other biotic and abiotic factors. Several Mediterranean oak species are endangered and at risk of local extirpation in Europe. This report was limited to pathogens, but other biotic (insects) and abiotic factors strongly contribute to oak health. Climate change, in particular, is a serious threat due to its unprecedented speed, exceeding the natural migration rate and adaptation potential of oak populations, despite their high genetic diversity. Research is in progress in relation to adaptive management strategies, including assisted migration, and conservation issues (Ducousso 2020; Mölder et al 2019; Quine et al 2019).

The content of this report can be assessed as reasonably well documented, although the understanding of the role of biotic factors in oak decline requires more investigation. Another knowledge gap relates to how pathogen damage affects the ecosystem services provided by oak forests and woodlands. Therefore, our level of confidence in this assessment is: reasonably confident.

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Forests (Eucalypts) in Australasia

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Background information

In Australia, eucalypts (*Eucalyptus, Corymbia, Angophora*; family Myrtaceae) are ubiquitous and dominant across most of the continent. About 17% (134 million hectares) of Australia's land area is forested, with eucalypt forest and woodland covering 101 million ha (77%) (ABARES 2018).

Eucalypts are believed to have evolved to adapt to nutrient-poor soils, aridity and frequent wildfires (Potts and Pederick 2000). They subsequently came to dominate much of the Australian landscape in response to a drying climate and increased fire frequency, the latter associated with the arrival of humans (Kershaw 1986). The fast growth and adaptability of certain species has led to eucalypts being a major plantation species globally, second only to *Pinus*, with more than 20 million ha planted ((http://git-forestry-blog.blogspot.com/2008/09/eucalyptus-global-map-2008-cultivated.html/). The second tallest tree in the world is a eucalypt (*Eucalyptus regnans*) — 'Centurion', in Tasmania (https://www.monumentaltrees.com/en/heightrecords/).

Eucalypt forests and woodlands are highly valued ecologically, economically and culturally (ABARES 2018). More than half of Australia's native forests are owned, used or managed by Indigenous peoples (ABARES 2018), including hundreds of individual eucalypt trees of cultural significance — typically scarred trees, where bark was removed for canoes and shields or to mark initiation or burial sites (Long 2005).

Eucalypt woodland (photo: A Carnegie)

Forty-six million ha of Australia's forest is managed for protection of biodiversity. Eucalypts are often foundational species and provide food and shelter for a wide range of flora and fauna, with many species of mammals and plants solely dependent on eucalypts (Bennett 2016). Several key eucalypt species are also economically important, with turnover from the Australian forest wood and products sector exceeding AU$23.5 billion/year and contributing more than AU$8.5 billion to Australia's gross domestic product, while non-wood forest products have an estimated gross production value of almost $200 million (ABARES 2018).

Eucalypt species diversity was one of the cited values underlying the declaration of the 103 million ha Greater Blue Mountains World Heritage area in New South Wales (https://whc.unesco.org/en/list/917/).

Ecosystem Services: Australian eucalypt forests and woodlands provide many benefits: 1. **Provisioning Services**: food, fibre, materials; 2. **Regulating Services**: climate, soils, water; 3. **Cultural Services**: culture, spiritual, beauty, medicinal.

PlantSystem considered in this report

The Plant System assessed in this section is eucalypts, including native forests and woodlands, but not plantations. Australia is the global centre of diversity of the eucalypt genera, with 849 species recognized within *Eucalyptus*, *Corymbia* and *Angophora* (Nicolle 2019), the vast majority endemic to Australia. They are long-lived evergreen, hardwood trees, taking on a range of forms, from tall majestic canopy or emergent trees in dense forests, to medium sized trees in open forests, smaller trees in woodlands, and mallees (<10 m multi-stemmed trees) in drier regions (Williams and Brooker 1997). Eucalypt forests (generally trees greater than 30–50 m) are primarily restricted to coastal zones in northern, eastern, south-eastern and south-western Australia, with woodlands (10–25 m) extending into drier inland areas. We use the term 'eucalypt forests' here to encompass all these forms as the Plant System considered. Here we also make the distinction between the impact of pathogens on eucalypts *per se* versus the impacts of pathogens on eucalypt-dominated ecosystems.

Eucalypts are dominant in most of the closed-forest (except rainforest) and woodland vegetation types in mesic-temperate and monsoon-tropical Australia. In the drier rangelands and semi-arid zone, they are less ubiquitous and absent in parts, but species of the mallee growth-form are still important over wide areas of the dry inland. A very large proportion of the terrestrial fauna of Australia (vertebrate, invertebrate and microbial) have evolved in eucalypt-dominated systems and are directly or indirectly adapted to or dependent on them.

Eucalyptus trees (photo: A Carnegie)

Eucalypt health in Australasia

State of eucalypt health in the past 30 years

There are numerous threats to eucalypt forest health that are not pathogenic (see Complementary information below); across the breadth of eucalypt forests in Australia, these 'other' damage agents (e.g., declines of novel aetiology, insect pests, drought) combine to cause areas of fair to poor health. The general state of eucalypt health with respect to pathogens specifically, however, is, overall, good. Although there are very many pathogens of eucalypts (Keane et al 2000), with the exception of parts of southwest Western Australia, the vast majority of eucalypt forest in Australia is not irrecoverably impacted by pathogens. Furthermore, few exotic pathogens have arrived in the past 30 years to threaten eucalypts — myrtle rust being the one exception — emphasising the need for continuing biosecurity (Nahrung & Carnegie 2020). The most significant pathogen of eucalypt forests is *Phytophthora cinnamomi* (ABARES 2018), which causes dieback and tree mortality, is known to infect more than 150 species of eucalypts, and is recognised as a Key Threatening Process (Cahill et al 2008; Keane et al 2000;). However, few eucalypt species are actually killed by *P. cinnamomi*; it is more the understorey species and thus the forest structure and composition that is affected. More than 274,000 ha of native forest have been mapped as dieback-affected in Western Australia (ABARES 2018) where the greatest impacts on eucalypts are evident; elsewhere in Australia, impacts to eucalypts tend to be minimal, although understorey vegetation can be severely affected (Cahill et al 2008; Keane et al 2000). In Western Australia, there is evidence that quarantine and strict hygiene measures can reduce the spread of *P. cinnamomi,* with a reduction in occurrence of Phytophthora dieback in 'Disease Risk Areas' (Conservation and Parks Commission 2019).

Root and butt rot associated with *Armillaria luteobubalina* causes sporadic and localised mortality or growth reduction in native forests in Western Australia, Victoria and Tasmania (Keane et al 2000; ABARES 2018). Myrtle rust (*Austropuccinia psidii*) has a broad host range in

Phytophthora dieback and tree mortality in eucalypt forest in Western Australia (photo: G Hardy)

Myrtaceae, including many eucalypt species, but the current strain in Australia is causing negligible damage to eucalypts (Carnegie and Pegg 2018). Marri canker, caused by the native *Quambalaria coyrecup*, causes severe cankers that can lead to tree mortality of *Corymbia calophylla* in southwest Western Australia (Paap et al 2017) — an example of where forest fragmentation and abiotic stress can exacerbate pathogen impacts— and leaf and shoot blight by the endemic *Quambalaria pitereka* is an emerging issue in Western Australia where it is exotic (Paap et al 2008). Several foliar fungi, notably *Aulographina eucalypti* and *Teratosphaeria cryptica*, can cause extensive and severe defoliation of mature and juvenile eucalypts in native forests (and more so in plantations; Keane et al 2000) but trees generally recover.

While there are many biotic and abiotic agents that damage eucalypts, the majority of the 101 million ha of eucalypt forest is in good health. Aerial surveys over large tracts of eucalypt forest (Carnegie et al 2021; Matusick et al 2013) reveals that 95% of the forest surveyed was in good health.

Evolution of eucalypt health over the recent 10 years

There is little systematic monitoring of forest health in native forests in Australia, although plantations are well covered (Carnegie et al 2018). In southwest Western Australia, regular monitoring is conducted for Phytophthora dieback, Armillaria root disease, key insect pests (often associated with production forests), and several eucalypt declines. In Victorian, a Forest Monitoring Program for Montreal Process reporting has been running for less than a decade, with a network of plots across public forests, including assessments of forest health (Office of the Commissioner for Environmental Sustainability 2018). There are also *ad hoc* assessments of native forest health in response to outbreaks or disorder-specific programs (e.g. bell miner associated dieback). The health of Australia's forest estate is captured every five years (from 1998) as part of national Montreal Process reporting, but is generally descriptive, and rarely qualitative or quantitative (ABARES 2018). The most recent report indicates that the activity of pathogens and insect pests in native forests has not changed significantly over the past two decades.

Mapping of Phytophthora dieback in eucalypt forests in southwest Western Australia has revealed an increase in area affected over the past decade to 274,000 ha (ABARES 2018). Although surveys are targeted to areas where disturbance activities are planned (for subsequent development of dieback management plans) and the data on extent thus reflects mapping effort, the area of Phytophthora dieback is likely to increase annually because the pathogen spreads autonomously and it has not occupied all available niches as yet. In the most recent Forest Management Plan for Western Australia (2014–2023), declines in forest condition (reported as vegetation density via Landsat image analysis) over the past decade were attributed to reduced rainfall, not primarily Phytophthora dieback (Conservation and Parks Commission 2019); an example of where abiotic stress can exacerbate the impact of pathogens. Elsewhere in Australia, while the distribution of *P. cinnamomi* may have increased — e.g., in Victoria (Office of the Commissioner for Environmental Sustainability 2018) and New South Wales (McDougall and Liew 2020) — there has been negligible change in impact of Phytophthora dieback to eucalypts (ABARES 2018). In Victoria, about one-fifth of the forests monitored recently were in poor health (defined as mortality, crown dieback or defoliation/discolouration), but no causal agents — including pathogens — were specifically identified, and no trend analysis is available because of the infancy of the Forest Monitoring Program (Office of the Commissioner for Environmental Sustainability 2018).

Monitoring of marri canker (*Q. coyrecup*) of *C. calophylla* indicated an increase in the extent of the disease in this keystone species in southwest Western Australia (Paap et al 2017) but was primarily in anthropogenically disturbed sites (road-side trees, remnant bush on farms and in peri-urban/urban areas and paddock trees), not native forests, and although representative for marri, was conducted on a relatively small number of trees. Levels of Armillaria root disease did not increase over this time period, and there were no records of severe epidemics of foliar fungi (ABARES 2018). A new exotic disease of Myrtaceae, myrtle rust, established in Australia in 2010 and has spread through natural ecosystems along the east coast of Australia and into the Northern Territory over the past 10 years and subsequently affected an increasing number of eucalypt species (Carnegie and Pegg 2018). No other exotic diseases of eucalypts have established in Australia over this time period (Nahrung and Carnegie 2020).

Eucalypt regenerating after fire infected by myrtle rust (photo: P Entwistle)

With all damaging agents being considered (see Complementary information below), there has been a decline in health of eucalypt forests across Australia over the past 10 years, with increases in drought and insect pest-related dieback, various eucalypt declines and a moderate increase in marri canker. Although pathogen impacts in the majority of Australia's eucalypt forest have been stable over the past 10 years, there has been significant increases in impact in southwest Western Australia. It is difficult to separate the impact to eucalypt forests solely from pathogens as opposed to those of damage agents.

Ecosystem services, as affected by plant disease

Provisioning **Regulating** **Cultural**

Level of provisioning, regulating, and cultural ecosystem services generated by eucalypts, as affected by plant disease, in the past 30 years

Eucalypt forests and woodlands in Australia provide a range of benefits including habitat for flora and fauna, wood and non-wood forest products, protection of water supply and soil, carbon storage and sequestration, tourism and recreation, and Indigenous and non-Indigenous cultural values. Damage to eucalypts by pathogens can thus impact on these values (e.g. tree mortality has immediate impacts, or knock-on effects to ecosystems). Because eucalypt forests and woodlands are so vast and ubiquitous across the landscape, damage from pathogens needs to be on a relatively large scale — geographically and/or temporally — to have significant impacts on these services at a national level. However, significant damage from pathogens at local scales (e.g. regional biomes) can have irreversible impacts on ecosystem services, and here we consider impacts at local scales just as important as those at broader scales.

Provisioning Services: food, fibre, materials, biodiversity

Here we include *biodiversity* under provisioning services, as it was not clear in the guidelines which ecosystem service it is represented by.

Eucalypt species account for most of the native timber harvesting in Australia, and eucalypt forests provide for a broad range of other services (ABARES 2018). The value of logs from native forests is AU$0.50 billion (cf plantations AU$1.88), primarily sawlogs, peeled veneer logs and pulpwood. The value of production of the whole wood products sector is AU$23.7 billion, while the value added to Australia is AU$8.6 billion, or 0.52% of GDP. The value of non-wood forest products exceeds AU$200 million, including honey and beeswax (AU$110 million), tea tree oil (AU$28 million), native bush foods (AU$18 million) and *Eucalyptus* oil (AU$1.2 million).

There has been a decrease in annual average volume of high-quality sawlogs harvested from native forests in the past two decades, from 1.96 million m^3 to 1.14 m^3, primarily due to a reduction in the area of native forest available for harvesting, bushfires, and increased restrictions on harvesting, i.e. not pathogens (ABARES 2018). Although Phytophthora dieback has the potential to impact on economic returns for timber harvesting in Western Australia (McLeod 2005), and prevention and management procedures can cost land management agencies in excess of AU$1.5 million per annum, the true impact over the past 30 years is unclear. The broad host range of *P. cinnamomi* means that its impact at infested sites in southwest Western Australia includes a reduction in biomass and biodiversity over time. There is no evidence that susceptible species can successfully recolonise infested sites, as the pathogen can persist in numerous asymptomatic hosts (Crone et al 2013); consequently, the pathogen will not disappear from an area due to loss of susceptible hosts. Weeds may invade heavily impacted sites, or the reduced shade and shelter may make recolonization, even by resistant species, difficult. *Phytophthora cinnamomi* is believed to have been introduced to southwest Western Australia in the early 1900s and it is unlikely we have seen the full extent of this pathogen's impact yet. The demonstrated impact of *P. cinnamomi* on biomass and biodiversity means that the current and potential future values of provisioning services arising from timber, tourism, apiary, wildflowers, pharmaceutical products and carbon sequestration, to name just a few, are all at risk.

Forty-six million ha (35%) of Australia's native forest is protected for biodiversity conservation, thus Australia has met and exceeded its commitment (of 17%) under Aichi Biodiversity Target 11. Many fauna species are dependent on eucalypts for food, shelter, and breeding sites. In New South Wales alone, at least 46 mammals, 81 birds, 31 reptiles and 16 frogs are reliant on tree hollows for shelter and nesting sites; such hollows develop naturally in eucalypts but are rare in non-myrtaceous Australian trees (NSW Scientific Committee 2007). Eucalypt species support a diverse assemblage of epiphytic parasitic mistletoe species (of three families) across mainland Australia (Watson 2001). Eucalypt-borne mistletoes have a number of strongly associated vertebrate and invertebrate fauna species and may be a primary food source in seasons when little else is available, especially in drier systems. Eucalypts also support a large assemblage of microbial biota, including large fungal communities. A review of published data reveals 1,350 species of fungi known from 150 eucalypt species; the most fungus-rich host eucalypt had 282 fungal species, 150 of which were not known from any other eucalypt (Tommerup and Bougher 2000). More than 700 species of fungi have known mycorrhizal associations with eucalypts.

The impact of Phytophthora dieback on forest biodiversity is well understood, with local extirpation of understorey species and changes in floristics and structure, including mortality of susceptible eucalypt species (Cahill et al 2008). Such modification of forest ecosystems by *P. cinnamomi* subsequently impacts on small-mammal communities reliant on eucalypt-dominated ecosystems (Garkaklis et al 2004).

Phytophthora cinnamomi threatens biodiversity values in the South West Biodiversity Hotspot.

Where pathogens — especially *Phytophthora* spp. — are causing significant impact, it results in irreparable damage to eucalypt forests and associated provisioning services. However, this damage is in only a small proportion of the total eucalypt forest area. As such, the provisioning service of eucalypt forests, with respect to pathogen impacts, was good over the past 30 years.

Regulating Services: climate, soils, water

Eucalypt forests provide a range of ecosystem services and all have generally been at a good level over the past 30 years as assessed under Montreal Process reporting criteria (ABARES 2018). Carbon stocks in Australia's native forests exceed 21,676 million tonnes, with carbon dioxide sequestration in forests for 2011–2016 equivalent to off-setting 3.5% of Australia's human-induced greenhouse gas emissions. Thirty-six million ha of native forest is managed primarily for protection of soil and water. Eucalypts constitute a large proportion of canopy cover over very large regions and play a major role in rainfall interception, water stemflow, provision of condensation surfaces, shading, and litter production. Pathogens such as *Phytophthora* spp. have impacted on these regulating services over the past 30 years. While the actual impact of pathogens on regulating services is not strictly assessed, we believe there is likely to be a measurable impact. However, these impacts are relatively restricted in area, resulting in the level of regulating services as overall good from eucalypt forests as affected by pathogens.

Cultural Services: culture, spiritual, beauty

Eucalypt forests contribute to numerous cultural services (ABARES 2018). More than 30 million ha of forest are available to the general public for recreation and on average 4.2 million people visit forested regions for bushwalking each year, 10% of them international visitors, as well as mountain bike riding. Almost 70 million ha of forest is Indigenous owned/managed, or under Native Title determinations or Indigenous Land Use Agreements. There are an estimated 126,000 registered Indigenous cultural heritage sites within these forests (protected by Commonwealth and state legislation), including middens, cave paintings, scarred trees and cultural dreaming sites. A further 11 million ha of forest are non-Indigenous heritage-listed, including UNESCO World Heritage Listed forests, and sites of social, economic or historical significance, including early gold mines and forestry camps.

The impact of pathogens on cultural services primarily concerns *P. cinnamomi*, including dieback and death of eucalypt trees, restricted access to forests and subsequent hygiene protocols (wash-down/cleaning facilities for vehicles and boots). As the majority of eucalypt forest is not impacted by pathogens, the overall value of cultural services from eucalypt forests is good.

Evolution of provisioning, regulating, and cultural ecosystem services generated by eucalypts, as affected by plant disease, over the recent 10 years

Although Phytophthora dieback has the potential to impact on economic returns for timber harvesting in Western Australia (McLeod 2005), and prevention and management procedures can cost land management agencies in excess of AU$1.5 million per annum, the social and economic benefits of the timber industry in Western Australia have remained stable over the past 10 years (Conservation and Parks Commission 2019).

Phytophthora cinnamomi is considered one of the greatest threats to the biodiversity hotspot of southwest Western Australia and is consequently listed as a key threatening process under the *Environment Protection and Biodiversity Conservation Act 1999*. The permanent removal of susceptible species by the disease leads to reduced biomass and biodiversity at infested sites with concomitant knock-on impacts to site conditions and remaining species, habitat and consequently dependent fauna. The Western Australian Forest Management Plan (2014–2023) identified Phytophthora dieback as contributing to a declining trend in health of Threatened Ecological Communities which are either dominated by or have eucalypts as a key component.

The incursion of the pandemic strain of myrtle rust in 2010 resulted in an economic impact during the eradication attempt, but no damage to eucalypts as it spread along the east coast (Carnegie and Pegg 2018). There has, however, been significant impacts on biodiversity values for highly susceptible native species that are co-occurring in eucalypt forests, with several species becoming Critically Endangered due to myrtle rust. This has subsequently led to increased management costs for the forest industry due to increased provisions for pre-harvesting surveys as two of these species are ubiquitous in eucalypt forests.

No other damaging pathogens have significantly expanded their range across Australia in the past 10 years.

There has been an increase in areas of eucalypt declines in Western Australia and eastern Australia (e.g. Brouwers et al 2013), but these are generally novel decline aetiologies associated with human disturbances and changing environmental conditions or associated primarily with insect outbreaks. The increase in marri dieback, caused by *Q. coyrecup* (Paap et al 2017), is likely to have major impacts on regulating and cultural services at local scales, with loss of iconic trees impacting tourism, increased tree maintenance along road corridors, knock-on effects of birds utilising horticultural crops (e.g. viticulture) in place of marri as a food source, and loss of habitat for Threatened species.

Loss of keystone species due to pathogens, such as *C. calophylla* (marri) due to *Q. coyrecup* (marri dieback), or ecosystem impacts in eucalypt forests due to Phytophthora dieback, can impede the regulating properties of soil and water.

Wildfires and drought significantly impacted on eucalypts in the past 10 years.

In spite of significant impacts of pathogens in eucalypt forests primarily in southwest Western Australia, we believe overall provisioning services have remained stable. However, pathogen impacts are causing a decline in regulating services and cultural services in Australia.

Complementary information

The health of eucalypts in Australia, in both native forests and plantations, is likely to change with an accidental introduction of a more virulent strain of *Aus. psiddii* (myrtle rust). Although the current 'pandemic' strain of *Aus. psidii* infects eucalypts, the impact is negligible in native forests or plantations (Carnegie and Pegg 2018). A strain that is more virulent on eucalypts (e.g. the 'Brazilian eucalypt' strain) is likely to greatly impact on regeneration of native forests.

In the forest system, considering only plant pathogens does not give a full and necessary appreciation of the compound impacts on eucalypt-dominated ecosystems that occur as a result of the interactions of pathogens with other threats such as insect pests, feral animals, climate change, fire and fragmentation. There are a broad range of native pests and pathogens that affect eucalypts in Australia, attacking foliage, stems, and roots (Elliott et al 1998; Keane et al 2000; ABARES 2018). Insect pests that periodically increase in population and cause extensive damage in native forests include psyllids, gum-leaf skeletoniser, cup moths, stick insects and longicorn beetles. Endemic pathogens associated with appreciable damage in eucalypt forests include *A. luteobubalina* (root rot), *Q. coyrecup* (cankers), and several foliar and shoot fungal pathogens (*Au. eucalypti, T. cryptica, Q. pitereka*). However, the most significant pathogen in Australian native forests is the invasive and introduced oomycete *P. cinnamomi*, associated with dieback and mortality on a broad scale, with *P. multivora* increasing in importance. A recently arrived invasive fungal pathogen, *Aus. psidii* (myrtle rust), currently causes negligible damage to eucalypts. It is important to note, though, that while most of the above pathogens cause damage solely to eucalypts, it is the effect of disease on the forest ecosystem that has the greatest impact on ecosystem services (e.g. by *P. cinnamomi*).

There are numerous threats to eucalypt forest health that are not pathogenic. Historically (since European settlement), forest clearance and fragmentation has been a major driver of ecological decline, and this continues in some eucalypt-dominated vegetation types. Forests of eastern Australia (including non-eucalypt types) have been reduced to approx. 35% of their pre-1750 extent; native vegetation of the south-west of Australia (including non-eucalypt systems) has been reduced by approx. 61% (IPBES 2018).

Climate change is predicted to result in major and predominantly adverse changes to habitat conditions for many eucalypt species, operating through changed temperature and rainfall regimes (Butt et al 2013) and associated changes in wildfire regime (Gonzales-Orozco et al 2016), and may also alter pest and disease occurrence and impact (Booth et al 2015). Wildfire is a major ecological process in eucalypt forests. All types of eucalypt forest are adapted to and require fire to some degree, but the now ubiquitously changed or inappropriate fire regimes (in terms of frequency, intensity, seasonal timing, and extent), drive structural and floristic change and may act synergistically with other threatening processes, including anthropogenic and natural vectoring and establishment of some pathogens (Commonwealth of Australia 2018). The unprecedented widespread and intense bushfires of 2019–2020 burnt more than 8.3 million ha of native forest (Whittle 2020), and the ecological effects will take many years to evaluate.

Sudden canopy collapse and subsequent dieback and tree mortality associated with severe drought also affects large areas in Australia (Fensham et al 2009; Matusick et al 2013; Hislop et al 2022). Bell miner associated dieback has been estimated to impact more than 1 million ha in coastal forests in eastern Australia, although significantly less area has actually been mapped (Carnegie et al 2021). Outbreaks of herbivorous insects also cause severe defoliation that can lead to dieback (Elliott et al 1998) but tend to be restricted in space and time. There are also several declines of individual eucalypt species in native forests, especially in Western Australia (Brouwers et al 2013; Paap et al 2017; Barber and Hardy 2006). Across the breadth of eucalypt forests in Australia, these 'other' damage agents (e.g., declines of novel aetiology, insect pests, drought) combine to cause areas of fair to poor health.

There is reasonably good information on the health of eucalypt forests in southwest Western Australia from research studies (e.g. Paap et al 2017) and forest management publications (e.g. Conservation and Parks Commission 2019). However, this project highlighted a lack of systematic monitoring of forest condition across the native forest estate in Australia (unlike e.g. United States, Bennett and Tkacz 2008). The Victorian Forest Monitoring Program (Office of the Commissioner for Environmental Sustainability 2018) is the most comprehensive cross-forest program on public lands in Australia, but has been running for less than a decade, and does not identify causal agent of damage, only dieback, mortality, discolouration or defoliation. There is targeted monitoring for pests and pathogens in Western Australia, but this is primarily of production forests and not across forest tenure. More often, forest health assessments of native forests in Australia are ad hoc or in response to major outbreaks — for example, bell miner associated dieback (Carnegie et al 2021) or periodic insect outbreaks (Farr et al 2004) — and not systematic. Forest health surveillance programs of plantations detect some issues, but these are not a priority to map or report.

There is no collaboration between land managers (private, production, conservation) in forest monitoring. Furthermore, any mapping that is conducted is not systematically collated at a national level. Montreal Process reporting (ABARES 2018) suffers from qualitative and descriptive reporting, lack of consolidation/consistency in reporting across tenures even within States, and lack of clear and meaningful guidelines for reporting — all stemming from the fact there is no national forest monitoring program. However, there is positive change, with the Victorian Forest Monitoring Program and a proposed NSW Forest Monitoring and Improvement Program (https://www.nrc.nsw.gov.au/forest-monitoring).

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Amazon Forest

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Background information

The Amazon rainforest is the largest tropical rainforest in the world, covering roughly 6 million square kilometres (Gomes et al 2019). The majority (64%) is in Brazil, but the region known globally as the Amazon also spans parts of eight other rapidly developing countries: Bolivia, Peru, Ecuador, Colombia, Venezuela, Guyana, Suriname and French Guiana.

The Amazon rainforest supports an extraordinary diversity of plants and animals, as well as an exceptionally high but mostly uncharacterized diversity of microbes (Flores et al 2020; Ploetz 2007). The region also plays an essential role in local and global climate regulation, is vital for carbon storage at a global scale (Walker et al 2020), and provides important provisioning services to a large diversity of local communities and their countries (Joly et al 2019; Peters et al 1989).

In this assessment, we focus on the impact of plant health on two services of the Amazon forest:

Regulating services: Arguably the most important service of the Amazon is climate regulation. Amazon evapotranspiration affects both local and regional climate via what is known as the Amazon's 'flying river,' which provides 70% of the rain that falls in the agriculturally-rich regions of central and southern Brazil, northern Argentina, Paraguay, and Uruguay (Joly et al 2019; Lovejoy and Nobre, 2019; Salati et al 1979). In addition, the Amazon is one of the largest repositories of terrestrial carbon, and therefore is a buffer against global warming (Joly et al 2019; Lovejoy and Nobre 2019).

Regenerating forest gap in Yasuni National Park, Ecuador, Ecuador (photo: Tania Brenes)

Mist over Yasuni National Park, Ecuador (photo: Tania Brenes)

Provisioning services: Thousands of fruiting tree species (e.g., wild fig, inga, palm fruits) are critical resources to animal populations. Humans exploit many forest plant species for food (e.g., Brazil nut, cacao, cashew) and building materials (e.g., palms, rubber; Peters et al 1989). The forest also contains commercially-valuable species used for timber (e.g., cedar and mahogany). Hunting wild game is an important source of food for forest dependent communities and often neighbouring towns (Peters et al 1989).

Tiputini River, Yasuni National Park, Ecuador (photo: Tania Brenes)

PlantSystems considered in this report

The **Amazon forest** is extremely diverse, harbouring an estimated 16,000 tree species (ter Steege et al 2013). Due to this high diversity, it is not possible to identify significant ecological or provisioning keystone species. A single hectare of forest can contain more tree species than all of the US and Canada combined (>650 species). This hyperdiversity provides stability to the system by playing a role in natural cycles of tree mortality and gap regeneration and providing resilience to plant pathogens (Ennos 2015). Numerous common species have been commercialized locally or globally and/or provide resources for wildlife and local indigenous groups in the Amazon basin (e.g. *Inga* spp, *Ficus* spp (figs), *Eschweilera* spp, *Bertholletia excelsa* (Brazil nut), *Iriartea deltoidea, Attalea butyracea, A. phalerata,* and *Mauritia flexuosa*; Peters and Gentry 1989)).

Here we focus on the health of two important commodities: (i) ***Hevea brasiliensis*** (natural rubber, an essential raw material with many uses and advantages over synthetic rubber), and (ii) ***Theobroma cacao*** (cacao, one of the world's most popular foods). These species have their centre of origin in the Amazon basin. Both cacao and rubber have played an important role as the foundation of the economy for the Amazon region (Lieberei 2007; Ploetz 2007, 2016). Although, today, about 86% of cacao production and 90% of rubber production come from the Eastern Hemisphere, both species are still cultivated or harvested at small scales in the Amazon basin (Lieberei 2007; Ploetz 2016). While productivity in the wild is rarely as high as in cultivation, the Amazon forest remains a valuable source of genetic diversity for both crops.

Rubber and cacao health in the Amazon forest

State of rubber and cacao health in the past 30 years

Favourable conditions for microbial growth throughout the year, coupled with a high diversity of host plants and endemic pathogens, make diseases of tropical perennial crops serious management challenges (Drenth and Guest 2016; Ploetz 2007). Most of the information about diseases of rubber and cacao comes from germplasm collections or planted trees, and very little is known about pathogens of naturally occurring trees (Gilbert and Hubbell 1996).

Dozens of cacao diseases have been described to date. Some of the best studied cacao diseases (mainly because of their economic impact on crop production) are caused by pathogens with restricted geographical distributions (.e.g., *Moniliophthora roreri, M. perniciosa, Phytophthora megakarya, Ceratobasidium theobromae*; Ploetz 2016). Damage from these pathogens is one of the main reasons behind the last century's shift in crop production from the centre of origin in the Amazon basin to Africa and Asia (Drenth and Guest 2016).

The dynamics of plant disease are often different in intact forests. Even though the rubber tree is one of the 20 most abundant species in the Amazon, it only occurs sporadically in mature forest (ter Steege et al 2013). At low rubber tree densities, the indigenous pathogen South American leaf blight (*Microcyclus ulei*) causes little damage in the forest, while all attempts at monocultures of rubber trees in its native range were severely impacted (Guyot and Le Guen 2018; Lieberei 2007). Additionally, when grown in the forest, both cacao and rubber trees harbour diverse, though largely uncharacterized, fungal endophyte communities that could contribute to biological control of the native diseases (Gazis and Chaverri 2015).

Detritivorous fungi in Amazon forest understory (photo: Tania Brenes)

Evolution of rubber and cacao health over the recent 10 years

Significant disease outbreaks have occurred in the past, and still occur, in **cacao and rubber** in plantations. These are well documented and explain the aforementioned shift in crop production out of its native range. However, disease pressure in natural populations of cacao and rubber has likely not changed over the past 10 years. High diversity causes a dilution effect which slows disease transmission and limits the potential for an epidemic (Ennos 2015; Gilbert and Hubbell 1996). This high diversity may also make the Amazon forest relatively resilient to the introduction of invasive species or new diseases (Gilbert and Hubbell, 1996). There is no documented evidence of significant incursion of non-native pathogens into the Amazon forest. However, the nature of the system (including the high diversity of hosts and pathogens) renders any such event unlikely to be noticed.

Disease caused mortality of tropical trees is common and creates canopy gaps and other disturbances that increase local tree diversity (Gilbert and Hubbell 1996). These dynamics of disease-caused mortality and regeneration of naturally occurring trees occur over time scales much longer than 10 years. Few studies have assessed inter-annual dynamics of pathogen cycles in intact Amazonian forests; the few that have focused on seedlings (Alvarez-Loayza and Terborgh 2011; Augspurger and Kelly 1984). There is even less information for inter-decadal disease dynamics or other longer-term trends of mortality or regeneration in productive size trees.

Ecosystem services, as affected by plant disease

Regulating **Provisioning**

Level of regulating and provisioning ecosystem services generated by rubber and cocoa, as affected by plant disease, in the past 30 years

Regulating services. The key carbon storage and climate regulation services of the Amazon forest are driven by the total extent of mature forested area and are mostly unaffected by the health of a few species. In mature forests, the spread and negative impacts of disease at the community scale are limited by the hyperdiversity of Amazonian forests (Ennos 2015; Ostfeld and Keesing 2012). Even in the event of an outbreak of native (or invasive) diseases, a forest with thousands of tree species typically is not likely subject to collapse, or the loss of ecosystem services, due to disease-driven population declines for a few susceptible tree species.

Thus, considering only disease and no other threats, there has been no documented disease-caused reductions in forest area over the past 30 years. However, diverse anthropogenic threats have caused considerable reduction in the total area of Amazonian forests, seriously threatening its regulating services (Gilbert and Hubbell 1996; Gomes et al 2019; Lovejoy and Nobre 2019). If diversity and resilience of the forest as a whole are reduced by processes such as deforestation and climate change the risks to the forest from pathogens may increase markedly (Gilbert and Hubbell 1996).

Provisioning services. In cultivation, tropical tree crops have generally been domesticated from limited germplasm diversity (Lieberei 2007). Despite significant threats of species extinction caused by global warming and deforestation, wild cacao and rubber trees are widespread and it is unlikely that they have suffered significant reductions in their range, abundance, or genetic diversity.

Furthermore, wild trees harbour diverse endosymbiotic microbes. The protective roles conferred by endophytes have been poorly studied in natural populations of tropical trees, but the case studies available point to these foliar symbionts promoting plant health. A recent study of endophytic fungi isolated from leaves and stems of *Hevea brasiliensis* in plantations and in wild trees, suggested that competitive fungal strains (i.e., *Trichoderma* and *Tolypocladium*) can protect against pathogens in wild trees (Gazis and Chaverri 2015).

Evolution of provisioning and regulating ecosystem services generated by rubber and cocoa, as affected by plant disease, over the recent 10 years

Over the last 10 years, diseases have not likely degraded the overall health of Amazonian forests. With respect to diseases, the generation of ecosystem services (provisioning, regulating) by the forests has therefore remained stable. However, regulating services are seriously threatened by forest destruction and degradation, especially in the context of climate change (see section on Complementary information). All these threats are likely to interact and could increase disease impacts on forest dynamics.

Complementary information

Plant diseases play a key role in the mortality and regeneration of trees in the Amazon forest. In largely undisturbed tropical forests, disease-caused mortality is common, but the high plant species diversity provides stability at the community and ecosystem level. In turn, provided a forest area is large and interconnected enough, high disease pressure increases species diversity.

While our assessment determined that ecosystem services are not likely affected by plant health in the Amazon forest, there are serious threats from deforestation, mining, industrial-scale agriculture, and other human impacts, including climate change. These anthropogenic threats have increased markedly in the past 10 years (Gomes et al 2019; Montibeller et al 2020).

The Amazon is believed to have two "tipping points": (1) a temperature increase ≥4 °C and (2) deforestation ≥40%. Approximately 17% of the original extent of the Brazilian Amazon (representing 64% of the Amazon rainforest) was lost between 1970 and 2018, and forests are becoming increasingly fragmented with fewer connections between fragments (Lovejoy and Nobre 2019; Montibeller et al 2020).

At present, the spread and negative impacts of disease at the community scale are limited by the hyperdiversity of Amazonian forests. However, forest degradation due to fragmentation and over-exploitation has had a negative impact on biodiversity and has slowed the natural cycles of regeneration. Disease epidemics and/or the introduction of novel pathogens with the capacity to diminish the ecosystem services, may occur in these scenarios. In addition, the introduction of novel diseases and disease spill-over from crops to wild plants could occur as agriculture encroaches on fragmented forest.

The working group has based this report on decades of research on tropical forest dynamics. This includes abundant literature on plant-pest interactions in tropical forests, the effect of diversity on distance and density dependent mortality of trees, and the effect of diversity on cycles of tree mortality and forest regeneration. The group however acknowledges that the study of diseases in unmanaged tropical forests is not nearly as extensive or as in depth as what is seen in crops and other managed systems. Hence, most pest information in this report come from cultivated systems.

The group feels very confident in its assessment of the stabilizing role of diversity for forest regeneration and decreasing pest impacts at the community level. However, because of the complexity of the system and the limited number of studies of tropical forest pathology, the group cannot clearly establish that invasions or epidemics have not already compounded forest degradation when combined with climate change and forest fragmentation.

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Standardised procedure to develop the reports

The following document is derived from the description of a report template which was sent to Lead Scientists in order to guide them to develop the reports.

Global Plant Health Assessment - Report template

About this report - General instructions

This template is intended to all Lead Scientists of the Global Plant Health Assessment. We provide this template to save your time, to guide your work as Lead Scientists, so that you only need to follow the suggestions we make. This template is also meant to ensure uniformity across reports. Lastly, we want to make sure that each report addresses four specific questions. All reports will be reviewed and discussed among the participants of the Global Plant Health Assessment, and a synthesis of reports will be made.

Your report is not meant to be comprehensive. It is not a review. Instead, this report should be seen as the *view* of a Lead Scientist, along with a few Experts, on the state of plant health in a given Plant System, in a chosen Ecoregion of the world. The guidelines in each of the following sections (in grey) should help you in preparing this report.

This view from a team of scientists (Lead Scientist + Experts) must be supported by references. A minimum of three references* per report is required; a maximum of 15 references is possible.

All participants to the Global Plant Health Assessment will be associated with any reporting or publication of this work. This is why we ask your *complete affiliation details* along with your *name and email*.

We estimate that the preparation of the report should not involve more than three working days (accumulated time) for each Lead Scientist. This includes the time that each Lead Scientist would take to share information and drafts of the report with Experts of her/his choice.

We shall be glad to help and answer queries. Please finalise and send your report **before July 31, 2020**. When completed, please sent the report to Serge Savary with copy to Paul Esker.

* Suggested reference format:

Smith J, Jones M Jr, Houghton L et al (1999) Future of health insurance. N Engl J Med 965:325–329

1. General information

[Ecoregion x PlantSystem]: example: South Asia x Peri-Urban Horticultural Systems and Household Gardens

Lead Scientist: please provide: (1) First name (middle name) Last name; (2) email; (3) Complete affiliation

Expert 1: please provide: (1) First name (middle name) Last name; (2) email; (3) Complete affiliation

Expert 2: please provide: (1) First name (middle name) Last name; (2) email; (3) Complete affiliation

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Expert n: please provide: (1) First name (middle name) Last name; (2) email; (3) Complete affiliation

To Lead Scientists: Please involve a limited number of Experts. Three Experts is usually enough. In some cases, more Experts may be needed - but keep this number small. Note: each expert MUST have contributed to the report.

2. Background information: Please describe the [Ecoregion x PlantSystem] considered in the present report

suggested length: 10-15 lines

Each report deals with one [Ecoregion x PlantSystem]. Please describe in a few sentences the [Ecoregion x PlantSystem] which is considered in the present report. What are its main characteristics? What are its main features? What makes this [Ecoregion x PlantSystem], considered in the present report, **special**? *Examples*: there will be reports on *grapevine in Europe (grapevine and wine making are a major economic activity, with very important cultural roots and meaning)*, on *wheat and maize in North America (cereal production in North America is a major economic activity and a vital component of global food security)*, on *forests in the Amazonas (the Amazon plays an essential role in climate regulation, is a vital repository of biological diversity)*.

Please explain why this [Ecoregion x PlantSystem] is important. What is its role in terms of Provisioning (food, fibre, materials), in terms of Regulation (climate, soils, water), or in terms of Culture (beauty, spiritual value, cultural value)? A brief description of these will explain which **Ecosystem Service** is considered in the report.

Please provide a few references.

Please specify which of the following groups of Ecosystem Services you have decided to report on in this Report (see the Table at the end of this document):

1. **Provisioning Services**: food, fibre, materials

2. **Regulating Services**: climate, soils, water

3. **Cultural Services**: culture, spiritual, beauty

3. Please specify the PlantSystem considered in the report

suggested length: 10-15 lines

This section **explains which plant or plants are considered in the report**. These plant or plants may be cultivated or not, they may be annual plants or perennial plants. The choice of plants should, essentially, be based on their **contribution to** the **ecosystem services** that they provide (Provisioning, Regulating, Culture) - that is to say the "importance" the chosen plants have towards these services.

Choice of plants in some **agricultural systems** is relatively easy: wheat for [Europe x Cereals], potato for [South America x Roots and Tubers], for example.

The choice is more difficult in **complex cultivated systems**: [Peri-Urban Horticulture and Household Gardens x Southeast Asia], for example. In this case, selecting some of the most frequent components of such systems is suggested, for example: leafy vegetables, solanaceae, crucifers. This kind of choice will allow comparison with other analogous PlantSystems in different Ecoregions, for example: [Peri-Urban Horticulture and Household Gardens x South Asia], or [... x sub-Saharan Africa].

The choice is perhaps even harder for **non-cultivated complex systems**: [Forest x Amazon], for example, where biological diversity is a key feature - which we want to address if possible. Considering **keystone species** is then advised. For this report on plant health assessment, two standpoints exist in the choice of keystone species. One is the frequency/importance of a given species in the PlantSystem considered; another is the existence of major disease problems. Although the prevalence of disease may be a reason to select a plant species as keystone, it perhaps is more advisable to prioritise the first criterion (frequency/importance of a given species).

The choice of plants considered is entirely that of the Lead Scientist and Experts. It may be that several species, or a group of species, are considered.

Please provide reference(s) to support these choices.

4. Question 1: How do you describe the state of plant health in the past 30 years for the considered plant(s)? suggested length: 10-20 lines

This section needs to provide information on the **overall state of health** of the considered Plant System, within a given Ecoregion. The state of health must refer to the keystone species (one or several), which have been specified in the previous section.

Broadly - the question is: Are there major diseases on this (these) keystone species? Please provide some background on why these diseases are important, in terms of their spread in plant populations, or in terms of their effects on plant populations.

Please provide reference(s).

Please summarise your answer to this question on a 5-point scale (Excellent / Good / Fair / Poor / Bad) using one of the coloured squares below.

Excellent **Good** **Fair** **Poor** **Bad**

Notes: (1) the notion of trend over time is addressed in Question 2; (2) the notion of effects on Ecosystem Services is addressed in Questions 3 and 4.

5. Question 2: How has plant health evolved for the considered plant(s) over the recent 10 years?

suggested length: 10-20 lines

This section complements the answer to question 1, with a **trend in plant health** over a shorter time-frame. We suggest 10 years as a reference period, but the time horizon may be expanded if relevant -- as long as the past 10 years are included.

Broadly - the question is: Has there been an increase in frequency of the major diseases indicated in answering Question 1? Have they been decreasing? Please provide some background on these changes over time.

Please provide reference(s).

Please summarise your answer to this question on a 3-point scale (Improving / Stable / Declining) using one of the arrows below.

Declining **Improving** **Stable**

Note: the notions of effects on Ecosystem Services are addressed in Questions 3 and 4.

6. Question 3: What has been the level of ecosystem services generated by the considered system (as affected by plant disease) in the past 30 years?

suggested length: 10-20 lines

This question shifts to the notion of **performance of plant systems under disease**. Performance is **scaled on the three types of Ecosystem Services**.

To address this question, each Lead Scientist needs to consider the Ecosystem Services which are generated by the considered system. **Please see the table** at the end of this template. **For some PlantSystems**, **only one Service** needs to be considered; **for others, two services** need to be considered (**and two responses** are requested for this question).

For each Ecosystem Service considered, the question asked amounts to the following: "How has this Ecosystem Service, as affected by plant health, been performing in the past 30 years?"

This question concerns the levels: (1) of **Provisioning Services**, (2) of **Regulating Services**, and (3) of **Cultural Services,** as affected by plant health

Please provide reference(s).

Please summarise your answers to this question (**one per each ecosystem service considered**) on a 5-point scale (Excellent / Good / Fair / Poor / Bad) using the coloured squares below.

Excellent **Good** **Fair** **Poor** **Bad**

Notes: the notions of trend over time for each Service are addressed in Question 4.

7. Question 4: How has the effect of plant health on the generation of the considered Ecosystem Services evolved over the recent 10 years?

suggested length: 10-15 lines

This last question complements the previous one in providing **trend(s)** over a ten year period.

For each of the Services reported in the previous Question 3, a trend is requested: has the generation of the considered service, as affected by plant health, been "Improving" / "Stable" / "Declining"?

Please provide references.

Please summarise your answers to this question (**one answer per each ecosystem service considered**) on a 3-point scale (Improving / Stable / Declining) using one of the arrows below.

Declining **Improving** **Stable**

8. Complementary information

suggested length: 10-15 lines

This is an open section, where each team (Lead Scientist and Experts) wants to complement information given in the report. This information pertains to critical aspects that are overlooked in answering in a simplistic way the questions of the report. These aspects may pertain, for example, to:

- the physical environment: climate change may be associated with (1) changes in the frequency / intensity of disease. The physical environment includes droughts, fires, and any element of the physical environment considered appropriate by the team.

- the biological environment: plant diseases may be related to the biological environment in many ways. In forest systems or urban systems, pathogens and insects may for instance be associated with tree decline; or, micro-organisms that are antagonists to pathogens may also be affected by a given dynamics/process. Please note that vectors of pathogens (arthropods, nematodes) are integral part of "disease" as addressed in Question 1.

- the social or economic environment: major shifts in systems are the results of social or economic changes. This may change (1) the disease status, (2) the level-importance of Ecosystem Services. This can be included, as appropriate.

Lastly, and importantly, please provide **your own assessment of the findings of the present report** -- how confident are you in your findings in this report. This can be scaled as follow:

1. very confident: many studies, publications, support your views. There are only few gaps in the literature.

2. reasonably confident: a number of studies, publications, support your views. There are gaps in the literature.

3. uncertain: there are very few studies, publications, to support your views. There are major gaps in the literature.

This section may prove to be extremely valuable for the Global Plant Health Assessment, in developing its conclusions. Any insight is useful.

Please provide references.

Annex: Suggested Ecosystem Services to consider by [PlantSystem x Ecoregion]

These are **only suggestions** towards Lead Scientists, who ultimately have to decide. It is very important to consider more than one group of Ecosystems Services whenever this makes sense, ***irrespective*** of the literature.

The diversity of Ecosystem Services is a main feature of the Assessment.

PlantSystem	World Eco-region	Main Ecosystem Service			Key Plant(s)/Crop
		P provisioning	R regulating	C culture	
Cereal systems	NW Europe	P			Wheat
	N. America	P			Wheat and Maize
	S. America	P			Wheat
	South Asia	P			Rice and Wheat
	East Asia	P			Wheat
	East Asia	P			Rice
	SE Asia	P			Rice
	SS Africa	P			Maize
	Australasia	P			Wheat
Roots & Tubers	South Asia	P			Potato
	East Asia	P			Potato
	SS Africa	P			Cassava
	NW Europe	P			Potato
	S. America	P			Potato
Banana & Plantains	SS Africa	P			Banana and Plantains
Fruit trees & Grape	NW Europe	P		C	Grapevine
	SE Asia	P			Mango
	N. America 1	P			Fruits and nuts
	N. America 2	P			Grapevine and almond
Horticultural Systems	South Asia	P		C	Multiple
	SE Asia	P		C	Multiple
	SS Africa	P		C	Multiple
Urban Vegetation	NW Europe		R	C	Plane tree
Forests	Amazon		R	C	Multiple
	Australasia		R	C	Eucalypts
	Europe	P	R	C	Oaks
	North Europe	P	R		Multiple
	N. America 1	P	R		Multiple
	N. America 2	P	R		Oaks