GLOBAL STRATEGY FOR THE CONSERVATION AND USE OF YAM GENETIC RESOURCES

With support from

CROP TRUST

The International Treaty
ON PLANT GENETIC RESOURCES
FOR FOOD AND AGRICULTURE

Federal Ministry
of Food
and Agriculture

Table of Contents

DISCLAIMER

This report aims to provide a framework for the efficient and effective *ex situ* conservation of globally important collections of edible yams (*Dioscorea* spp.*).* The Crop Trust supported this initiative and commissioned CIRAD to coordinate the development of the strategy. The overall objective is to share the responsibility for maintaining in perpetuity a representative sample of edible *Dioscorea* spp. diversity in *ex situ* collections and to facilitate its use for food security. The Crop Trust considers this document to be an important framework for guiding the allocation of its resources. However, the Crop Trust does not take responsibility for the relevance, accuracy or completeness of the information in this document and does not commit to funding any of the priorities identified. This strategy document (dated 15 November 2021) is expected to continue to evolve and be updated as and when circumstances change or new information becomes available. Please direct any specific questions and/or comments to the strategy coordinator (Vincent Lebot, email: lebot@vanuatu.com.vu or vincent.lebot@cirad.fr).

ACKNOWLEDGMENTS

This 2021 edition of the *Global Strategy for the Conservation and Use of Yam* builds on the first strategy (2010). It goes beyond the focus on *ex situ* conservation of *Dioscorea* genetic resources to include priority actions in the areas of germplasm characterization, evaluation and genetic improvement. We consider this global strategy to be a collaborative effort, which could not have been accomplished without both individual and group contributions. We would like to thank all who participated actively in discussions and in reviewing the final draft, which was circulated to all partners and yam collection curators, with special thanks to A. Alvarez, R. Asiedu, S. Cuquma, B. Gueye, I.A. Ikoro, A.M. Kouakou, M. Jordan, N. Kien, H. dos Santos Pereira, M.N. Sheela, M.T. Rajanoah, M. Roux-Cuvelier, A. Sukal and L.W. Waqainabete. The contribution of E. Dulloo, who wrote the two chapters on *in situ* conservation, is highly appreciated. Thanks are also due to P. Bissessur for analyzing the GBIF data and preparing the maps. Special thanks are also due to G.V.H. Jackson for his constructive comments on the draft. The present version of the global strategy is therefore the fruit of the work of many yam scientists and conservation and use practitioners, and will be discussed regularly in the near future.

The development of this Crop Conservation Strategy was funded by the Government of Germany (BMEL) as part of the three-year project led by the Crop Trust: "Breathing new life into the Global Crop Conservation Strategies: Providing an Evidence Base for the Global System of *Ex Situ* Conservation of Crop Diversity." The F.A.O. funded the developement of the expanded *in situ* section of this Crop Conservation Strategy.

The information in Annex 4 of this document is a summary of "The plants that feed the world: baseline information to underpin strategies for their conservation and use" a study produced as a collaboration led by the Treaty Secretariat, and funded by NORAD, also involving the Alliance of Bioversity and CIAT and the Crop Trust.

Text from other relevant Global Crop Conservation Strategies (Crop Trust 2006; Crop Trust 2010; MusaNet 2016) was used in some part of this document and adapted to the specific of the yam crop.

AUTHORS

Vincent Lebot (Lead author)

CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement), AGAP (Amélioration Génétique et Adaptation des Plantes), CTRAV (Centre Technique de Recherche Agronomique du Vanuatu), BP 946, Port-Vila, Vanuatu, lebot@vanuatu.com.vu

Ehsan Dulloo (Sections on *in situ* conservation)
International Consultant, Global Crop Diversity Trust

Cover: Yam diversity, by Vanuatu artist John Joseph

Recommended citation: Lebot, V. and Dulloo E. 2021. Global strategy for the conservation and use of yam genetic resources. Global Crop Diversity Trust, Bonn, Germany.

ACRONYMS AND ABBREVIATIONS

ADECAL	Agence pour le Développement Economique de la Nouvelle-Calédonie
AFLP	amplified fragment length polymorphism
CARDI	Caribbean Agricultural Research and Development Institute
CGIAR	Consultative Group on International Agricultural Research
CIAT	International Center for Tropical Agriculture
CIP	International Potato Center
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement
CIS	constant immersion system
CNRA	Centre National de la Recherche Agronomique, Côte d'Ivoire
cpDNA	chloroplast DNA
CRB	Centre de Ressources Biologiques
CSIR	Council for Scientific and Industrial Research, Ghana
CTCRI	Central Tuber Crops Research Institute, India
CWR	crop wild relatives
DaBV	Dioscorea alata bacilliform virus
DAV	Dioscorea alata virus
DbBV	Dioscorea bulbifera badnavirus
DDA/SE	Direction Départementale Agricole du Sud Est, Haiti
DM	dry matter
DNA	deoxyribonucleic acid
ELISA	enzyme-linked immunosorbent assay
FAO	Food and Agriculture Organization of the United Nations
FCRDI	Field Crops Research and Development Institute, Sri Lanka
GBIF	Global Biodiversity Information Facility
GBS	genotyping by sequencing
GRENEWECA	Genetic Resources Network for West and Central Africa
HPLC	high performance liquid chromatography
HPTLC	high performance thin layer chromatography
ICAR	Indian Council of Agricultural Research
IITA	International Institute for Tropical Agriculture
IRD	Institut de Recherche pour le Développement, Montpellier, France
INERA	Institut de l'Environnement et de Recherches Agricoles, Burkina Faso
INIVIT	Instituto de Investigaciones de Viandas Tropicales, Cuba
INRAE	Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement, France
IPGRI	International Plant Genetic Resources Institute
IRAD	Institut de Recherche Agronomique pour le Développement, Cameroun
ITPGRFA	International Treaty on Plant Genetic Resources for Food and Agriculture
ITRA	Institut Togolais de Recherches Agronomiques
KRC	Koronivia Research Station, Fiji
LIPI	Indonesian Institute of Sciences, Bogor
MAS	marker-assisted selection
NARI	National Agricultural Research Institute, Lae, Papua New Guinea
NARO	National Agriculture and Food Research Organization, Japan

NBPGR	National Bureau of Plant Genetic Resources, India
NGS	next generation sequencing
NIRS	near infra-red spectroscopy
NRCRI	National Root Crops Research Institute, Nigeria
PCR	polymerase chain reaction
PGRFA	plant genetic resources for food and agriculture
PGRRI	Plant Genetic Resources Research Institute
PhilRootCrops	The Philippine Root Crop Research and Training Center
PRA	participatory rural appraisal
PRC	Plant Resources Center, Vietnam
RCA	rolling circle amplification
SMTA	Standard Material Transfer Agreement
SNGF	Silo National des Graines Forestières
SNP	single nucleotide polymorphisms
SOP	standard operating procedure
SPC	South Pacific Community, Fiji
SPYN	South Pacific Yam Network
SSR	simple sequence repeats
TCRC	Tuber Crops Research Centre, Bangladesh
TIS	temporary immersion system
UAC	Université d'Abomey-Calavi, Benin
UCC	Universidad de Cordoba, Colombia
UFAM	Universidade Federal do Amazonas, Manaus, Brazil
USDA	United States Department of Agriculture
VARTC	Vanuatu Agricultural Research and Training Centre
WDPA	World Database on Protected Areas
WR	wild relatives
YaV1	yam asymptomatic virus 1
YGIS	yam Germplasm Information System
YMV	yam mosaic potyvirus

EXECUTIVE SUMMARY

Yams (*Dioscorea* spp.) are a staple food for millions of people in tropical countries. They also provide pharmacologically active compounds in traditional medicine and for the pharmaceutical industry. Yams are cultivated in about 50 tropical countries, not all of which provide their annual production statistics to the UN Food and Agriculture Organization. The world annual production is approximately 72 million tonnes of fresh tubers. More than 98% of this is cultivated in Africa, with only four countries (Nigeria, Côte d'Ivoire, Ghana and Benin) accounting for 93% of this output. Latin America and the Caribbean rank a distant second among the three producing regions. Asia and Oceania together account for less than 1% of global production. There are 11 main food yam species (*D. alata, D. bulbifera, D. cayenensis, D. dumetorum, D. esculenta, D. japonica, D. nummularia, D. oppositifolia, D. pentaphylla, D. rotundata and D. trifida*). Yam species are generally dioecious and present male and female flowers on different plants.

For the present study, stakeholders were surveyed in order to gather data about existing *ex situ* collections of relevant *Dioscorea* spp., and the results from returned questionnaires were summarized and analyzed. The number of accessions maintained in the 31 *ex situ* collections identified varies greatly depending on the yam species. Not surprisingly, the most represented species are the two major cultivated yams, *D. alata* (4,524 acc.) and *D. rotundata* (6,358 acc.), which are well preserved in most countries. Minor species are poorly represented in all collections, with the exception of *D. esculenta* (668 acc.). As expected, in West Africa, important *ex situ* collections exist in the major producing countries (Nigeria, Benin, Togo, Ghana, Côte d'Ivoire), with IITA's international collection (5,839 acc.) accounting for 42.6% of the total number of accessions maintained in *ex situ* collections in the world (13,706 acc.). Most collections are funded by governments (or through institutions funded with public grants). Unfortunately, in many countries, the collections are not used regularly for breeding or scientific studies or to supply germplasm. This low use increases their vulnerability because of the high costs involved in their management and maintenance. Very often, few staff fully funded by their home institutions are involved in full-time maintenance and characterization work.

The overall objective of the proposed Global Strategy for the Conservation and Use of Yam is the effective, permanent conservation of the maximum edible *Dioscorea* spp. diversity, through a network of *ex situ* collections that actively contribute to and benefit from common standards and techniques and the effective exchange of both germplasm and information.

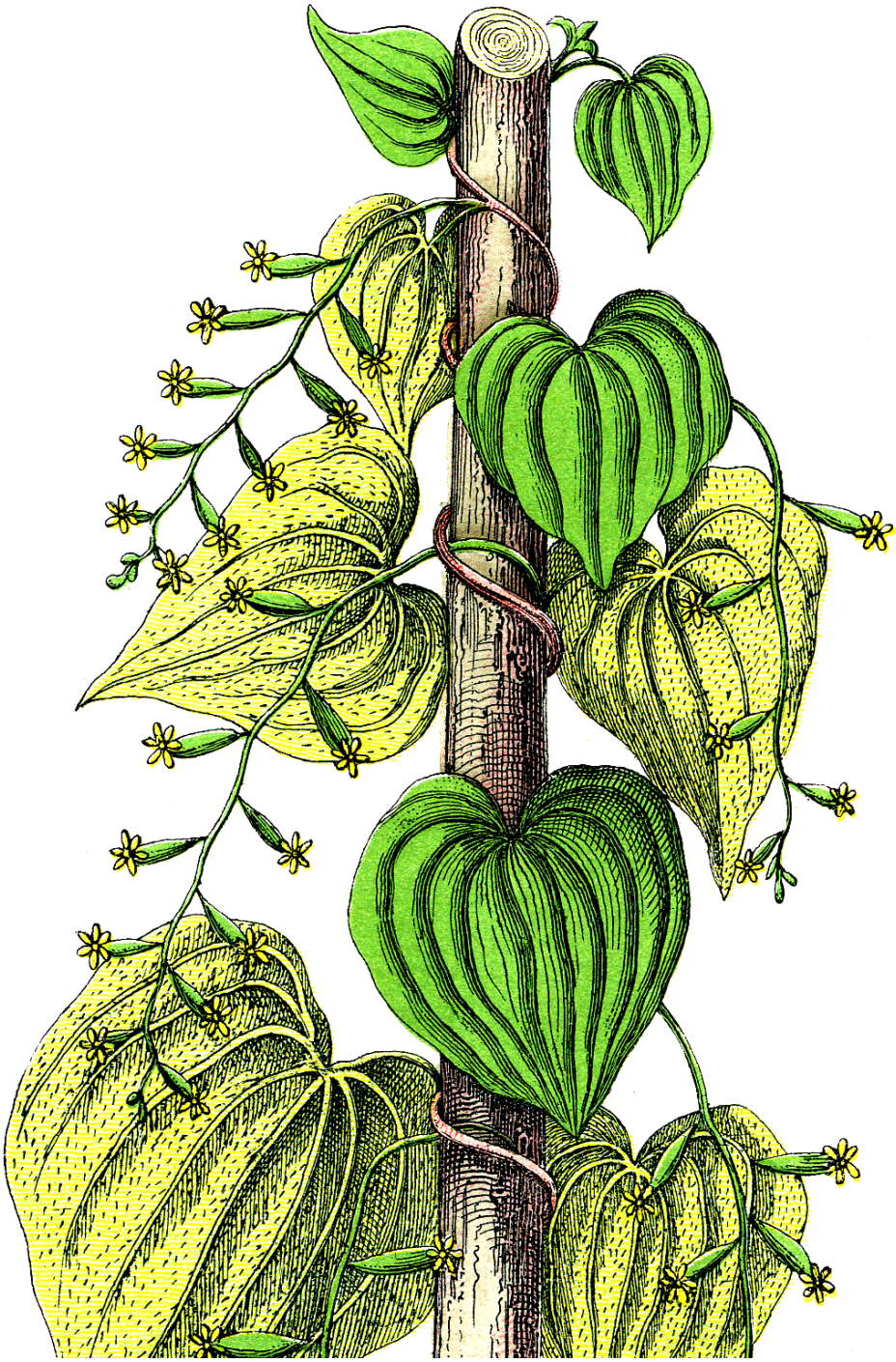
This global strategy adopts a threefold approach:

1) To stratify *D. alata*, *D. rotundata* and *D. cayenensis* germplasm based on ploidy and sex and to detect duplicates using molecular markers if needed.

2) To assemble elite subsets for each of the 11 *Dioscorea* spp. from among elite cultivars (approximately 10% of the total number of accessions) selected according to their tuber shape, tuber quality and tolerance to major diseases.

3) To collect, produce, exchange and preserve true seeds from wild relatives and selected cultivars to broaden the genetic base of collections for future use in breeding programs.

The technical and financial constraints that curators will face in implementing this global strategy are detailed. A project proposal is outlined, and its implementation, governance and funding needs are discussed.



***Dioscorea alata*, illustration from *Naturgeschichte des Pflanzenreichs* CREDIT: Gotthilf Heinrich von Schubert / Wikimedia**

ABOUT THIS STRATEGY

The Crop Trust commissioned CIRAD to coordinate the development of a global conservation strategy for edible yams. To complete this task, CIRAD sought the assistance of experts worldwide, to form a consortium to bring about a consensus on each of the edible yam species (*Dioscorea* spp.) of concern.

To facilitate the process, it was agreed to:

- Conduct background research using the relevant scientific literature.
- Liaise with stakeholders to gather data on existing *ex situ* collections of relevant *Dioscorea* species.
- Analyze and summarize data on existing *ex situ* collections of relevant *Dioscorea* species, including data obtained through surveys.
- Contribute to organizing and participate in virtual meetings of crop stakeholder communities for relevant *Dioscorea* species.
- Provide written content for yam (*Dioscorea* spp.) conservation strategies.
- Liaise with other experts to get input and feedback on crop diversity tree(s).
- Liaise with other experts to get input and feedback on the draft of the global conservation strategy.

The process started in August 2020. A questionnaire was developed (Annex 1) and sent worldwide to 105 partners, curators of yam collections and other relevant experts, in order to obtain the information upon which a comprehensive strategy could be based. The home institutions, names and email addresses of the persons to whom the questionnaire was sent, as well as those invited to take part in developing the strategy, are provided in Annex 2.

The information provided by respondents was incorporated into the strategy, which was then circulated for review and comments. This global strategy is therefore the product of experts' opinions and detailed discussions among a range of stakeholders involved in the conservation and use of edible *Dioscorea* spp. genetic resources since 2010, when the first global strategy was developed by the Crop Trust (Crop Trust 2010).

The present document is divided into three sections:

- Section 1 reviews the existing knowledge and literature on the conservation and use of edible *Dioscorea* spp. diversity (basic information from Lebot 2020 and updated).
- Section 2 presents information on existing *ex situ* collections and analyzes the data provided by curators in their returned questionnaires (14 August 2020 – 15 September 2020).
- Section 3 sets out the Global Strategy for the Conservation and Use of Yam and formulates recommendations for its implementation.

The development of this Crop Conservation Strategy was funded by the Government of Germany (BMEL), through its Federal Office for Agriculture and Food (BLE) as part of the three-year project led by the Crop Trust: "Breathing new life into the Global Crop Conservation Strategies: Providing an Evidence Base for the Global System of *Ex Situ* Conservation of Crop Diversity." The F.A.O. funded the developement of the expanded *in situ* section of this Crop Conservation Strategy.

1 BACKGROUND RESEARCH AND LITERATURE REVIEW

1.1 GEOGRAPHIC DISTRIBUTION

Yams (*Dioscorea* spp., Dioscoreaceae, Monocotyledons) are a staple food for millions of people in tropical countries. They also provide pharmacologically active compounds in traditional medicine and for the pharmaceutical industry. In most yam species, the tubers are renewed and produced annually; in some, they are perennial. Unlike other tropical root and tuber crop species, major cultivated yam species are dioecious and present male and female flowers on different plants. Yams are harvested every season and replanted using tuber pieces to regenerate the plant. Yam tubers can be stored for 4–6 months in ambient tropical conditions without significant deterioration of their nutritional properties. In many regions, yams play a very important part in the cultural life of the people, especially in the "yam belt" of West Africa but also in parts of Asia, the Caribbean and the Pacific (Table 1.1).

Yams are cultivated in about 50 tropical countries. According to the available FAO statistics, the world annual production is approximately 72 million tonnes of fresh tubers. However, this figure is likely to be very conservative, as many countries where yams are cultivated (Lebot, personal field observation) do not provide their statistics to the FAO. Even in countries that do provide yam statistics, it is very difficult to be accurate as yams are often intercropped with other species and/or cultivated in small plots by smallholders and are not recorded in official surveys.

More than 98% of the world's yam production is cultivated in Africa, with only four countries (Nigeria, Côte d'Ivoire, Ghana and Benin) accounting for 93% of this output, or more than 67 million tonnes per year (FAOSTAT 2020). Latin America and the Caribbean rank a distant second among the three producing regions. Asia and Oceania together account for less than 1% of global production.

In most countries, yam farmers maintain a wide range of genetic diversity (Scarcelli et al. 2005a; Scarcelli et al. 2006; Camus and Lebot 2010) but, as pressures on land availability increase, fewer cultivars are grown, thus intensifying the effects of yam diseases. However, increases in production in West Africa during the past two decades were due largely to increases in cultivated area rather than in yield per hectare (FAOSTAT 2020b). Through the diversity of cultivated species, cultivars and adaptation to various ecological zones and maturity periods, yams bring great flexibility to the annual cycle of food supply. The long tuber dormancy (2–4 months at ambient temperatures) ensures sufficient storage life. Yam production faces various technical constraints, but opportunities exist for expanding the consumption of yams. Urbanization is leading to rapid changes in diets, and the overall trend in developing countries is toward the consumption of more processed foods, such as ready-to-use yam flours.

The international trade in yam is fairly limited, probably because the product has a rather low economic value. However, there are some ethnic markets in Europe for West African countries (Ghana is the main exporter), in the USA for Central American countries (Costa Rica is the main exporter) and in Australia and New Zealand for Pacific island countries.

Additional information on the economic importance of yams is reported in Annex 4, which summarizes the relevant results from the study "The plants that feed the world: baseline information to underpin strategies for their conservation and use." (Khoury et al. 2019).

Table 1.1 Major yam-producing countries, 2018 Source: FAOSTAT (2020). *The accuracy of the very high average yield reported from Ethiopia is questionable.

Region	Country	Production (000 t)	Area (000 ha)	Average yield (t/ha)
Africa	Nigeria	47,532	5,990	7.9
	Ghana	7,853	448	17.5
	Côte d'Ivoire	7,256	1,313	5.5
	Benin	2,944	217	13.6
	Ethiopia*	1,356	45	30.1*
	Togo	859	94	9.1
	Cameroon	675	59	11.4
	Chad	485	51	9.5
	Central African Republic	513	60	8.6
	Gabon	227	42	5.4
	Sudan	187	86	2.2
	Guinea	188	20	9.4
	D. R. Congo	90	21	4.3
Latin America & Caribbean	Haiti	424	42	10.1
	Colombia	419	41	10.2
	Brazil	251	26	9.7
	Jamaica	148	9	16.4
	Cuba	87	15	5.8
	Venezuela	47	5	9.4
	Costa Rica	23	1.6	14.4
	Dominican Rep.	15	5	3.0
	Panama	12	5	2.4
	Guyana	2.3	0.3	7.7
	Saint Vincent	2.3	0.2	11.5
Asia & Oceania	Papua New Guinea	376	21	17.9
	Japan	164	7	23.4
	Solomon Islands	47	4.2	11.2
	Philippines	15	2.5	6.0
	Samoa	7	1.8	3.9

1.2 DOMESTICATION

A range of *Dioscorea* species have been domesticated independently in Latin America, Africa, Madagascar, South Asia, Southeast Asia, Australia and Melanesia. Of the more than 640 *Dioscorea* species (Govaerts et al. 2007), 11 are staple crops. In addition, many varieties of wild yams are important in times of food scarcity and for medicinal purposes. These 11 staple crops are:

- *D. alata* L., greater yam, water yam, winged yam (Southeast Asia, Melanesia)

- *D. bulbifera* L., aerial yam, bulbil-bearing yam (Latin America, Africa, Asia, Melanesia)
- *D. cayenensis* Lam., yellow Guinea yam (West Africa)
- *D. dumetorum* (Kunth) pax, sweet yam (West Africa)
- *D. esculenta* (Lour.) Burkill, lesser yam, Asiatic yam (Southeast Asia, Melanesia)
- *D. japonica* Thunb., glutinous yam, Japanese yam (Japan)
- *D. nummularia* Lam., Pacific yam, spiny yam (Melanesia)
- *D. oppositifolia* L., Chinese yam (China)
- D. pentaphylla L., five-leaved yam (Southeast Asia, Melanesia)
- *D. rotundata* Poir., white Guinea yam (West Africa)
- *D. trifida* L., aja, aje, cush-cush, yampi (Latin America).

The greater yam and the two Guinea yams are the major cultivated species; the other eight are referred to as the minor yams. With the exceptions of *D. cayenensis/D. rotundata* and *D. japonica/D. oppositifolia*, all cultivated species are clearly defined and are easy to differentiate morphologically.

Yams were among the first plant species to be domesticated. Tubers may have been cooked on the fire, and pieces rejected from cooking might then have taken root and grown, indicating the possibility of vegetative propagation and cultivation (Coursey 1967). Abundant starch grains of *D. alata, D. bulbifera, D. esculenta, D. nummularia* and *D. pentaphylla* were extracted from stone tools found on archaeological sites in the New Guinea Highlands and dated 46,000 BP (Summerhayes et al. 2010). However, it has been argued that the processing of yam commenced around 10,200 BP in the New Guinea Highlands, which indicates that they are likely to have been integrated into cultivation practices by that time (Fullagar et al. 2006).

Dioscorea cayenensis and *D. rotundata* were domesticated in West Africa by nomadic Paleolithic peoples while food gathering. A tuber from a wild plant can be removed without fatal damage to the vine; the plant will recover and produce another tuber a year or so later. It is possible that hunter-gatherers noticed this interesting phenomenon and returned regularly to harvest edible wild forms. This process could have started c. 7000 BP for West African yams (Dumont et al. 2006), although there is no accurate dating to support this hypothesis. It has been suggested that African yam production expanded from the Niger River basin (Scarcelli et al. 2019). The yam domestication process has been described in great detail for West African species (Dumont et al. 2006). Yams are selected for domestication based mainly on their physicochemical characteristics, with the aerial morphological traits of less importance. Cultivated and wild forms do not differ greatly morphologically, but they do have chemical differences. Wild forms produce some secondary metabolites, which protect them from predators.

In West Africa, the wild species used for domestication are *D. abyssinica*, *D. praehensilis* and *D. burkilliana*. The morphological transformations induced during the domestication process cannot be controlled genetically, and other biological variations also play an important role (Dumont et al. 2006). In West Africa, some cultivars are clones of edible wild forms, and a few putative wild forms probably escaped cultivation. Some cultivars are also clones of hybrids between wild forms and feral or cultivated plants. Through domestication, farmers increase genetic diversity via sexual reproduction of wild and possibly cultivated genotypes. This practice allows farmers to select cultivars with new genetic combinations. This system ensures cultivation of the best (i.e. currently preferred) genotypes, while preserving the potential for future adaptation (Scarcelli et al. 2005a; Scarcelli et al. 2006). Whole-genome

sequencing of wild and cultivated African yam provides evidence that *D. praehensilis* is the most likely progenitor of *D. rotundata* (Scarcelli et al. 2019). *Dioscorea dumetorum* is still being domesticated (Laly et al. 2019).

With a few minor differences, this process is common to yam species cultivated in other geographic regions. In Melanesia, the domestication of wild forms of *D. nummularia* is an ongoing process in the Solomon Islands and Vanuatu. The current domestication observed and documented in Melanesia and Africa is most likely very similar, if not identical, to the practices of hunter-gatherers thousands of years ago.

Dioscorea alata was previously thought to result from interspecific hybridization between two Asian species (*D. hamiltonii* and *D. persimilis*) (Burkill 1960), but these two are synonyms (Wilkin et al. 2007). However, DNA (AFLP) markers indicate that *D. alata* has a common genetic background with *D. nummularia* (Malapa et al. 2005), a species found only in eastern Indonesia and Melanesia. This geographic region is also the center of diversity of *D. alata* (Martin and Rhodes 1977). Moreover, the fact that fertile tetraploid males with 80 chromosomes are absent from India (Abraham and Nair 1991) but present in Melanesia (Abraham et al. 2013) might be an indication of an independent and early domestication process in New Guinea and Melanesia. However, studies with broader sampling of wild and cultivated species, including specimens from Southeast Asia and New Guinea, are necessary to elucidate the origin of this highly polymorphic species (Chaïr et al. 2016).

When the Austronesians colonized Madagascar approximately 2,000 years ago, it was very likely that they introduced *D. alata*, along with bananas (*Musa* spp.). From there, *D. alata* could have spread to East Africa and later to Central Africa, and thence to the yam belt of West Africa. The slave trade and the establishment of Spanish colonies in the Caribbean probably contributed to the movement of Guinea yams (*D. cayenensis* and *D. rotundata*). At the end of the 16th century, D. alata, also imported from the Portuguese trading base on the island of São Tomé in the Guinea Gulf, was cultivated in the Caribbean. Only a few clones were distributed, and the genetic base is narrow (Sharif et al. 2020).

Dioscorea esculenta is an ancient crop in the Pacific, as revealed by the dating of starch grains from Viti Levu, Fiji, to 3050–2500 BP (Horrocks and Nunn 2006). Dioscorea esculenta was probably already being cultivated in Papua New Guinea and the Solomon Islands when Austronesian sailors took it into the Pacific islands.

Dioscorea bulbifera is still under domestication in Melanesia, where toxic wild forms occur spontaneously, but the species is pantropical and it is possible that it could have been domesticated elsewhere, as indicated by the different chloroplast DNA gene pools (Terauchi et al. 1991).

Dioscorea trifida is certainly the only American species to have been domesticated by the Amerindians.

Dioscorea hispida Dennst. (section Lasiophyton) is occasionally consumed in Indonesia and the Philippines but first needs to be detoxified in water.

Dioscorea transversa L., the pencil yam, was domesticated by Indigenous Australians.

Many wild relatives of the edible yams cited above are now endangered. They have been overexploited, for medicinal purposes or for food, or their natural habitat has been destroyed (Scarcelli et al. 2006; Wilkin et al. 2007).

1.3 TAXONOMY AND CLASSIFICATION OF EDIBLE DIOSCOREA SPECIES

The genus *Dioscorea* is the type genus of the family Dioscoreaceae and is the largest genus within this

family, with 644 known species (Govaerts et al. 2007). Many wild *Dioscorea* species are used as medicinal plants or as famine foods in Asia (Wilkin et al. 2007), Africa (Maurin et al. 2016; Magwé-Tindo et al. 2015; 2018) and the Americas (Couto et al. 2018). All Dioscorea species are dioecious twining climbers that produce dry capsules. The genus *Dioscorea* is divided into sections according to their taxonomic status. The 11 main food yam species belong to five taxonomic sections:

- Enantiophyllum (*D. alata, D. cayenensis, D. japonica, D. nummularia, D. oppositifolia, D. rotundata*)
- Combilium (*D. esculenta*)
- Opsophyton (*D. bulbifera*)
- Macrogynodium (*D. trifida*)
- Lasiophyton (*D. dumetorum*, *D. pentaphylla*).

The Enantiophyllum section hosts three different gene pools: Africa (*D. cayenensis* and *D. rotundata*), temperate Asia (*D. japonica* and *D. oppositifolia*) and tropical Asia (*D. alata* and *D. nummularia*). In each gene pool, cultivated species have different wild relatives (WR). Species in the Enantiophyllum section twine to the right (clockwise), and those in the Combilium, Opsophyton, Macrogynodium and Lasiophyton sections twine to the left. The Enantiophyllum species usually produce one to three large tubers, while the Combilium species (*D. esculenta*) and Macrogynodium species (*D. trifida*) produce a greater number of smaller tubers. The stems may be winged, spiny or spineless, hairy or glabrous, and circular, rectangular or polygonal in section (Coursey 1967). Some species (*D. cayenensis*, *D. esculenta* and *D. nummularia*) have spiny stems, especially at their base, to protect the plant and to assist in supporting the young stem. The length of the stem varies from a few meters for *D. esculenta* to more than 15 m for *D. nummularia*.

Dioscorea alata, *D. bulbifera* and *D. pentaphylla* produce bulbils in the axils of the leaves. These bulbils contribute to the vegetative propagation of the plant in natural conditions. Depending on the genotypes, some are toxic, while others are appreciated for their fine texture and taste (*D. bulbifera*). The bulbil production trait means some genotypes can be invasive and weedy (Wheeler et al. 2007).

The leaves are always carried on long, not sheathing, petioles and are usually simple and cordate, but can also be lobed, consisting of three leaflets (*D. dumetorum*, *D. trifida*) or five leaflets (*D. pentaphylla*). Each leaf or leaflet has three primary nerves joining at the tip of the lamina. The leaves vary in size between species, between cultivars and between different parts of a single plant.

The flowers are usually unisexual. Many cultivars flower only rarely and, even more rarely, set fertile seeds. Within all species, there are more male than female plants, and male flowers are usually more numerous than female ones. The flowers are supposedly entomophilous and, being insignificant in color but sweetly scented, are thought to be pollinated by night-flying insects and thrips that do not require visual attraction. Each loculus of the ovary contains two ovules (Govaerts et al. 2007).

The fruits are dry dehiscent trilocular capsules (1–3 cm long) and, theoretically, each fruit can produce six seeds. The seeds are flat and light, and their wings are an efficient aid to their wind dispersion. Species such as *D. alata* and *D. esculenta* are not found in the wild state, but were probably distributed over very wide geographic areas before humans and pigs started to deplete natural resources.

Some *Dioscorea* species are so variable morphologically that taxonomists have attempted to describe botanical varieties to organize this intraspecific variation hierarchically. For example: *D. alata*, var. *tarri* and var. *vera*; *D. esculenta* var. *spinosa* and var. *fulvidotomentosa*; *D. japonica* var. *japonica*, var. *nagarum*, var. *oldhamii*, and var. *pilifera*; and for *D. pentaphylla* at least 11 botanical

varieties have been described (Govaerts et al. 2007).

Hence, for *Dioscorea* species, the term "variety" corresponds to a taxonomic classification, and it is more appropriate to designate farmers' varieties (or landraces) as "cultivars."

1.3.1 Brief description of cultivated Dioscorea species

D. alata **L. (Enantiophyllum):** The greater yam is the most widely distributed species. Together with *D. rotundata*, it accounts for the bulk of world production. In most tropical countries, it is the preferred species because of its ease of cultivation, taste and long postharvest life. In West Africa, however, it is considered to be inferior for the production of the local dish fufu. It is susceptible to anthracnose (*Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc.). Great variation exists and tubers present all sorts of shapes. The flesh color can vary from bright white to a deep purple. The leaves vary greatly in size and form. When flowering, male and female plants of equivalent ploidy levels are planted together, and the female cultivars produce several hundred fertile seeds every year.

D. cayenensis **Lam. (Enantiophyllum):** The species status of *D. cayenensis* is debated. It has been considered to be a group of cultivars of *D. rotundata* (Dumont et al. 2006). Govaerts et al. (2007) consider there to be two subspecies of *D. cayenensis* (subsp. *cayenensis* and subsp. *rotundata*). Debate continues between "splitters" and "lumpers." *D. cayenensis* was described by Lamarck in 1792 (based on a specimen from Cayenne, French Guyana), and *D. rotundata* was described by Poiret in 1813 (based on a specimen from Puerto Rico), but their descriptions were not sufficient to differentiate the two species. The Plant List considers *D. rotundata* Poir. to be a synonym of *D. cayenensis* subsp. *rotundata* (Poir.) J. Miège (www.theplantlist.org). *Dioscorea cayenensis* bears the same chloroplast DNA as *D. rotundata* (Chaïr et al. 2005), but other studies clearly separate the two taxa (Asiedu and Sartie 2010; Sartie et al. 2012).

D. rotundata Poir. (Enantiophyllum): The growth cycle is 6–8 months and varies between cultivars. The tubers are produced in pairs or in small groups of four or five and have a long dormancy period of up to five months. Tuber shapes vary, but the flesh of the white Guinea yam does not vary much in color. The tuber skin is dark and smooth and nearly free of rootlets. Cultivars are grouped into double-harvest or early-maturing yams and single-harvest or late-maturing yams.

D. bulbifera **L. (Opsophyton):** The flowers are larger than other Dioscorea spp. and have spreading perianths. Fertile seeds are produced easily and, in some cases, *D. bulbifera* can be very invasive and behave like a weed. This species is characterized by the profuse production of large bulbils located at the base of the petioles. The largest bulbils can reach a diameter of 15 cm and a weight of 2 kg, but average 300–500 g. Wild forms are not edible. Bulbils vary in shape, skin color, skin texture, flesh color and taste. Some cultivars produce palatable tubers. The species is found in the wild state in Africa, Asia and Oceania and is now cultivated throughout the tropics.

D. dumetorum **(Kunth) Pax (Enantiophyllum):** This species is widely cultivated in eastern Nigeria and in Benin. It is very high yielding, and the tubers may be single or form a cluster. The leaves are trifoliate, which differentiates this species from other edible and cultivated African yams. There are some toxic wild forms unsuitable for consumption. The leaves are susceptible to anthracnose. The tubers can be boiled without being peeled. There is considerable varietal diversity in Benin (Laly et al. 2019).

D. esculenta **(Lour.) Burkill (Combilium):** Numerous cultivars exist across India, Southeast Asia and the Pacific islands. However, compared to other cultivated species, morphological variation is

limited. The individual tubers are small and are produced in a considerable number per plant, about 5–20 annually. The tuber flesh color varies from pure white to a deep purple. The tubers are of good palatability, have a soft flesh texture and are free from toxicity and bitterness. In New Guinea, the species is replacing *D. alata*, which is contributing to the latter's genetic erosion. In West Africa, it is considered less desirable because its low dry matter (DM) makes it unsuitable for fufu.

D. japonica Thunb. (Enantiophyllum): This species is mostly cultivated in Japan (where it is called Yamaimo), including in the Ryukyu and Bonin Islands, as well as in Korea and Taiwan. In these places, it is highly appreciated. It is morphologically very similar to *D. oppositifolia*, and some authors consider the two species to be conspecifics. However, they are considered different species in the most recent taxonomic review of the Dioscoreaceae (Govaerts et al. 2007). The plant produces bulbils, and the long smooth tubers can be eaten raw.

D. oppositifolia L. (Enantiophyllum): This species, often called *D. opposita*, is the major yam of economic importance grown in temperate regions. The tubers are spindle-shaped, grow up to 1 m long and are relatively thin, with an average diameter of 8–10 cm. They descend vertically into the ground, and their cultivation requires intensive land preparation to ease harvest. There are numerous cultivars, and the trend is to select those with a more compact tuber shape. It is also known under the name of *D. polystachya* Turcz. (Govaerts et al. 2007) and is cultivated throughout China. The species is poorly described, and it is possible that different species are lumped together under this taxa.

D. nummularia Lam. (Enantiophyllum): The tuber flesh varies between cultivars, from white to purple, and some oxidize faster than others. It is the most important species in some parts of New Guinea, Solomon Islands and Samoa (Cable and Wilson 1984). It is hardy, resistant to diseases and high yielding (Lebot et al. 2017). There are natural interspecific hybrids between *D. nummularia* and *D. alata* (Chaïr et al. 2016). These hybrids are greatly valued for their high dry matter (DM) content and good organoleptic quality. Confusion between *D. alata* and *D. nummularia* has been reported in the Philippines (Cruz and Ramirez 1999) and in Indonesia (Sastrapradja 1982). Different species might be included in this taxa.

D. pentaphylla L. (Lasiophyton): This is a highly polymorphic species with numerous cultivars; five botanical varieties have been proposed by taxonomists (var. javanica, malaica, palmata, papuana and sacerdotalis), but their value is debatable. In Melanesia, it is widespread and important, especially in times of scarcity. It is also cultivated in Indonesia. The tubers are not toxic. A plant can produce a yield of 5–10 kg of one or two tubers per plant, after a growth cycle of 10 months. Its fine taste is comparable to Irish potato.

D. trifida L. (Macrogynodium): Numerous cultivars exist, with tuber flesh varying from white to yellow, pink and purple. All have a pleasant aroma and highly appreciated taste. This species originates from northern Latin America (probably in the Guianas) and is very popular in the West Indies (it is called cousse couche in Guadeloupe). It has been introduced into Melanesia, where it is also appreciated for its taste. This species is highly susceptible to viruses, which are responsible for the decline of its cultivation in the West Indies (Degras 1993).

1.3.2 Related species used as medicinal plants

Wild yams are medicinal plants of economic value traded for the properties of their tubers' secondary metabolites, mostly allantoin and steroidal saponins (Chandrasekara and Kumar 2016; Takagi et al. 2016).

Allantoin has antihypertensive action and has the potential to increase the smoothness of the skin (Chen et al. 2014) and to promote cell proliferation and wound healing (Go et al. 2015; Liu et al. 2016).

Steroidal saponins have a number of pharmacological properties, including activities that are cytotoxic, blood pressure-lowering, anti-inflammatory and antifungal. They produce, after hydrolysis, a steroidal aglycone called diosgenin, which is used as a source of steroid hormones by the pharmaceutical industry (Yoon and Kim 2008; Jesus et al. 2016). The global market for diosgenin is approximately 1500 tons/year. Sources are mostly wild *Dioscorea* spp. (Cheng et al. 2015), but these natural resources are undergoing rapid depletion (Deshpande and Bhalsing 2014).

The most traded medicinal wild yam is *D. villosa* L. It is native to North America but, due to habitat loss and over-harvesting, it is currently listed as "at risk" (Pengelly and Bennett 2011). Wild yams should be at least four years old before harvesting. Dietary supplements derived from their tubers are used to enhance the appearance of dry or damaged skin. *Dioscorea villosa* commercial products are known to treat low progesterone levels and reduce post-menopausal symptoms (Avula et al. 2014). *Dioscorea zingiberensis* C.H. Wright is not traded internationally but is sold in China as a treatment for cardiovascular diseases; however, the species is in danger of extinction due to overexploitation (Zhang et al. 2017).

1.4 CYTOLOGY AND PLOIDY LEVELS

The base number of major cultivated yam species is considered to be x = 20. The diploid nature of *2n* = 40 chromosome types of *D. alata* is evidenced from microsatellite marker inheritance. *Dioscorea alata* is a polyploid species with di- (40), tri- (60) and tetraploid (80) cultivars. Triploids would have been produced through the formation of *2n* gametes in diploid females caused by the nonviability of seeds resulting from the formation of *2n* sperm and of the nonviability of intercytotype crosses (Arnau et al. 2009). The tetraploids would have appeared through sexual polyploidization caused by unreduced gametes and the sterility of triploids (Nemorin et al. 2013).

It is observed that higher ploidy levels tend to produce larger tubers. This is quite clear for *D. alata* tetraploids, which produce long and large tubers that penetrate deep into the soil. These are often used as gifts and for ceremonial purposes. Almost two decades of data recording on the harvest of the Vanuatu *D. alata* germplasm collection has shown that, on average, diploids yield 2 kg of fresh tubers/plant, while triploids yield 2.5 kg/plant and tetraploids can yield more than 3 kg/plant. These are low yields obtained with low inputs, and these cultivars have greater yield potential, but the influence of the ploidy level on the yield seems to be confirmed. If tetraploids with compact tuber shape could be developed, they would present a definite advantage in cultivation.

The most widely cultivated yam in West Africa, *D. rotundata*, has 40 and 60 chromosomes (Scarcelli et al. 2005b) and plants are, therefore, diploids or triploids. However, very few accessions have been analyzed for ploidy, and there is an urgent need for a comprehensive screening of germplasm (Girma et al. 2014). For other species, ploidy is not yet confirmed because very few accessions per species have been analyzed (Table 1.2).

Table 1.2 Reported chromosome numbers and ploidy levels in cultivated yams. Source: Araki et al. (1983); Essad (1984); Zoundjihékpon et al. (1994); Daïnou et al. (2002); Mignouna et al. (2002a, b); Scarcelli et al. (2005b); Boussalem et al. (2006); Girma et al. (2014)

Dioscorea spp.	2n numbers	Ploidy levels
D. alata	40, 60, 80	2x, 3x, 4x
D. bulbifera	40, 60, 80, 100	2x, 3x, 4x, 5x
D. cayenensis	40, 60, 80, 140	2x, 3x, 4x, 7x
D. dumetorum	40	2x
D. esculenta	40, 60, 100	2x, 3x, 5x
D. japonica	80	4x
D. oppositifolia	40, 140	2x, 7x
D. nummularia	60, 80, 100, 120	3x, 4x, 5x, 6x
D. pentaphylla	40, 80, 140	2x, 4x, 7x
D. rotundata	40	2x, 3x
D. trifida	60, 80	3x, 4x

Microsatellite marker segregations suggest that the American species, *D. trifida*, also has a base chromosome number of 20 (Boussalem et al. 2006). It is, however, reasonable to assume that other Enantiophyllum species could also have a base number of x = 20. Chromosome counts have been produced, and it is possible to hypothesize that most cultivars could be di-, tri- or tetraploid, or have even higher ploidy levels (e.g. *D. nummularia*). It appears, however, that polyploidy operates actively and that accessions with 40 chromosomes are the most numerous, followed by accessions with 60 and 80 chromosomes. Accessions with 100 chromosomes (*D. bulbifera* and *D. esculenta*), 120 (*D. nummularia*) and 140 (*D. oppositifolia*, *D. pentaphylla* and *D. cayenensis*) have also been encountered.

Various protocols have been developed to count chromosomes in root tips at meiosis. Tips of approximately 1.5 cm long are treated in a suspension of α-monobromo- or chloro-naphthalene. The tips are then fixed in alcohol:acetic acid (3:1) and preserved at 5 °C. The samples are hydrolyzed in HCL and stained with Feulgen (Essad 1984). An alternative, simplified protocol involves the fixation of root tips in alcohol:acetic acid (3:1) without any pretreatment, their storage at room temperature for 48 h and squashing in 2% acetocarmine (Abraham and Nair 1991).

Flow cytometry is a rapid and reliable technique that allows the quantification of DNA content in a large number of nuclei and is of particular interest for yams (Babil et al. 2010; Bhattacharjee et al. 2011). Three different ploidy levels were detected using flow cytometry in Guadeloupe for *D. alata* (Gamiette et al. 1999) and in Cameroon in *D. cayenensis* and *D. rotundata* (Dansi et al. 2001). The ploidy levels of 170 accessions of Guinea yams were determined using flow cytometry; of these, 108 were found to be diploids, 47 were triploids and five were tetraploids. For *D. rotundata*, the majority were diploids, but for *D. cayenensis* this ploidy level was not detected in any of the accessions. Also, no association was found between place of cultivation and ploidy level (Obidiegwu et al. 2009).

A single ploidy level was found across *D. cayenensis* (triploid), *D. praehensilis* (diploid) and *D. mangenotiana* (triploid) accessions, whereas both diploid and triploid accessions were present in *D. rotundata*. SNP markers revealed *D. cayenensis* formed a single genetic group, while *D. rotundata* comprised three separate groups, namely a group of diploids similar to *D. praehensilis*, a group of diploids similar to *D. cayenensis* and a group of triploids. It was concluded that flow cytometry gave results in agreement with chromosome counts and offered a reliable tool for routine ploidy determination in *Dioscorea* spp. (Girma et al.

2014; Muthamia et al. 2014). The genome sequence of *D. rotundata* has been produced, and markers suitable for sex determination have been identified (Tamiru et al. 2017; Girma et al. 2019; Asfaw et al. 2020). For *D. alata*, a high-density SNP genetic map has been developed covering 94% of the genome, and a locus determining sex was identified (Cormier et al. 2019a). There are now efficient molecular tools to screen germplasm and identify sex and ploidy for the three major species: *D. alata*, *D. cayenensis* and *D. rotundata*.

1.5 ATTEMPTS TO STRUCTURE YAM DIVERSITY

1.5.1 Phylogenetic studies

Molecular tools have been used to clarify *Dioscorea* spp. phylogeny. For Asian species, 48 taxa from seven different sections were analyzed using chloroplast markers. The DNA phylogeny confirmed the classification into seven taxonomic sections. In the Enantiophyllum section, the species were found to be closely related, with *D. japonica* clustering with *D. oppositifolia*, *D. formosana* and *D. cirrhosa*. *Dioscorea alata* was found to be closer to *D. hamiltonii* (syn. *persimilis*) than to *D. nummularia*, although the distances between the three species were very small (Hsu et al. 2013). A study conducted using four plastid DNA markers and SSRs confirmed that the Enantiophyllum section was clearly differentiated from the other sections. *Dioscorea alata* was found to be closer to *D. calcicola*, *D. fordii* and *D. glabra,* while *D. hamiltonii* and *D. nummularia* were found to be quite distant from this group with *D. nummularia* being closer to *D. hastifolia* (Viruel et al. 2016), a species endemic to western Australia, which, surprisingly, is morphologically very different. Another phylogenetic tree based on a low-copy nuclear gene (xanthine dehydrogenase, Xdh) confirmed the previous tree and revealed the congruence among plastid and nuclear phylogenetic topologies (Viruel et al. 2018).

The plastid DNA regions (matK, trnLF and atpB) have been used to classify yams in Africa with convincing results (Ude et al. 2019). They were amplified and sequenced to build a tree for 176 taxa, and *D. alata* appeared much closer to *D. nummularia* than to *D. hamiltonii* (Couto et al. 2018). In India, the use of SSRs revealed that *D. alata* was closer to *D. oppositifolia* than to *D. hamiltonii*, *D. pubera*, D. glabra and D. wallichii, although the distances between them were small (Padhan et al. 2019). Soto-Gomez et al. (2019) used 260 low- to single-copy nuclear genes and found *D. calcicola* to be closer to *D. alata* than to *D. nummularia*. Finally, chloroplast genome sequences were used to construct a phylogenetic tree using maximum likelihood for 51 individuals in 58 *Dioscorea* species; in this work, *D. alata* was found to be closely related to *D. persimilis* (syn. *D. hamiltonii*), *D. polystachya* and *D. glabra* (Xia et al. 2019). Comparing these studies is somewhat difficult because they were conducted using different markers and different species. However, overall, they confirm the classification into taxonomic sections but also reveal that some taxa are so close that they might not be different species.

An impressive amount of research has attempted to clarify the taxonomic positions of the two Guinea yams (*D. cayenensis* and *D. rotundata*). Where morphological descriptions are not conclusive, molecular markers add little clarification and may even contribute to the confusion. Molecular and morphological classifications do not necessarily produce matching groups (Dansi et al. 2000; Scarcelli et al. 2011; Kouam et al. 2018; Darkwa et al. 2020c). Studies conducted using chloroplast DNA simple sequence repeats (cpSSR) show that some accessions of *D. cayenensis* and *D. rotundata* have the same haplotype as *D. praehensilis*, suggesting that the three might belong to the same species. A similar case involves three wild species, *D. minutiflora*, *D. smilacifolia* and *D. burkilliana*, which

might be considered to belong to the same species (Chaïr et al. 2005). Part of the problem comes from the insufficient or approximative passport data of the analyzed samples.

SNP analyses reveal that wild Guinea yam populations, *D. togoensis* and *D. burkilliana*, are distant from *D. cayenensis* and *D. rotundata*, whereas *D. abyssinica*, *D. mangenotiana*, and *D. praehensilis* are closer. *Dioscorea cayenensis* forms a single genetic group, while *D. rotundata* comprises three groups (Girma et al. 2014). However, none of the DNA barcode markers (rbcL, matK loci, non-coding intergenic spacer trnH-psbA of the chloroplast genome, and the nuclear ITS regions) can distinguish between the five species groups (*D. rotundata*, *D. cayenensis*, *D. abyssinica*, D. *praehensilis*, *D. mangenotiana*). This could be explained by potential unreliability of previous taxonomic classifications or by a recent genetic divergence among the species (Girma et al. 2015).

Genomic studies provide evidence that the forest species, *D. praehensilis*, is the most likely progenitor of *D. rotundata* (Scarcelli et al. 2019). Using SNP information, it was shown that *D. abyssinica* is of an older lineage than *D. praehensilis* and that the place of origin of *D. rotundata* and *D. praehensilis* is probably in Nigeria or Benin. Some wild species have plastid genomes identical to those of cultivated Guinea yams. This may have originated from gene flow from cultivated yams to wild yams (Sugihara et al. 2020). Conspecificity cannot be excluded.

1.5.2 Use of molecular markers for intraspecific genetic diversity studies

AFLP markers used to assess intraspecific variability among accessions of *D. alata* could not differentiate between Asian, African and Melanesian cultivars. An attempt to classify 333 accessions into groups of related cultivars based on morphological traits and multivariate analyses resulted in 36 groups with no clear matching with AFLP groups. It is observed that clones have been distributed widely, and the diversification process involves fixed somatic mutations, polyploidization and sexual recombination. Hence, the wide variation observed in *D. alata* at the morphological level reflects a genomic plasticity magnified by the outcrossing mating system (Malapa 2005).

Another AFLP study on accessions of diverse geographic origins revealed similar results. The accessions clustered into groups that were a mix of cultivars from different geographic origins, indicating that geography has not played a major role in the differentiation between species. A few accessions clustered very tightly, suggesting that there may be duplicate accessions in the collection. Although *D. alata* is an introduced species in Africa, the genetic variation observed at the AFLP level was found to constitute a good basis for genetic improvement (Egesi et al. 2006).

Dioscorea alata accessions from the Pacific were introduced *in vitro* in Benin and field evaluated for their major morpho-agronomic traits, fingerprinted with SSRs and compared to local cultivars. The introduced accessions are morphologically and genetically well diversified and contribute significantly to germplasm base broadening (Adoukonou-Sagbadja et al. 2014). A global study using SSRs on 384 *D. alata* accessions from Asia, Africa, the Caribbean and the Pacific found wide genetic diversity and structuring associated with ploidy levels (2×, 3×, 4×) and geographic origin. Two gene pools (Vanuatu and India) were differentiated (Arnau et al. 2017, Cormier et al. 2019b).

Another global analysis of 643 *D. alata* accessions that used genotyping by sequencing (GBS) confirmed these results: diploids are more frequent than triploids and tetraploids, clonality is a major factor of variation and domestication occurred independently in Asia and in the Pacific (Sharif et al. 2020). Morphological and molecular

groups do not match (Agre et al. 2019). In China, ISSR and SPRAP markers showed that *D. alata* and *D. persimilis* are well differentiated with low genetic diversity within each species (Wu et al. 2014). The analysis of 142 *D. alata* accessions from China using 186 EST-SSR markers concluded that China might be an important and somewhat isolated domestication center for this species (Wu et al. 2019).

The genetic diversity of yam cultivars from Ethiopia and their relatedness to commonly cultivated species in West Africa has been studied using AFLPs. The results reveal that Ethiopian cultivars are significantly distinct. The groups detected by AFLP markers were found to be consistent with the local yam classification system and also reflect the main structure of morphological diversity (Tamiru et al. 2007). AFLP and chloroplast DNA (cpDNA) were used to study *D. dumetorum* in West and Central Africa. The highest genetic diversity in accessions from Togo and Nigeria indicates that these are the center of origin and diversity of *D. dumetorum* (Sonibare et al. 2010).

Microsatellite markers have been developed for *D. japonica* (Mizuki et al. 2005), the Guinea yams, *D. alata* and minor species, and were found to be very useful tools for germplasm characterization and classification (Tamiru et al. 2015). GBS has also been used to clarify the patterns of diversity within and between *D. rotundata* and *D. cayenensis*. A single ploidy level was detected in *D. cayenensis*, whereas diploid and triploid accessions were present in *D. rotundata*. While *D. cayenensis* formed a single group, it seems that *D. rotundata* is composed of diploids genetically similar to *D. praehensilis*, of diploids similar to *D. cayenensis* and of triploids (Girma et al. 2014).

In Taiwan, the genetic diversity and phylogenetic relationships of *D. japonica* were evaluated using ISSR markers. Accessions belonging to var. *oldhamii* and var. *pseudojaponica* were separated into different groups. The results of this study also suggested that var. *japonica* is a possible intermediate variety between var. *oldhamii* and var. *pseudojaponica*. The northern region of Taiwan is proposed as the center of diversity due to the high genetic diversity (Kung et al. 2016).

1.5.3 Morphological descriptors

Various attempts to determine the intraspecific classification of *D. alata* using a morphological description of aerial and underground organs have failed to produce a clear structure. For example, Martin and Rhodes (1977) suggested 15 different groups after intense morphological description of 235 accessions. The classification was found to have the errors or ambiguities of any within-species classification system. The authors recognized that these groups had weak delimitations and were not taxonomically useful, as only a limited subset of the variation existing within the species was described. A comprehensive list of descriptors was developed by experts in 1980 and revised in 1997 (IPGRI/IITA 1997); the PDF is freely accessible online. This list includes a basic list of descriptors for major edible yam species. These morphological descriptors have been used on a range of species in various countries in an attempt to organize the diversity within germplasm collections. As yam is a tuber crop, tuber shape and tuber quality are essential traits.

In an initial attempt to organize the large IITA collection, the concept of core collection was applied to identify a set of genotypes representative of the diversity maintained across all the germplasm (Mahalakshmi et al. 2007). Another attempt used 56 morphological traits, new accessions and presence of duplicates for six different species. The core included 843 accessions (20.3% of the IITA collection) and reflected the predominance of *D. rotundata* (620 acc.; 73.5%) followed by *D. alata* (180 acc.; 21.4%), *D. bulbifera* (14 acc.; 1.7%), *D. cayenensis* (12 acc.; 1.4%), *D. dumetorum* (12 acc.; 1.4%) and *D.*

esculenta (5 acc.; 0.6%). For both entire and core collection representing all the six species, the largest numbers of accessions in descending order were from Togo, Nigeria and Benin. *Dioscorea rotundata* accounts for about 70% of the entire IITA collection (3113 acc., with only 343 females and 1121 males identified). Of the 620 *D. rotundata* accessions in the core collection, 88.6% were diploid and 11.4% were triploid. Only 300 accessions were flowering (230 male, 64 female) (Girma et al. 2017).

Over the years, collections in Africa, Latin America and Asia have been described using these IPGRI descriptors, and the data have undergone a range of multivariate analyses (Principal Component Analysis, Cluster analyses using various aggregative algorithms). However, no clear morphological groups have been identified. In most studies, it was concluded that no strict division could be achieved on either geographic or morphological grounds. The variation was defined as a "vast continuum." However, for many *Dioscorea* spp., it appears as an interlaced network rather than as a dichotomously branched tree (Martin and Rhodes 1977). There are biological reasons for this complex situation, discussed in the following.

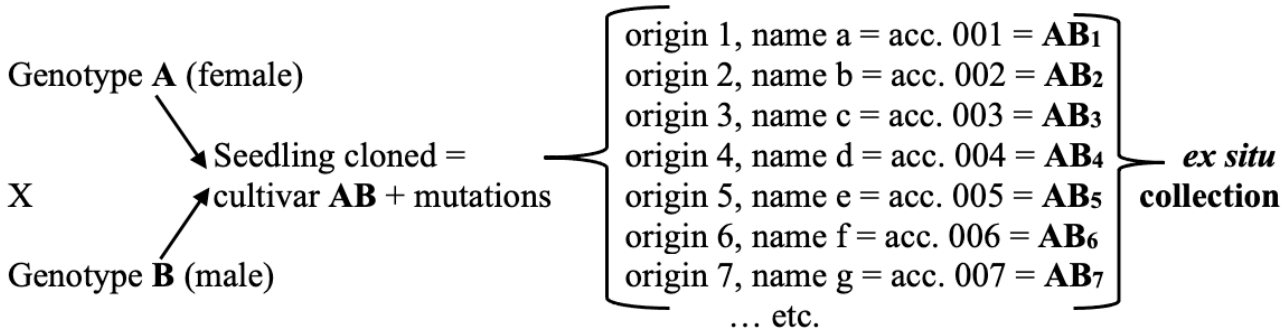
As *Dioscorea* spp. are dioecious with genetically different male and female plants, all seedlings are distinct genotypes and, once propagated vegetatively, are clones of hybrids because they result from crosses between two distinct genotypes. Apomixy has been reported but is minor. In most cases, a genotype is unique and results from a single true botanical seed. "Dioecy decreases the possibility of natural crossing as both sexes need to be nearby and synchronized. Flowering synchrony is rare, and an unbalanced sex ratio within diploids has been reported with dominant male plants (3:1) (Abraham and Nair 1990)" (Vandenbroucke et al., 2016) for *D. alata.* The same is true for other *Dioscorea* spp. as all are dioecious and asynchrony is observed. Consequently, polyploidy and dioecy make it more difficult for farmers to incorporate seedlings in their varietal portfolios, although it has been reported that some farmers are known to do this (Scarcelli et al. 2019).

PHOTO CREDIT: Charlotte Lusty

Dioscorea species, like most polyploidy plants that are propagated asexually, are prone to somatic variation. Phenotypic plasticity (the ability of a genotype to generate a range of phenotypes depending on the environment) may be an important cause of morphological variation. Farmers give different names to different morphotypes. Upon detecting a plant with distinctive variation, they will often give this plant a new name. The name might refer to the most distinctive morphological feature (e.g. anthocyaned leaves) or a chemical characteristic (red tuber flesh), or commemorate the farmer who discovered the plant or its geographic origin (Tamiru et al. 2008).

The same genotype can be dispersed across very wide distances and have a number of different names. 'Florido' from the USDA collection in Mayaguez (Puerto Rico) is known as 'Salemanu' on the island of Efaté (Vanuatu) (Malapa 2005). In such cases, morphologically distinct accessions are in fact clones of the same genotype (Figure 1.1). Vice versa, cultivars acquired from different farmers may have the same name but be genetically different (Sartie et al. 2012).

Figure 1.1 Cultivar AB originates from a single seed, but phenotypic plasticity and somatic mutations can result in different names given to morphologically distinct landraces in different geographic locations, resulting in numerous duplicates maintained in *ex situ* collections.



When clonal lineages are identified using molecular markers (e.g. SSR and DArT markers), many yam accessions maintained in germplasm collections show variation in qualitative traits, such as pigmentation, and quantitative traits, such as tuber shape. This finding suggests that significant variation is produced through clonal propagation (Vandenbroucke et al. 2016). When accessions, often from distant origins, are gathered into a germplasm collection, numerous duplicates are maintained *ex situ*, at high cost. Factors that contribute to changes in the next clonal generation are "size of the propagule, physiological age, chronological age, the nature of the multiplication unit, its position on the mother plant and its composition in nutrients" (Vandenbroucke et al. 2016). For *D. alata*, the low number of unique genotypes and the numerous cultivars with a common clonal origin caused a low varietal richness index (R = 0.26). This low index and the short external branches of the SSR and DArT NJ-trees indicates that sexuality is of secondary importance in the local diversification process (Vandenbroucke et al. 2016).

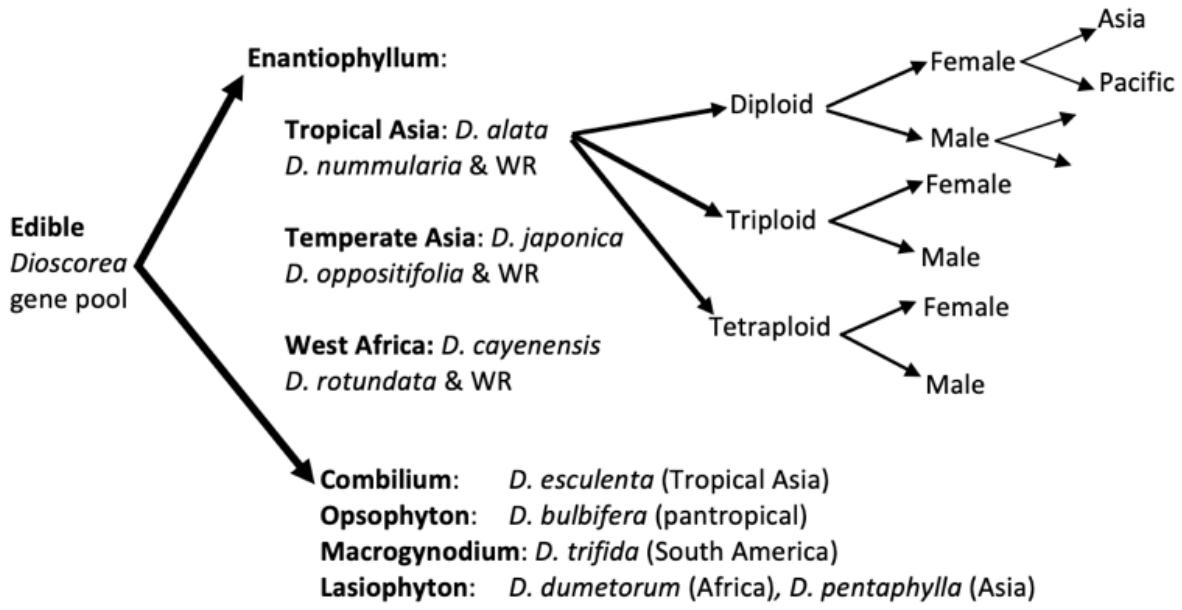
In New Caledonia, the cultivars 'Nouméa blanc' and 'Nouméa rouge' are the non-anthocyaned and the anthocyaned morphotypes of the same genotype. When the two are intensively propagated to produce seed tubers on long lines of plants, it is quite frequent to observe mutants again. In Japan, the tracing of clonal pedigrees and analyses of variance suggested that "these variants may be caused by tissue chimeras resulting from changes in the number or structure of chromosomes. The possibility that transposable elements were involved was not excluded" (Babil et al. 2012). It was concluded that recurrent somaclonal variation affects the genetic diversity of *D. alata* (Babil et al. 2012).

The question is how to detect duplicates using a rational and systematic approach that is more reliable than morpho-agronomic descriptions of qualitative traits. Attempts to structure the diversity of yams tend to favor geographic origins and morphological descriptions of qualitative traits. The results are unsatisfactory, because clones have been distributed across large geographic distances and there are no morphological traits that are correlated significantly with ploidy levels or sex (plants flower rarely). Those with high polyploidy (triploids and tetraploids) are more vigorous and produce larger leaves and tubers, but there is no reliable systematic morphological key to distinguish between them.

As yam is a polyploid dioecious species, hierarchical structuring of the gene pool (Van Treuren et al. 2009) is needed, assigning relative importance to the two essential components: ploidy and sex. The tree in Figure 1.2 offers a suitable representation by organizing the diversity as follows: botanical section > species > ploidy level > sex > origin > tuber shape > chemotype.


PHOTO CREDIT: Charlotte Lusty

Figure 1.2 Diversity structure of the edible *Dioscorea* gene pool. Within the Enantiophyllum section, three gene pools are identified. The major species (greater yam and Guinea yams) belong to two distinct geographic gene pools (West Africa and tropical Asia). Only the stratification of six groups of *D. alata* is shown. The same hierarchical approach, based on ploidy level, sex and region of origin, can be used for other species. Within each subgroup, tuber shape and chemotype can be used for further stratification. WR = wild relatives



1.5.4 Chemotaxonomy

The African species have been studied thoroughly. Research has shown significant variation within *D. cayenensis* and *D. rotundata* for the major components of their tubers (Trèche 1998). Some cultivars have a chemical composition that is well suited to traditional uses (e.g. fufu), whereas others do not. *Dioscorea alata* cultivars with good eating quality are characterized by high DM, starch and amylose content. The amylose (A) versus starch (S) ratio is an important palatability trait. Preferred cultivars seem to have a high A/S ratio, and all cultivars that have tubers with poor eating quality are characterized by a low A/S ratio, high mineral content and high protein content. Chemotypes are controlled genetically and are useful for intraspecific classification (Lebot et al. 1998). For making boiled yam, the best varieties present a smooth tuber appearance (absence of rootlets), ease of peeling, stability of white or yellow color during peeling and cooking, viscosity of cooking water and the ease of breaking the yam piece with a fork. For boiled yam, *D. rotundata* is preferred to *D. alata* in West Africa (Honfonzo et al. 2020).

The total sugar content is another important characteristic. Some cultivars are appreciated for their sweet taste, which has been confirmed analytically by the high sugar content. However, sugar content alone cannot determine quality. Starch, amylose and total sugar content are correlated positively with DM. Mineral, lipid and protein content are correlated positively with each other, but correlated negatively with DM, starch and amylose. Total sugar content is correlated negatively with mineral and protein content. For

recommended cultivars, this often corresponds to a white flesh that is not susceptible to oxidation when exposed to air (Lebot et al. 2006).

Most yam consumers are looking for a nonoxidizing white flesh, low or no sweetness and no bitterness. Dry matter and starch content are determinants for fresh tuber flesh quality and the texture and elasticity in the mouth. Sugar content is responsible for sweetness and browning of the fried yam. For processing yam into fried products, low reducing sugars content is a major quality trait. For processing yam into flour, there is variation between and within yam species: some are nonoxidizing, while others turn brown almost immediately after the tuber is peeled and cut. Browning correlates with total phenol and DM content. It is genetically controlled (Graham-Acquaah et al. 2014).

In West Africa, the key preferred food quality attributes for pounded yam are appearance and textural quality (Otegbayo et al. 2020). The flesh of *D. alata* is usually not as firm as that of *D. rotundata*, which makes *D. alata* less suitable for pounded yam. In Ghana, *D. alata* cultivars have significantly higher moisture and protein content with higher peak time and pasting temperature, compared with *D. rotundata*. Furthermore, *D. alata* has lower DM and starch content, swelling power and pasting viscosities than *D. rotundata* (Wireko-Manu et al. 2011). *Dioscorea rotundata* ('Pona' variety) is recommended for flour production because of its high DM and starch content (Polycarp et al. 2012).

The chemical analysis of tubers is a necessary prerequisite for proper germplasm evaluation, but it is cumbersome and expensive when several hundreds of accessions need to be analyzed. Near infra-red spectroscopy (NIRS) calibrations were developed for use in breeding programs to characterize high numbers of accessions rapidly and at low cost (Lebot and Malapa 2012). An early attempt to predict the dioscin content using NIRS concluded that the accuracy was average because of the low concentration of dioscin (Kwon et al. 2015). Using HPTLC, dioscin and gracillin were detected in *D. cayenensis* and *D. esculenta* but were found to be absent in *D. alata* (Lebot et al. 2018a).

Dioscorea cayenensis, *D. esculenta*, and *D. rotundata* are good sources of allantoin and total saponins. Within *D. rotundata*, some accessions present very high levels of allantoin and saponins. Cultivars or breeding lines that are rich in total saponins could represent a potentially interesting source of raw material for diosgenin production and an alternative to endangered wild species (Lebot et al. 2019a). HPLC analysis of carotenoids in different yams has shown that there is significant variation between cultivars for β-carotene content, but that the β-carotene content of the yellow Guinea yam (*D. cayenensis*) is not higher than that of the white Guinea yam (*D. rotundata*). Overall, the use of chemical fingerprints is considered to be an attractive tool for improving the use and management of yam germplasm (Price et al. 2016; Price at al. 2017; Price et al. 2018).

1.6 GERMPLASM CONSERVATION

1.6.1 *Ex situ* conservation

FAO reported 15,903 accessions of *Dioscorea* spp. maintained in 99 *ex situ* collections worldwide in 2008 (FAO 2010). In the Genesys database (2020), the statistics indicate that around 6,704 accessions are presently maintained in collections, but many countries do not report their accessions (Table 1.3).

IITA holds the world's largest collection: it includes nine *Dioscorea* species representing 87% of all accessions. Not surprisingly, the two major species, *D. alata* and *D. rotundata*, together account for more than 83% of the total number of accessions. About 81% of these accessions are landraces (farmers' varieties) and 58% originate from only two countries, Benin and Nigeria. The majority are maintained in *ex situ* field collections (67%) or *in vitro* (36%).

CTCRI in Trivandrum (India), PRC in Hanoi (Vietnam), PhilRootCrops in Baybay (the Philippines), VARTC in Santo (Vanuatu) and INRAE in Guadeloupe (West Indies) also maintain several hundred *Dioscorea* spp. accessions each in *ex situ* collections. Very small collections of *D. oppositifolia* and *D. japonica* are also maintained in China, Taiwan and Japan, mostly for research. In West Africa, several national collections have been assembled and characterized in Côte d'Ivoire (Hamon and Touré 1990) and in Benin (Dansi et al. 1999), but difficulties with maintaining these collections have led to the loss of numerous accessions. In some cases, a whole collection has disappeared and must be assembled again. Dioscorea alata collections of yam were made in Fiji, Papua New Guinea, Solomon Islands, Tonga, Samoa and Vanuatu as part of the regional root crop programs of the 1980s (Jackson 1994). Most have been documented using international descriptors (Guarino and Jackson 1986). Some collections have been evaluated for yield, disease resistance and ease of harvest.

In the early 2000s, the South Pacific Yam Network (SPYN) stratified *D. alata ex situ* collections in Fiji (108 acc.), Papua New Guinea (209 acc.), Solomon Islands (392 acc.) and Vanuatu (331 acc.) using 32 IPGRI descriptors. Eighty-eight cultivars were selected based on their palatability (according to preferences among local communities), tuber shape (compact shape allows for ease of harvest, in contrast to long, vertical tubers) and tolerance to anthracnose. These three major traits were evaluated "on station" in each participating country (Papua New Guinea, Solomon Islands, Vanuatu, Fiji) (Lebot 2003). The selected genotypes are now maintained *in vitro* in the regional germplasm centre managed by the Secretariat of the Pacific Community in Suva, Fiji (Kenyon et al. 2008). Some of these selected genotypes were introduced in Guadeloupe and are used in the CIRAD breeding program (Arnau et al. 2017).

Conservation of germplasm of the minor species (*D. bulbifera*, *D. esculenta*, *D. nummularia*, and *D. trifida*) is fraught with difficulty: *ex situ* collections are expensive to maintain and methods of on-farm conservation have not been studied.

Table 1.3 Genesys database records (2020) of countries that preserve yam genetic resources. Source: https://www.genesys-pgr.org/ accessed 6 August 2020. * Accessions are duplicated in two storage systems.

Country	No. acc.	Species	No. acc.:	Provenance	No. acc.	Type	No. acc.	Storage system	No. acc.:
Nigeria (IITA)	5,839	*D. rotundata*	3,968	Nigeria	1,949	Landraces	5,453	Field *ex situ*	6,062
Fiji (SPC)	329	*D. alata*	1,590	Benin	1,922	Wild	412	*In vitro*	3,325
UK	225	*D. burkilliana*	300	India	385	Other	357	True seed	227
Philippines	159	*D. esculenta*	121	Ghana	266	Natural	224	Cryopreserved	14
Costa Rica	58	*D. bulbifera*	105	Côte d'Ivoire	260	Breeders	71	Medium t. seed	6
Germany (IPK)	50	*D. cayenensis*	99	Togo	185	Weedy	3	Long t. seed	1
Brazil	19	*D. abyssinica*	95	Madagascar	166	Research	1		
Kenya	9	*D. dumetorum*	83	Philippines	141	Unknown	183		
Croatia	6	*D. sansibarensis*	33	Vanuatu	81				
Taiwan	4	*D. sp.*	54	Fiji	74				
Other	6	Other	256	Other	415				
				Unknown	860				
Total	6,704		6,704		6,704		6,704		9,365*

In most research stations around the world, tubers are kept in buildings with a concrete floor, half walls with wooden racks and insect screens instead of windows, and an insulated corrugated iron roof. These structures can hold more than 10,000 tubers for five months with minimal microbial decay. The incidence of scale insects and nematodes might become serious over such a long period. *Ex situ* collections are replanted annually. Depending on the species and cultivar, plants are harvested after 7–9 months of field cycle. The tubers are then preserved in a special shed until the time for planting. There are a few basic requirements for good storage of tubers. The area must be well ventilated so that moisture does not remain on the tuber surface, where it would enable a variety of microorganism infestations. The temperature should be as low as possible, but not below 12 °C. At ambient temperatures, between 25 and 35 °C, tuber respiration is high, which decreases DM and accelerates sprouting. Unfortunately, in most countries worldwide, institutions do not have the financial means or technology to lower the temperature, and shading is the only practical way of keeping the tubers cool. Finally, tubers require regular inspections, and rot should be removed as soon as possible. Any sprouts should also be removed regularly, until planting time.

International guidelines for the safe movement of yam have been published (Brunt et al. 1989), but, in practice, exchanges between collections are extremely limited or nonexistent. Virus indexing is essential not only for plants moved internationally, but also for those conserved in active and base genebanks. Conservation *in vitro* can be done at ambient temperatures (Malaurie et al. 1993) on slow-growth medium (Nair and Chandrababu 1994) or at lower than ambient temperatures, but losses may occur and subculturing is required at 6–12-month intervals.

Cryopreservation offers a more cost-effective alternative for selected cultivars that are not in

constant use. To date, methods of encapsulation in alginate beads (Malaurie et al. 1993) or vitrification have shown a 50% success rate. However, this work has been carried out with only the most economically important species, namely *D. alata*, *D. cayenensis* and *D. rotundata*. Therapies for infected plants of the minor *Dioscorea* species have not been tested to determine whether meristem culture techniques or antiviral compounds are needed to raise healthier planting materials.

Transfer of germplasm depends on the efficiency of the rapid propagation technique, either to propagate recently introduced genotypes or to propagate a recently improved hybrid for advanced clonal evaluation or distribution. Multiplication by *in vitro* growth of nodal segments is a practical way for rapid clonal multiplication, but only a few agricultural research stations can afford to do it. *In vitro* techniques are used for the rapid propagation of virus-free clonal material (Kenyon et al. 2008). Antisera have been produced for several of the viruses that infect cultivated yams, and diagnostic protocols have been developed (Phillips et al. 1999). However, for all species, meristem culture techniques or antiviral compounds are needed to raise healthy planting materials. In some species, such as *D. esculenta*, meristem extraction is very difficult or almost impossible.

For rapid propagation, plants are grown in quarantine glasshouses from small tuber pieces. Nodes taken from these plants are surface-sterilized and transferred to a range of tissue culture media of different compositions and incubated in a controlled light and temperature. Even when great care is taken with the surface sterilization of nodes, several accessions can fail to be established in tissue culture with MS (Murashige and Skoog's) based medium. *In vitro* microtuber production has been studied as an alternative for safely propagating and distributing germplasm, as microtubers have been reported as less vulnerable to transport conditions and easier to establish in the soil (John et al. 1993). The number of shoots and nodes is increased by the addition of jasmonic acid, which also induces an increase in microtuber numbers (Ovono et al. 2007). However, this technique is not used on a routine basis, and *in vitro* plantlets are still the most practical way of distributing germplasm internationally, where there is demand.

The culture system type in liquid media influences the growth of the yam plant. Two systems have been tested: the Temporary Immersion System (TIS) and Constant Immersion System (CIS). Higher results were obtained with TIS. With TIS, the depletion of reducing sugars and the lower mineral nutrients of contents in culture medium were thought to be related to fast plant growth (Cabrera et al. 2011). The use of rooted stem cuttings for the production of planting setts is a technique first developed in IITA (Akoroda and Okonmah 1982; Wilson 1982); this technique not only accelerates propagation of selected clones but, if carried out with sterilized substrate, produces minitubers free of nematodes. The best results are obtained when the cuttings are taken on plants in full vegetative phase, before tuber initiation.

1.6.2 *In situ* conservation

As reported above, the *ex situ* conservation of yam genetic resources is still very limited and is fraught with difficulties. Of the 644 known *Dioscorea* species (of which only 11 are known to be edible), only two species, *D. alata* and *D. rotundata*, make up 83% of *ex situ* collections, and most of those are farmers' varieties from two countries (see Table 1.3). Furthermore, *ex situ* conservation technologies are not well developed, which limits the types of species that can be safely conserved in genebanks. More specifically, reliable *in vitro* techniques exist for the three major species (*D. alata*, *D. cayenensis*, *D. rotundata*) but not for any minor species. *Dioscorea esculenta*, for example, is

very difficult to maintain *in vitro*. Conservation technologies need to be developed. Most of these species do not produce true botanical seeds. Protocols for the conservation of true botanical seeds do not exist for the minor species; even for the three major ones, there is a need to develop protocols and technologies for the conservation of true seeds.

The centers of yam cultivation and diversity are all developing countries where *ex situ* conservation is difficult (Camus and Lebot 2010), and most collections are severely underfunded. As a result, the majority of the genetic diversity of yams is not conserved in the world's genebanks but either is managed by farmers on farm or occurs in the wild in their natural habitats. The effective conservation and management of the diversity in these wild and on-farm areas would thus constitute an important conservation strategy for yam genetic resources as a complement to the *ex situ* conservation efforts reported above. This is even more important considering that the cultural practice of ennoblement, where wild tubers are collected and planted in the field together with cultivars, is common in West Africa (Scarcelli et al. 2006). This makes *in situ*/on-farm conservation and management of the diversity critical to enable adaptations to future stochastic events such as climate change and to ensure food security among the local communities who depend on yam as their staple food.

It would seem from the published literature and country reports (FAO 2010) that there are very few initiatives dedicated to the *in situ* conservation and on-farm management of yam genetic resources. Most studies have focused on understanding the diversity of *Dioscorea* spp. that are maintained by farmers on farm (Camus and Lebot 2010; Sardos et al. 2015), the domestication of wild yams (Scarcelli et al. 2006; Chaïr et al. 2011), documenting wild edible yams that are sources of food during lean periods (Rakotondratsimba 2008) or the ethnobiology of wild yams (Kumar et al. 2017; Beinart and Beinart 2019).

Regional initiatives

In Vanuatu, Camus and Lebot (2010) evaluated the "potential of geographic distribution of allelic diversity as a complementary conservation strategy for root crops" including taro, yams, sweet potatoes and cassava. The diversity of landraces of root crops was studied across 10 villages located on the 10 most populated islands where yams and taro were the major crops. Participatory rural appraisals (PRA) and inventory of the traditional cultivars being grown were carried out. A baseline of the 48 best cultivars of *D. alata*, *D. bulbifera*, *D. esculenta* and *D. nummularia*, taken from a core sample of yams, were introduced to these villages to broaden the genetic base. The acceptability of the introduced species was assessed after two years, along with information on the impact on the household varietal portfolio and how these introduced cultivars were managed in the village. Their findings showed a general acceptability of the introduced cultivars, as evidenced by the high levels of varietal gains in the communities, which was 87% in the yam villages. It was also noted that farmers preserved all their local cultivars, claiming to protect their own cultivars despite the introduced cultivars, which is known to be a strong cultural practice in Vanuatu. The results of this study show farmers' interest in using new yam cultivars and in maintaining diversity. Farmers benefited from introduced cultivars through a broader varietal portfolio and protection against the risk of an epidemic. Nevertheless, farmers also care to safeguard their own local cultivars. The genetic base is narrow; therefore, the crossing of local cultivars with exotic germplasm will lead to greater allelic diversity over the long term. The key lesson from this study is that, for on-farm conservation of any given variety to succeed, it is important that the variety meets farmers'

expectations, particularly their organoleptic preferences (Camus and Lebot 2010).

In Benin, in West Africa, wild yams *D. praehensilis* from five forests in different climatic zones and under different management strategies have been characterized for their genetic diversity (Chaïr et al. 2011). Most of the forested areas were in an agriculture-dominated landscape. Within these forests, wild yams are cultivated in slash-and-burn fields. It was found that a cluster of accessions from different forested areas were closely related, which the authors attributed to farmers' practice of ennoblement and to migration of farmers from one region to another. Similarly, Scarcelli et al. (2006) reported that in northern Benin, farmers may cultivate 5–22 cultivars of yam. They practice ennoblement, where wild genotypes are collected and planted in the field together with cultivars. The relationships between agronomic, social and cultural factors and the continuation of ennoblement in some farming communities is mostly unknown. Given the role of this practice in nurturing yam diversity, investigating these factors is essential.

By contrast, in Madagascar, wild yam species are rarely introduced into farming systems (National Strategy on Plant Genetic Resources for Food and Agriculture (PGRFA), Madagascar, 2018). Rather, as yam is considered to be an important famine crop, most of the conservation activities for yam in Madagascar take place within their natural habitat in forested ecosystems. Despite the recognized value of these wild relatives of yams for food security, national agencies have widely neglected their conservation, resulting in inadequate conservation of their populations both *in situ* and in *ex situ* collections. Several studies on wild yams have been undertaken in Madagascar.

In southern Africa, Tanzania, Zambia and Malawi are developing National Strategy Action Plans for the *in situ* conservation of CWR for priority crops, including yam. They are also undertaking conservation planning exercises to identify priority sites for the establishment of genetic reserves. This work is part of a Darwin Initiative project (2019–2022) on "Bridging agriculture and environment: Southern African crop wild relative regional network," led by the Alliance of Bioversity International and CIAT. Tanzania, Zambia, South Africa and Malawi have all selected yam as one of their priority crops. In Zambia, for example, five of the 30 prioritized CWR belong to the genus of *Dioscorea* (*D. bulbifera*, *D. dumetorum*, *D. praehensilis*, *D. schimperiana*). In Malawi, *D. praehensilis*, *D. hirtifolia*, *D. asteriscus* and *D. bulbifera* are among the priority CWR targeted for conservation. A previous project on *in situ* conservation of CWR in the SADC region, funded under the European Union/ACP cooperation program and led by Bioversity International, also developed a National Strategy Action Plan for South Africa that included yam as a priority crop.

In Madagascar, a project funded by the Darwin Initiative (2015–2018) and the April Trust, and led by the Royal Botanical Gardens, Kew, studied wild and cultivated yam species and developed a wild yam strategy to complement that of cultivated yams (Darwin Initiative, 2018). The project also assessed the conservation of 29 species of wild yams and found that 38% of the species are threatened; this assessment was published in the IUCN Red List. More recently, Kew Gardens developed a specific national strategy on yam under a Darwin Initiative project.

In South Africa, also, numerous conservation initiatives involve yam species. For example, the Mohammad Bin Zayed Species Conservation Fund supported a project to enhance conservation measures for a wild yam species, *D. strydomiana*, by using drones to produce high-precision maps of predicted wild populations located in remote areas. This made it possible for the additional population of *D. strydomiana* to be conserved *in situ* and provides materials for *ex situ* conservation

and sites for re-introduction under community protection.

Many wild yam species in South Africa have important medicinal properties, which has led to conservation and protective action to safeguard these resources against over-collection and biopiracy. For example, the overharvesting of *D. sylvatica* and *D. elephantipes* to provide diosgenin to pharmaceutical companies has prompted the South African Cape provinces to take control measures, in order to protect the species and ensure its sustainable use (Beinart and Beinart 2019).

In India, Kumar et al. (2017) reviewed the ethnopharmacological and traditional use of *Dioscorea* spp. in the Similipal Biosphere Reserve in Eastern Ghats, an area inhabited by many local communities. They discussed the ethnobotanical, nutritional and pharmacological values of 13 species of *Dioscorea* in this biosphere reserve.

The CGIAR Research Program on Roots, Tubers and Bananas (RTB) is undertaking an assessment of the yam diversity in two hotspots in Papua New Guinea and Benin. The information is captured via an *in situ* monitoring system that is being developed as part of the program. In Papua New Guinea, the first mission was undertaken in October 2019 in the village of Konguan, located inland in Bogia district (Madang Province). Local farmers took part in discussion groups, in which they were asked to list cultivars of banana, sweet potato and yam. Farmers listed 23 cultivars of yam, including three wild species. However, not all cultivars could be verified in the field at the time of the visit, either because farmers no longer grow them, or they were not in production. In addition, 14 yams were collected from the bush close to farmers' fields. It is still uncertain to which known species they belong; molecular analysis is currently being undertaken to check their identity. Five individuals could not be assigned to any known species.

Country reports submitted to the FAO (FAO 2010) may contain useful information about how countries are implementing the Second Global Plan of Action for Plant Genetic Resources for Food and Agriculture, which has 18 priority actions, including four priority actions on *in situ* conservation and management. Most of the reports date back to 2008. Currently, FAO member states are preparing their third report, which will provide updates on progress made in the past decade. An analysis of the reports by key countries in several yam-growing regions that mentioned yam genetic resources was undertaken for the purposes of this strategy. The analysis showed that very few *in situ* conservation and on-farm management activities were reported. Following are some key findings by region.

Most of the yam belt countries mentioned that wild species with traditional food, medicinal or cultural values are passively conserved within the network of protected areas in their countries. In some countries, such as Nigeria, inventories of these parks have been conducted. In Côte d'Ivoire, some wild yam species have benefited from *in situ* conservation initiatives, such as in the forest reserve of Foro-foro, north of Bouaké, where wild yams are conserved *in situ* (Country report, Côte d'Ivoire). In Benin, the sacred forest of d'Adakplamè in the commune of Ketou was mentioned as containing important populations of the wild yam *D. praehensilis* (Country report, Benin).

In southern and eastern Africa in general, CWR are passively conserved within protected areas. In Madagascar, a management plan for the *in situ* conservation of wild yams was prepared for Ankarafantsika National Park, as part of a UNEP/GEF project led by Bioversity International. The project adopted a participatory approach to develop a management plan that will allow local communities to sustainably harvest and manage these yam CWRs (Hunter and Heywood 2011).

The Tanzania country report mentions inventories and surveying, as well as *in situ* conservation of CWR, but does not state which CWR have been targeted.

In Southeast Asia, yam is mentioned as an important subsistence and staple crop (Papua New Guinea, Philippines and Vietnam country reports) and the region is mentioned as part of the center of diversity for yam. In the Philippines, there are five species of *Dioscorea*, namely *D. alata*, *D. bulbifera*, *D. esculenta*, *D. hispida* and *D. pentaphylla*. With the exception of *D. alata*, these species are generally not widely cultivated or used, and are under threat of genetic erosion. In the Philippines, *D. hispida* has also contributed significantly to the diversification of agricultural systems. In Vietnam, *D bulbifera*, *D. esculenta*, *D. alata*, *D. cirrhosa*, *D. persimilis*, *D. hispida*, *D. floribunda* and *D. deltoidea* are found.

In Papua New Guinea, it is reported that 300 landraces or farmers' cultivars of yam are currently being conserved in *ex situ* collections. Furthermore, there are numerous accessions or landraces of these food crop species growing in farmers' fields or in *in situ* conditions that have not been collected, especially in isolated and more remote areas of the country. As in other regions, there has been no systematic national effort addressing *in situ* conservation nor have any inventories or surveys of wild species useful for food and agriculture been undertaken. Much of the diversity is located within diversity-rich areas that have been set aside as nature reserves and national parks, but no detailed biodiversity inventories have been undertaken in these areas. It is assumed that any wild species that are documented within these protected areas, including yam, are protected. However, it is known that many wild species are often gathered unsustainably from the forest and in areas adjoining farms. For example, in Papua New Guinea, the rural population greatly depends on a number of wild yam species, such as *D. pentaphylla*, *D. hispida* and *D. nummularia*, to meet their needs in times of food scarcity.

There is a dearth of initiatives targeting farm management of yam diversity in the region. Generally, the maintenance of plant genetic resources in farmers' fields and in natural habitats is still common in some communities, where these resources are maintained as a part of traditional farming systems, such as home gardens. Farmers will grow traditional cultivars only when the economic benefits are comparable to growing high-yielding cultivars. In the Philippines, farmers get a premium price for traditional cultivars, because of consumer preference and market forces (Altoveros and Borromeo 2007).

In September 2006, NARI in Papua New Guinea undertook a project on *in situ* (on-farm) conservation in a banana–yam-based farming system in Gabadi in Central Province (FAO 2009). A survey was undertaken to investigate the food crop diversity present in farmers' fields, the proportions of traditional and introduced cultivars, local knowledge of "genetic erosion" and reasons for the erosion, the main uses of the existing on-farm diversity, farmers' reasons for maintaining diversity on farm, and their perception of what would happen to their food system or their livelihood if diversity of food crops is lost. The study revealed that each farmer maintains 8–10 cultivars of banana and 5–6 cultivars of yam, plus many cultivars and landraces of other food crops. Altogether, more than 30 cultivars of banana and six cultivars of yam were found in the area studied (FAO 2009).

In the Pacific, yams are relatively less important than crops such as taro, cassava and sweet potatoes. In the Cook Islands, there have been no inventories, surveys or evaluations to determine the continuing use, conservation and genetic erosion of traditional crops in farmers' fields and in other areas of the country. Fiji mentions some activities where farmers support the on-farm

approach, but none target yams. Samoa reports that on-farm management is not a high priority area, but it does mention that a few national policies are in place to encourage on-farm management of PGRFA. "The Samoan government, through the Ministry of Agriculture and Fisheries, provides extension services to support farmers, seed production and distribution services, and supportive research. These incentives are offered to farmers either free of charge or at a very low price" (Tuivavalagi 2010: page 11).

In the Americas and the Caribbean, yam is a minor crop, although Cuba mentions it as one of the most important food crops in the country. Cuba lists 30 cultivars, of which 15 are local cultivars. Throughout the region, there are no reports on *in situ* conservation or on-farm management of yam diversity, except for some ongoing projects on yams in Brazil, for which no details are provided. Costa Rica does not mention yam as being an important crop.

Threats

Identifying the major threats to the genetic diversity of yams is critical for developing *in situ* conservation and use strategies. The major threats to PGRFA include land clearing, population pressure, overgrazing, environmental degradation and changing agricultural practices (FAO 2010). All are pertinent to the erosion of yam genetic resources. Many global assessments (FAO 2010), FAO State of the World's Biodiversity for Food and Agriculture (FAO 2019), IPBES Global Assessment Report (IPBES 2019) and Millennium Ecosystem Assessment (2005) have reviewed the drivers of change that affect biodiversity, including agrobiodiversity. In this section, we review the evidence from the literature, projects and country reports to the FAO on the key threats to both wild and cultivated yam genetic resources.

In the yam belt, the principal causes of the disappearance of wild edible species and their wild relatives are high rates of deforestation due to population growth, land clearing for agriculture and forest fires, uncontrolled expansion of housing, invasive species, climate change, and the erosion of traditional religious beliefs (Kokou et al. 2008 in Chaïr et al. 2011; Nigeria country report to FAO 2008).

Chaïr et al. (2011) considered that, in Benin, *D. praehensilis* was the species most under threat. The National Biodiversity Strategy and Action Plan for Benin indicates that local yams have suffered because crops such as millet and high-yielding yam species have been prioritized over indigenous crops. In addition, the government's promotion of cotton since 2006 has reduced the area of land available for food crops. Furthermore, farmers' reports indicate the loss of many traditional yam cultivars because of susceptibility to pests and diseases, poor soil quality, weeds and drought, which make them less productive or more costly to grow compared to other food crops, such as cassava (Crop Trust, Press release, 8 September 2010). Dansi et al. (2013) found that in Togo, the rate of cultivar loss was very high (37% on average) and called for urgent action to preserve their local yam diversity.

In Madagascar, wild species of yams that contribute to local communities' food security are under intense pressure and are highly threatened by unsustainable collection from the wild and by habitat loss (Hunter and Heywood 2011; Andriamparany 2015; Kobbe et al. 2017; National Strategy on PGRFA, Madagascar 2018). In its latest publication, the IUCN Red List published an assessment made by the Royal Botanic Gardens, Kew of 41 species of *Dioscorea* found in Madagascar and southern Africa, reporting that: "Over 30 yam species in Madagascar are only found there and, based on our assessments, many of these are likely to continue to decline if no action is taken". Furthermore, wild yams are harvested by digging large holes, using a locally made spear-like tool, in order to collect the tubers

without damaging them, but this often causes soil degradation (Andriamparany 2015).

"The risk of extinction in southern Africa is even greater than that in Madagascar; 44% are at risk of extinction", according to Kew's assessments, "mostly due to habitat decline, from overgrazing, agricultural changes and other land development" (Heargreaves and Wilkin 2019). In southern Zambia, for example, Zulu et al. (2019) reported that the widely foraged edible wild yam, *D. hirtiflora*, collected from natural forests in southern Zambia, is threatened by deforestation and agricultural expansion. Wilkin et al. (2010) also mentioned *D. strydomiana*, which is "harvested for its supposed cancer-curing properties" and is "one of the most endangered yams anywhere in the world" (Heargreaves and Wilkin 2019).

Scarcelli et al. (2017) suggest that wild yam diversity is at risk due to crop-to-wild gene flow. In California, for instance, interspecific hybrids of a cultivated species (*Raphanus sativus*) and a wild species (*R. raphanistrum*), have replaced *R. raphanistrum* (Hegde et al. 2006). Similarly, high rates of crop-to-wild introgression betwee wild and cultivated rice (*Oryza sativa*) have been observed in China, Taiwan and Thailand (Kiang et al. 1979; Akimoto et al. 1999; Song et al. 2006).

In Southeast Asia, the replacement of traditional cultivars by improved cultivars is considered a major threat to genetic diversity, leading to a narrowing of the genetic base of their crops. In Vietnam, it is estimated that about 80% of local cultivars no longer exist in production systems. In Papua New Guinea, the study on the banana–yam-based farming system of the Gabadi people in Central Province showed rapid loss of the diversity of food crops (FAO 2009). Women, who mostly grow the yams, indicated that they maintained fewer than five cultivars, compared with more than 10 previously. Other threats mentioned include land conversion, pest and disease epidemics, mining operations, climate change, abandonment of farming, damage by wild animals, and negligence and insufficient management. The lack of demand for local cultivars in urban markets and changing lifestyles were also mentioned as a driver of genetic erosion in Papua New Guinea.

Landraces

Generally, it is not known how many different cultivars of yam are still extant in farmers' fields. Farmers have been maintaining landraces (or traditional cultivars) for generations as part of their traditional farming systems, and continue to do so. In Papua New Guinea, for example, where 85% of the population live in rural areas, farmers continue to maintain their own food crop diversity on farm in their backyard gardens and kitchen gardens or in wild habitats owned by tribes or local communities (FAO 2010). As reported above, most countries have not made any systematic inventory of on-farm yam diversity, except for specific ad hoc studies where an assessment has been done at specific sites. Dansi et al. (2013) assessed the varietal diversity of the *D. cayenensis/rotundata* complex and *D. alata* in Togo and found 470 cultivars of *D. cayenensis/rotundata* and 134 cultivars of *D. alata*.

Scarcelli et al. (2006) reported that in northern Benin, farmers cultivate 5–22 cultivars of yam. Sardos et al. (2015) studied the landrace diversity of several root crops, including yams, in 10 villages across the islands of Vanuatu and calculated the landrace richness of each species. Their study revealed a total of 12 crop species, which included seven species of yam and an overall diversity of 1,005 landraces of root crops, of which 380 were yam landraces.

Some attempts to fill these gaps have been made by the Global Crop Diversity Trust, which has supported national research organizations in conducting surveys of on-farm yam diversity. In Togo, for instance, a survey of 50 yam-producing villages was carried out "with the aim of gathering information for farmers and breeders to facilitate

access to existing diversity" (Crop Trust, 2020). In Benin, the Crop Trust also supported the Plant Genetic Resources Research Institute (PGRRI) in surveying yam-production areas and gathering information on existing yam diversity and farmers' preferences.

Understanding the diversity of yam cultivars on farms is quite challenging, because the vernacular names provided by farmers are not always consistent across different ethnic groups (Dansi et al. 1999). It is, nonetheless, important to study how the genetic diversity of yam cultivars is structured and how farmers manage it. Interestingly, in a study of farmers and their genetic classification of cultivars, Scarcelli et al. (2011) found that each genotype lineage was specific to a cultivar cluster, suggesting they represent a single genetic pool derived by mutation. Scarcelli et al. (2013) found that farmers' management of yam cultivars avoids mixing different groups, and selects against off-types when tubers are chosen for propagation. As a result, cultivars are well differentiated, and within-cultivar genetic diversity is very low. It is, therefore, possible to consider that a yam cultivar is a single genotype that has evolved by accumulating mutations.

Constraints and obstacles

One of the main constraints to on-farm conservation is that, in many countries where yam is not a priority crop, national governments provide limited support for on-farm conservation activities. The lack of policies to promote the local diversity of yam genetic resources means farmers have no incentive to continue to grow indigenous yams. Some of the key constraints and obstacles to on-farm conservation are: lack of adequate incentive mechanisms (India Costa Rica, Tanzania, Papua New Guinea), insufficient seed and planting materials (India, Tanzania), insufficient and unskilled staff (India, Tanzania) and insufficient finances (India, Tanzania).

In most developing countries, "on-farm management and improvement of PGRFA are not a national priority" (Altoveros and Borromeo, 2007). As a result, "the technical and scientific bases of effective *in situ* management have not been established" (Altoveros and Borromeo, 2007). Constraints include: "inadequate information on effective population size, population biology and species interaction; inadequate incentives provided to farmers; insufficient seed or planting materials; insufficient number of staff; insufficient skills and staff training; and insufficient financial support. One way to overcome these obstacles is to make *in situ* management of PGRFA a component of the national program, with appropriate government support in terms of funding, training and research. It will also help if plant genetic resources in general are made part of the formal seed supply system to ensure the availability of planting materials for farmers" (Altoveros and Borromeo, 2007).

On-farm monitoring of landraces

There are, in general, no inventories or information/data collected on PGRFA in farmers' fields or in wild habitats at a national level. The FAO WIEWS (World Information and Early Warning System on Plant Genetic Resources for Food and Agriculture) has developed a monitoring system for the implementation of the Second Global Plan of Action. The inventories of yam diversity in farmers' fields that have been undertaken as part of research studies (see above) could be used to serve as baselines for future monitoring of the diversity. For example, the assessments made by Sardos et al. (2015) and Camus and Lebot (2010) on the diversity of yam landraces in 10 villages in Vanuatu could be used as a baseline for monitoring. The CGIAR Research Program on Roots, Tubers and Bananas is also developing an *in situ* conservation monitoring system for genetic diversity of root, tubers and bananas, including yam.

Crop wild relatives Inventories

Very few of the range states for yam have undertaken any inventories of their CWR. Notable exceptions include Benin (Idahou et al. 2013), Madagascar (Caddick et al. 2002; Schols et al. 2005) and China (Kell et al. 2015), among others. Benin has carried out an inventory and prioritization of CWR, with yam representing more than 5% of their priority CWR species (Idahou et al. 2010). In Madagascar, there may be more than 40 species (see case study below), representing about 10% of the world's yam diversity. In Cameroon, Yasuoka (2013) mentions that there are 15–17 wild yam species, of which 10 are edible *Dioscorea* spp. and one is an edible yam-like plant, Dioscoreophyllum sp. The inventory of CWR in China listed 49 native species of yam (Kell et al. 2015).

An analysis of occurrence data of yams from GBIF (Global Biodiversity Information Facility; accessed 21 September 2020) resulted in a list of 518 *Dioscorea* species. The distribution of these occurrence data is shown in the map in Figure 2.1. However, the threat status of 81 *Dioscorea* CWR species (as at 21 April 2020, IUCN) assessed using the IUCN Red List (IUCN 2001), considers only 15.6% of the known *Dioscorea* CWR species retrieved from the global CWR inventory (Harlan and de Wet CWR Inventory, accessed 22 September 2020). Around 46% of *Dioscorea* spp. (37) are in the Least Concern (LC) category, with about 15% (12 spp.) assessed as Vulnerable (VU), about 14% (11 spp.) as Near Threatened (NT), about 12% (10 spp.) as Endangered (EN) and about 4% (3 spp.) as Critically Endangered (CR). About 10% of the *Dioscorea* spp. (8 spp.) are reported as Data Deficient (DD).

Vincent et al. (2013) estimated CWR relatedness for 173 priority crops, including yams, to define priority CWR species. They prioritized 33 *Dioscorea* species for germplasm collections and *in situ* conservation. Annex 5 lists the 33 priority Dioscorea CWR species and provides information on their gene pool level, yam crop type, IUCN Red List status, and the number of non-duplicated GBIF occurrences. Out of the 33 priority *Dioscorea* CWR spp., only 11 (33.3%) have been assessed by the IUCN Red List. The total occurrence data for these priority species available on the GBIF portal comprises 2,439 entries. However, upon data cleaning (removal of duplicates and invalid coordinates), only 970 records (39.8%) have valid coordinates, representing only 23 species. Of these records, only 641 are unique values (nonduplicated data). The highest number of valid, unique coordinates is recorded for *D. cayenensis* (160), followed by *D. bulbifera* (125) and *D. transversa* (66). No valid data are recorded for five species, namely, *D. birmanica*, *D. calcicola*, *D. pseudonitens*, *D. rotundata* and *D. wallichii*. Of the 33 priority species, only one has a potential use trait recorded: *D. abyssinica* for resistance to yam mosaic virus (Kikuno et al. 2011). The 641 valid and unique entries in GBIF (GBIF.org, accessed 21 September 2020) span 48 countries worldwide. According to these data, Thailand and Cameroon have the highest diversity according to occurrences, with 10 and nine species recorded, respectively (Figure 2.2).

Figure 2.1 Global distribution map of all the valid GBIF occurrences recorded for 518 *Dioscorea* species (Data source: GBIF.org, accessed 21 September 2020).

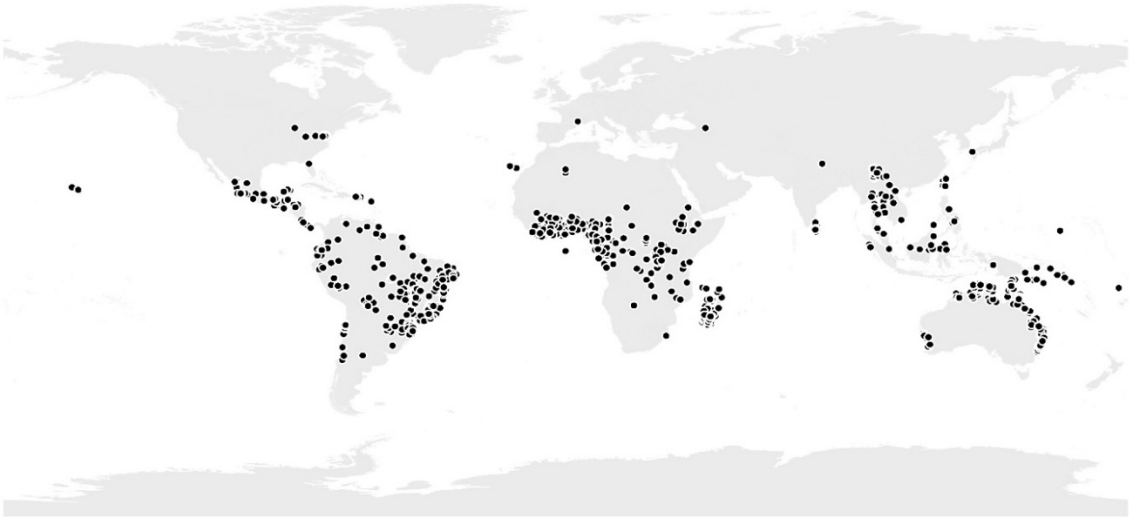
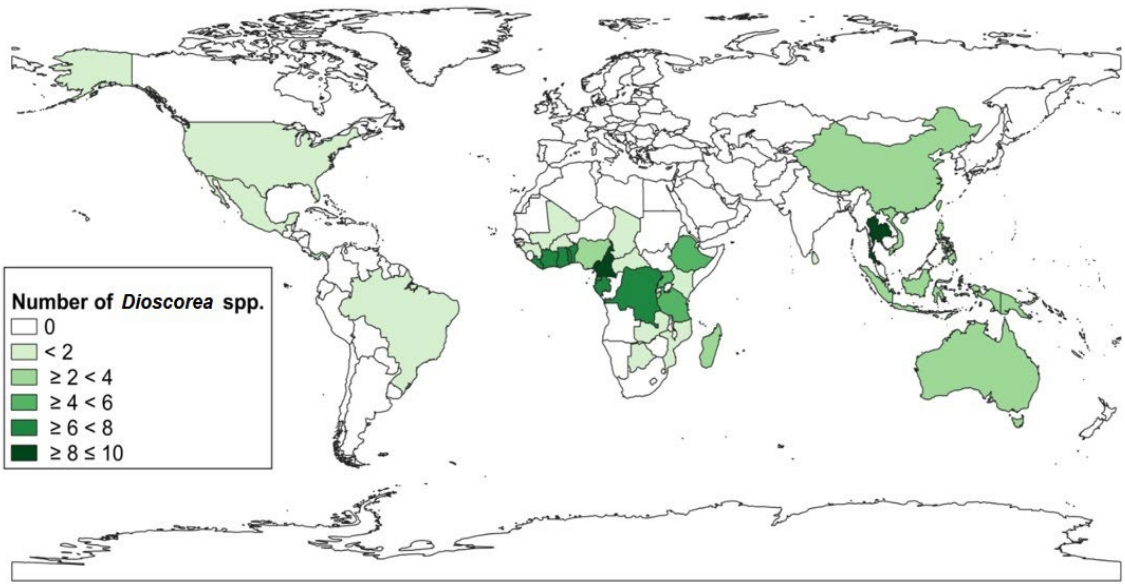


Figure 2.2 Global priority *Dioscorea* species richness map based on the number of valid GBIF occurrences. (Data sources: Harlan and de Wet Inventory, accessed 22 September 2020; GBIF.org, accessed 21 September 2020)

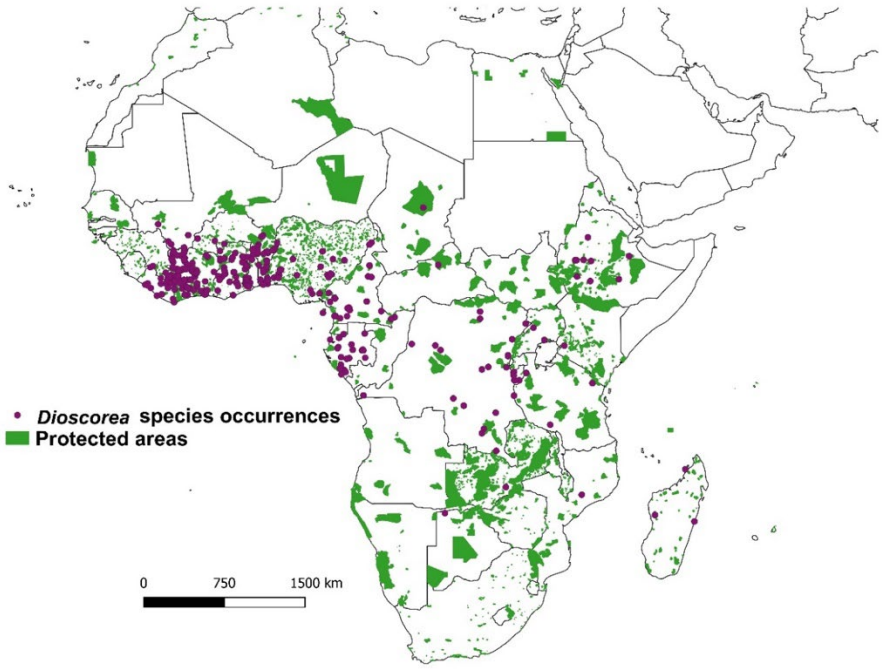


Coverage within protected areas

An exercise was carried out to define how many priority CWR of *Dioscorea* (as defined by Vincent et al. (2013)) are located within protected areas, as a proxy for *in situ* conservation, using existing data in the GBIF and the World Database on Protected Areas (WDPA). The results show that most of the occurrence data points retrieved appear to be fairly scattered and very few are within designated protected areas. For example, among countries in Africa, Cameroon (9 spp.), Ghana (8 spp.) and Côte d'Ivoire (8 spp.) have the greatest species diversity recorded (Figure 2.2). However, in terms of valid occurrences recorded in the GBIF database, the numbers for Cameroon (22) and Ghana (41) are quite low compared to Côte d'Ivoire (104) (Figure 2.3).

Close examination of the occurrence data in Côte d'Ivoire and Ghana reveals only 16 occurrences (representing 15.4%) and five occurrences (representing 12.2%), respectively, within protected areas (Figure 2.4a), while in Cameroon, which according to the GBIF data is the second most diverse country in terms of the priority *Dioscorea* CWR species, only two (9.1%) of the 22 occurrences recorded are within designated protected areas (Figure 2.4b).

Figure 2.3 Map of Africa showing the occurrences of priority crop wild relatives of *Dioscorea* spp. retrieved from GBIF within and outside protected areas (Data sources: GBIF.org and WDPA, accessed September 2020)



Constraints and obstacles

An analysis of the yam range states' country reports to FAO on *in situ* conservation showed that the major constraints for implementing *in situ* conservation of CWR and other wild plants include:

- Insufficient inventory and assessment of diversity
- Lack of information on indigenous knowledge
- Extent of the protected areas within the country not covering key ecological regions
- Poor management of existing protected area sites
- Lack of technical knowhow on *in situ* conservation (especially in protected areas)
- Lack of financial resources
- Poor databases and documentation and poor information sharing between institutions
- Lack of policies to support *in situ* conservation
- Low awareness of the value of CWR among local communities and protected area managers.

It is concluded that a better understanding of the distribution and patterns of CWR diversity is needed to develop a rational *in situ* conservation strategy that will allow the effective implementation of reintroduction methodologies and management of wild populations.

Case study: Conservation through cultivation of wild yams in Madagascar

Madagascar is home to 38 species of yam (*Dioscorea* spp.), all but seven of which occur nowhere else. At least five more are yet to be described, and we expect the final total to approach 50. The IUCN Red List status has been published for 30 species of *Dioscorea* from Madagascar and two endemic species from Mayotte and the Comoros, respectively. According to this global assessment, 38% of species are threatened; when those that are near threatened are added, the total reaches 56%. The principal threats are overexploitation and land use change. All are wild relatives of the commodity crops Guinea yam (*D. rotundata*, *D. cayenensis*) and greater yam (*D. alata*). The latter has historically been cultivated at a small scale in Madagascar following its introduction from tropical Asia.

Under two projects funded by the Darwin Initiative, "Conserving Madagascar's yams through cultivation for livelihoods and food security" and "Sustainable yam markets for conservation and food security in Madagascar", 60 rural communities in Antsiranana and Fianarantsoa Provinces were given support to cultivate both greater yams (for nutrition and income) via provision of planting materials and wild yam species (for nutrition, income and conservation) from community-adjacent forests. The most threatened and preferred wild-extracted edible species were selected for cultivation. Conservation was also achieved via community and centralized living collections and seed banking. Further work using the same approaches has taken place with communities in other areas of Madagascar. This has helped to conserve 25 species, an endemic subspecies and five winged yam varieties in germplasm collections and in cultivation with communities, with 23 species banked as seed. Of the 25 species, 12 have been assessed as threathened (iucnredlist.org) or provisionally demonstrated to be threatened. At the same time, mean household annual calorific intake, annual protein intake and income increased for participating communities across the project.

Figure 2.4a Map showing the occurrence data of priority crop wild relatives of *Dioscorea* spp. within and outside protected areas in Côte d'Ivoire and Ghana (Data sources: GBIF.org and WDPA, accessed September 2020)

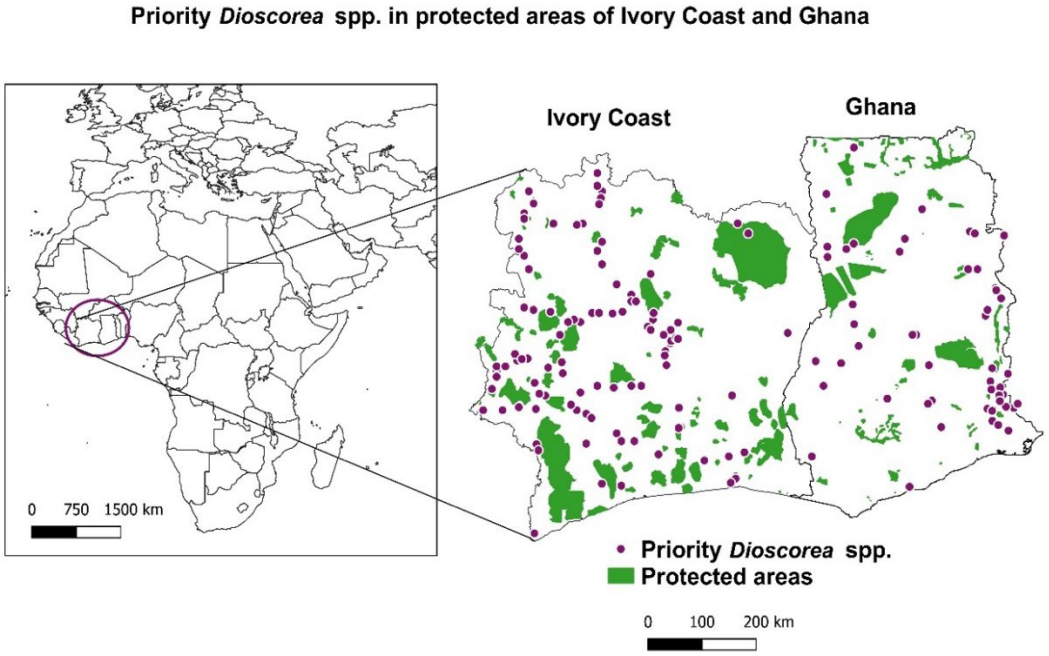
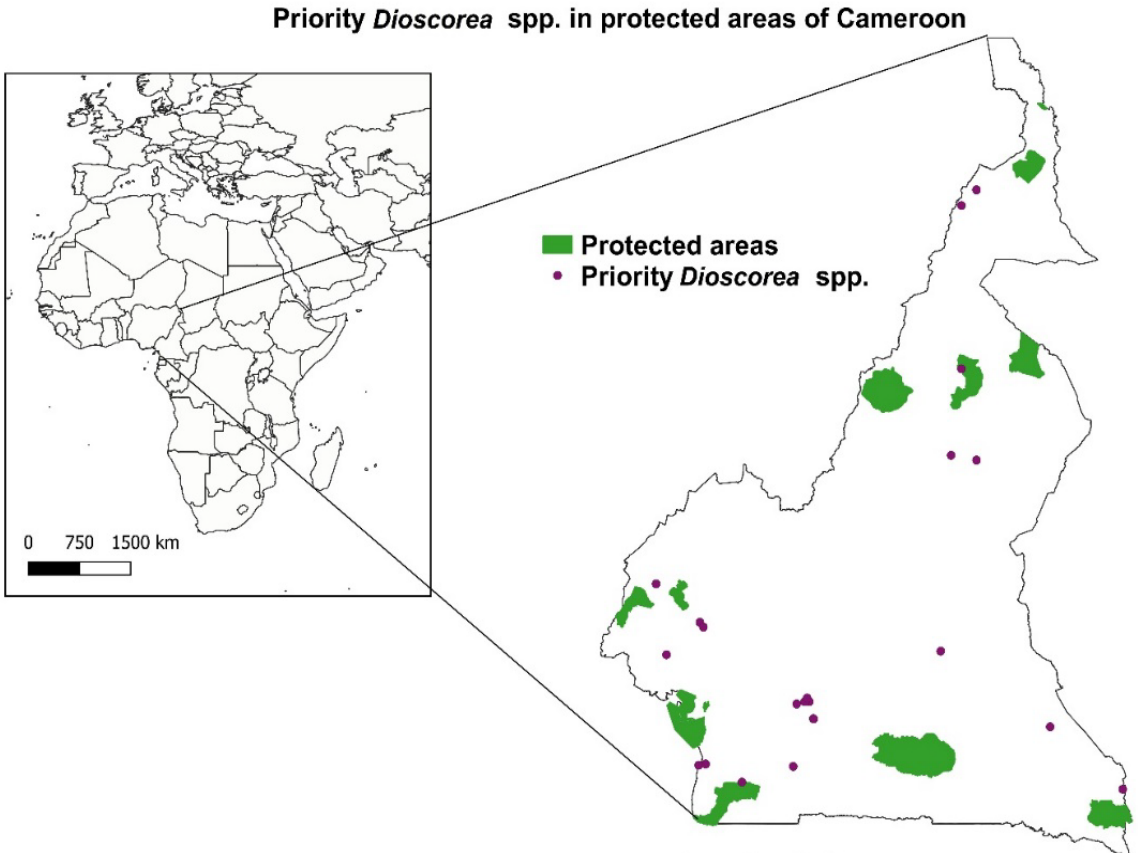


Figure 2.4b Map showing the occurrence data of priority crop wild relatives of *Dioscorea* spp. within and outside protected areas in Cameroon (Data sources: GBIF.org and WDPA, accessed September 2020)



1.7 PEST AND DISEASES

1.7.1 Anthracnose

Yam anthracnose is caused by the fungus *Colletotrichum gloeosporioides*, and is characterized by blackening and dieback of the leaves and shoots. This disease has been reported in all the regions of the world that produce yams. It. Unfortunately, the most popular cultivars, or those adapted to commercial production, are those which are the most susceptible (Lebot, 2020).

Colletotrichum gloeosporioides has also been found in yam tubers, which confirms that the fungus is tuber-borne and can infect and persist in tuber tissues for more than one season. Infected tubers, used as planting material, can be a primary source of inoculum, playing an important role in the epidemiology of the pathogen in the field (Green and Simons 1994). However, the mechanism of the spread of *C. gloeosporioides* from tuber to canopy is yet to be understood fully.

The heterogeneity exhibited at the molecular level by isolates of *C. gloeosporioides* indicates the existence of a complex population structure in which sexual recombination probably plays a major role in generating variation (Abang et al. 2006). The lack of clear relationships between molecular groups and geographic origins, coupled with the evidence that closely similar strains are present in widely separate localities, probably reflects the historical movement of clonal germplasm between countries. Two distinct morphotypes are associated with anthracnose disease, with molecular differentiation clearly separating isolates of the aggressive defoliating morphotype from the moderately virulent, nondefoliating strain (Abang et al. 2002, 2005).

The most appropriate approach to controlling the spread of this disease is to breed new cultivars with parents that originate from different gene pools and that are resistant or tolerant to anthracnose. However, "identification of the levels of resistance to anthracnose is laborious and cumbersome" (Lebot, 2020). The use of the spray inoculation method is reliable. In this regard, the the use of tissue culture-derived whole-plant assay for anthracnose-resistance breeding programs could accelerate the selection of resistant cultivars (Onyeka et al. 2006a,b). Screening yam germplasm in the field for anthracnose resistance can be a complex exercise. The reliability of anthracnose severity rating parameters has been compared, and it appears that all evaluated parameters (detached-leaf severity, whole-plant severity, lesion size and spore production) can be successfully scored and used for assessing severity of the disease. However, detached-leaf and whole-plant evaluation have a positive agreement with the field evaluation (Nwalili et al. 2017). Molecular markers might help (Darkwa et al. 2020b).


PHOTO CREDIT: Charlotte Lusty

1.7.2 Viruses

Efforts to broaden the genetic base of *ex situ* collections and breeding programs need to take into consideration the possible introduction of viruses. Twenty viruses have been described (Table 1.4).

Table 1.4 The main viruses known to infect yams (*Dioscorea* spp.)

Family	Genus	Species
Alphaflexiviridae	Potexvirus	Yam virus X
Betaflexiviridae	Carlavirus	Yam latent virus
Tombusviridae	Aureusvirus	Yam spherical virus
Potyviridae	Macluravirus	Chinese yam necrotic mosaic virus
Potyviridae	Macluravirus	Yam chlorotic mosaic virus
Potyviridae	Macluravirus	Yam chlorotic necrosis virus
Potyviridae	Potyvirus	Dioscorea alata virus
Potyviridae	Potyvirus	Japanese yam mosaic virus
Potyviridae	Potyvirus	Yam mild mosaic virus
Potyviridae	Potyvirus	Yam mosaic virus
Caulimoviridae	Badnavirus	Dioscorea bacilliform AL virus
Caulimoviridae	Badnavirus	Dioscorea bacilliform AL virus 2
Caulimoviridae	Badnavirus	Dioscorea bacilliform ES virus
Caulimoviridae	Badnavirus	Dioscorea bacilliform RT virus 1
Caulimoviridae	Badnavirus	Dioscorea bacilliform RT virus 2
Caulimoviridae	Badnavirus	Dioscorea bacilliform SN virus
Caulimoviridae	Badnavirus	Dioscorea bacilliform TR virus
Secoviridae	Sadwavirus	Dioscorea mosaic associated virus
Potyviridae	Potyvirus	Dioscorea mosaic virus
Caulimoviridae	Dioscovirus	Dioscorea nummularia associated virus

Although it is difficult to quantify the effects of the diseases on yield, it is well established that infection reduces tuber size and vegetative growth (Thouvenel and Dumont 1990). Detection of viruses is done using serological tests (enzyme-linked immunosorbent assay, ELISA), electron microscopy and DNA techniques such as cDNA probes and polymerase chain reaction (PCR). Viruses can be removed from infected plants using meristem-tip excision techniques, often done in conjunction with thermotherapy or chemotherapy. Plants derived from therapy need to be reindexed.

Two viruses of the family Potyviridae are reported to be the most widespread and economically important viruses worldwide. They are a major constraint to the international movement of germplasm, as very few laboratories have the means to produce virus-free yam germplasm (Lebas 2002). Of the two, yam mosaic potyvirus (YMV) is the most important. It causes symptoms ranging from mild mosaic on leaves to stunted

growth. YMV is transmitted mechanically from plant to plant and by *Aphis gossypii*, *A. craccivora*, *Rhopalosiphum maidis* and *Toxoptera citricidus* (Odu et al. 2004a,b). In West Africa, the virus is present in all cultivated yams, while in Guadeloupe, it is detected mostly in *D. trifida*, *D. cayenensis* and *D. rotundata* (Urbino et al. 1998).

Dioscorea alata virus (DAV) is transmissible only by aphids. It induces mild mottling, veinal chlorosis, occasional vein banding, leaf distortion and, occasionally, severe chlorosis. DAV (potyvirus) is the virus detected most commonly by serology (ELISA) in *D. alata*, *D. esculenta* and *D. bulbifera*. The molecular technique, RT-PCR, is generally more sensitive than ELISA for detecting DAV. Sequence analysis suggests that there are many different strains of DAV, but there is no strong association between particular sequence types (strains) and geographic or host origin (Lebot 2003).

Badnaviruses often go undetected, due to their very low virus titers and ability not to produce any clear symptoms. *Dioscorea alata* bacilliform virus (DaBV) is transmitted mechanically and by mealy bugs from *D. alata* to other *Dioscorea* spp. It may cause leaf distortion, crinkling and mottling in infected plants. In Nigeria, YMV, DaBV and CMV can be found together with DAV infecting *D. alata* cultivars, which are natural hosts of these viruses (Odu et al. 2006). The presence of another yam bacilliform virus has been indicated by DaBV being related serologically to a badnavirus from *D. bulbifera*, named *Dioscorea bulbifera* badnavirus (DbBV). Badnaviruses are highly diverse and prevalent in *Dioscorea* spp. of the Pacific and have been reported in *D. alata*, *D. bulbifera*, *D. esculenta*, *D. nummularia*, *D. pentaphylla*, *D. rotundata* and *D. trifida* (Kenyon et al. 2008). Powerful analytical tools are now allowing virologists to progress rapidly in the detection and identification of badnaviruses. In West Africa and the West Indies, the genomes of five yam badnaviruses have been elucidated (Umber et al. 2016). The complete genome sequences of three new yam badnaviruses from Fiji, Papua New Guinea and Samoa have been determined (Sukal et al. 2017).

The high prevalence of badnaviruses in West Africa suggests that the introduction of sanitized yam propagules could have an impact in reducing the incidence of virus disease. There are integrated badnavirus sequences (eDBVs) in yam. Unfortunately, PCR diagnostic techniques are not reliable enough to enable decisions regarding germplasm distribution. The existing serological techniques fail to react sufficiently to badnaviruses. The use of ELISA tests, with existing antisera as well as PCR, could make it possible to confirm their presence (Seal et al. 2014). NGS detects the genomes of novel isolates of already characterized viral species of the genera Badnavirus and Potyvirus, confirming the utility of NGS in diagnosing yam viruses (Bömer et al. 2019). Rolling circle amplification (RCA) is another method that can be used for yam badnavirus detection (Bömer et al. 2016; Sukal et al. 2019). RCA coupled with NGS has also been shown to be effective not only for detecting but also for characterizing yam badnaviruses, without the risk of detecting eDBVs (Sukal et al. 2020).

A novel virus named "yam asymptomatic virus 1" (YaV1) was sequenced from an asymptomatic *D. alata* cultivar from Vanuatu. The screening of a yam germplasm collection conserved in Guadeloupe showed that YaV1 is prevalent in *D. alata*, *D. bulbifera*, *D. cayenensis*, *D. esculenta* and *D. trifida* accessions but causes no apparent symptoms (Marais et al. 2020).

Sanitation of yam germplasm is a technically complex, slow and fairly expensive process that requires expertise and technical skills. The implementation of reliable PCR-based detection tools targeting eight different yam-infecting viruses in Guadeloupe has been described in detail (Umber et al. 2020). The high level of coinfections complexifies the process, and there is a need to combine thermotherapy and meristem

culture. Sanitation rates are, however, highly variable depending on viruses. It is very likely that in the near future, the powerful new molecular tools will allow virologists to detect new asymptomatic viruses, new viruses or new strains of already well-documented viruses. The situation will become increasingly complex for quarantine departments and for the international exchange of germplasm.

1.8 BREEDING PROGRAMS

The productivity of yam cultivation is under increasing pressure due to the shortening of fallows, reduction in soil fertility, and pest and disease build-up. Numerous pests and diseases are increasing in importance. Nematodes (*Scutellomena bradys* and *Meloidogyne* spp.) often interact with fungi (*Botryodiplodia*, *Fusarium*) and bacteria (*Erwinia* spp.) to damage *D. cayenensis* and *D. rotundata* tubers in the field and in storage. Anthracnose (*C. gloeosporioides*) and viruses infect *D. alata* foliage.

Yam breeding occurs in Nigeria, Benin, Côte d'Ivoire, Ghana, India, Guadeloupe, New Caledonia and Vanuatu, but it is focused only on the most economically important species (*D. alata*, *D. cayenensis* and *D. rotundata*). A comprehensive review of yam-breeding studies reveals that most activities concern the development of molecular markers, transcriptome and metabolome profiles of crucial traits, trait mapping and the generation of reference genome sequences for these three species. However, there is clearly a very slow translation of research results into practical applications (Darkwa et al. 2020a). This is not surprising considering the difficulties in accessing useful germplasm and the very small number of yam breeders worldwide. The other cultivated species (*D. bulbifera*, *D. dumetorum*, *D. esculenta, D. japonica*, *D. nummularia*, *D. oppositifolia*, *D. pentaphylla* and *D. trifida*) have not yet seen any breeding activity.

The breeding and selection of Guinea yams has been carried out at IITA since the 1970s with the primary focus on *D. rotundata*, the most important species throughout the yam belt (Mignouna et al. 2007). The principal objectives include high and stable yield of marketable tubers, suitability to prevalent cropping systems (plant architecture), good quality (DM content, texture, taste, rate of oxidation), resistance to biotic stresses in the field and good postharvest storage. As harvesting is the most expensive operation (in terms of labor requirements) throughout the crop cycle, the long-term objectives are to release genotypes that produce high yields without the need to stake, and to partially or completely mechanize harvesting. Other objectives would be to produce plants with several compact, oval or round tubers, with tough skins that are formed close to the soil surface.

The objectives for the genetic improvement of D. alata are almost identical across IITA (Nigeria), CNRA (Côte d'Ivoire), CSIR (Ghana), CIRAD and INRAE (Guadeloupe), ADECAL (New Caledonia), VARTC (Vanuatu) and CTCRI (India), except for a different emphasis on anthracnose (Arnau et al. 2010). The physicochemical characteristics of *D. alata* are a major challenge for West African breeders. This species has very desirable agronomic attributes but its suitability for traditional processing is far from accepted. In Nigeria, improving the nutritional quality of *D. alata* is a priority as this species is gaining in popularity among farmers because of its ease of cultivation, a situation observed through all of West Africa, from Cameroon to Guinea. Although *D. alata* is an introduced species in Nigeria with a genetic base assumed to be narrow, two-thirds of the accessions have been identified as being suitable for the preparation of boiled tubers, while only half were good for pounding. The challenge now is to breed cultivars that can be pounded into fufu and that are tolerant to anthracnose (Egesi et al. 2003).

1.8.1 Breeding techniques

Thousands of accessions from the large germplasm collections have been screened over the years to identify parental genotypes with breeding potential. Advances have been made in understanding the reproductive biology of yams, especially of *D. alata*, *D. cayenensis* and *D. rotundata*. Unfortunately, the cultivars that have the most desirable characteristics—either agronomic (e.g. compact tubers) or palatability (e.g. appropriate chemotype)—are those that do not flower. Various flower-induction techniques have been attempted, with disappointing results; more research is needed on this particular aspect.

An efficient and reliable controlled pollination technique is necessary to produce full sibs and progenies aimed at Mendelian segregation studies. In Nigeria, and for *D. rotundata*, which has male flowers of a size comparable to those of *D. alata*, the brush method has been found superior to other methods producing only 27.8% of fruit set (Akoroda et al. 1981). In India, the absence of efficient pollinators contributes to low seed set and, although it is time-consuming and labor-expensive, artificial pollination without bagging the female flowers is the only efficient way of producing hybrids. The rather long period of stigma receptivity of *D. alata* (Abraham and Nair 1990) and *D. rotundata* (Akoroda 1983) is an advantage for breeders.

In Côte d'Ivoire, it has been shown that for *D. cayenensis* and *D. rotundata*, polycross nurseries composed of parents that are selected carefully for their ploidy level and sex and established in plots isolated from pollen pollution can set fruits and produce considerable quantities of viable botanical seeds under normal conditions. Such polycross blocks offer the possibility of producing substantial populations of half-sibs (only the mothers being known) and to initiate a cycle of recurrent selection (Zoundjihékpon 1993).

In Vanuatu and New Caledonia, open and natural pollinations are very successful in *D. alata*, and numerous seeds have been produced in polycross nurseries using carefully selected anthracnose-resistant female plants. Profuse fruit set occurs naturally, but the capsules of anthracnose-susceptible female plants tend to be burnt during epidemics of the disease in wet weather, although weekly sprays of fungicide can be used to maintain the plants until the seeds are fully mature. Flowering ability is significantly improved in the hybrids; flowers can be observed as soon as the first clonal generation, and occasionally as soon as the F_1, in the seminal generation. The rate of flowering increases with the number of crossing cycles with a sex ratio tending to balance, becoming less favorable to males. In most breeding programs, the number of seed-setting cultivars is limited at first but, in the breeding process, it soon becomes possible to choose from clones resulting from crossings and, in fact, considerable variation is found in the progenies because of the highly heterozygous genetic makeup of yams. Polycross blocks are efficient for producing heterogeneous progenies (Norman et al. 2020). In New Caledonia, ADECAL has developed *D. alata* hybrids, 19 of which have been released officially to growers.

A critical step involves the identification of flowering genotypes with equivalent ploidy levels and good tuber quality. Parents showing traits relevant to the objectives of the breeding program are then selected for hybridization. The breeding process of *Dioscorea* spp. is very long, between 8 and 10 years, because of the very low multiplication rate of propagules and the existence of a juvenile phase during the seminal generation. Plants resulting from true botanical seeds cannot be evaluated properly during their first generation (F_1) and have to be propagated clonally before a reasonable assessment of their characteristics can be done during the first clonal generation.

In India, CTCRI in Trivandrum (Kerala) has developed *D. alata* hybrids, and several improved cultivars have been released to growers. Differences have been observed in the performance of sexually propagated seedlings of *D. alata* and their subsequent clonal derivatives. Seedlings are generally poor in field vigor, flowering and tuber yield, whereas their clonal descendants are vigorous and characterized by greater flowering and yield. In the second clonal generation (C_2), the majority of genotypes flower, facilitating hybridization, and tuber yield increases significantly, which aids the selection of high-yielding plants (Abraham 2002). Since compact tuber shape is one of the most desirable attributes of an acceptable cultivar, direct selection can be practiced, starting from the second clonal harvest (Abraham et al. 2006).

In Guadeloupe, CIRAD has developed a breeding program aimed at producing cultivars of *D. alata* resistant to anthracnose with high-quality tubers. Improved hybrids are now being evaluated in farmers' fields (Arnau et al. 2009; 2010; 2017). In Vanuatu, hybrids resistant to anthracnose have been produced, as have hybrids with *D. nummularia* (Lebot et al. 2019b).

At present, farmers' varieties (landraces) are the dominant cultivars in West Africa and elsewhere. This is thought to be due to the limited dissemination rate of improved hybrids. One major constraint is the breeding period needed to develop improved cultivars with consumer-preferred traits. At IITA, it is expected that the implementation of a new scheme could reduce the time to develop and recommend new cultivars from 9 to 3.5 years (Lopez-Montes et al. 2012). However, the greater yam, *D. alata*, was introduced clonally in Africa and its genetic base is narrow (Otoo 2017). There are many *D. alata* landraces around the world, especially in Melanesia, with attractive traits that could be introduced into Africa and provided to farmers, which could complement current breeding efforts. However, the presence of viruses is a constraint.

Another constraint in breeding yam is that, as *Dioscorea* spp. are dioecious, it is often difficult to identify diploid parents with synchronous flowering to produce enough seedlings to establish conventional heritability trials. Most germplasm collections are morphologically described, but the number of female parents with known ploidy is often very limited. This represents a major constraint for breeders, and there is a need to exchange female plants to broaden the genetic bases of breeding programs. In many countries, the female plants used for crosses are selected because of their sex and flowering ability but not necessarily because of their agronomic value.

For *D. alata*, successful crosses between diploids × tetraploids and tetraploids × tetraploids have been conducted, in addition to diploid × diploid crosses, to develop hybrids resistant to anthracnose. Parents from India and Vanuatu have been used. Anthracnose-resistant *D. alata* hybrids have been produced utilizing the tetraploid fertility in the species. The desired trait of oval, compact tuber shape, needed for ease of harvest, was found to occur in less than 10% of the evaluated hybrids (Lebot et al. 2019b). Breeders are attempting to produce round and compact cultivars with 80 chromosomes, as it is most likely that this type of genotype would be useful because these plants usually produce an exuberant foliage with large leaves. Such hybrids offer great potential to the improvement of the crop.

In *D. alata*, the observation of quadrivalents in the tetraploids provides cytological evidence for autotetraploidy. Sexually fertile natural autotetraploids of *D. alata* are of great interest because polyploidy breeding by conventional hybridization could produce tetraploids and triploids that are more vigorous and higher

yielding than diploids (Abraham et al. 2013). Enantiophyllum male and female plants of the same ploidy levels probably could be crossed; attempts at IITA and CTCRI have failed so far, but success may be achieved if breeders could have access to appropriate germplasm. Wide crosses with a great number of related species will give breeders access to a wide range of useful genes. However, it might be necessary to develop embryo rescue techniques to complement such work.

1.8.2 Use of wild relatives

Wild relatives are not used in breeding programs. Wild *Dioscorea* species' adaptation to a wide range of environments makes them attractive, but their use is constrained by the absence or small size and poor quality of their tubers. There is also the possibility of sexual barriers to hybridization with cultivars due to different ploidy levels (Lebot et al. 2019b). Furthermore, when two selected cultivars are crossed, the number of seedlings that exhibit wild traits (e.g. deformed tubers penetrating deep into the soil, profuse spininess, oxidation or bitterness of the tuber flesh) is very high, which requires removal in the F_1 generation and cloning of those remaining with potential.

However, there is considerable potential for the use of wild relatives to improve cultivated species. To date, studies using molecular markers have identified the wild relatives of *D. cayenensis* and *D. rotundata* (*D. abyssinica*, *D. mangenotiana*, *D. praehensilis*), but there is the question of conspecificity: these five taxa might represent wild and cultivated forms of fewer species. Sequencing of *D. rotundata* accessions and comparison with the sequences of the WR using an improved reference genome sequence of *D. rotundata* suggest a hybrid origin of white Guinea yam. It could have resulted from crosses between the rainforest wild species *D. praehensilis* and the savannah-adapted *D. abyssinica*. These highlight the importance of wild species as gene donors for improvement (Sugihara et al. 2020). The situation is more complex for *D. alata*. Factors such as the vast area of distribution (from India to Melanesia) and the fact that many cultivars are poorly improved (deformed tubers and flesh oxidation) and might be just clones of wild forms strengthen the case for a well-delimited species (Lebot et al. 2018b). The use of transgenic technologies to incorporate desired traits into the most popular cultivars is interesting because they allow rapid gene transfer from one cultivar to another, or from a wild species to a cultivar, bypassing problems related to heterozygosity. For example, if anthracnose resistance could be transferred to 'Florido,' the new cultivar would have greater potential. In West Africa, it has been shown that cultivars of the species *D. cayenensis* and *D. rotundata* can cross-pollinate naturally with wild relatives (Scarcelli et al. 2006; 2011) and therefore, transgenes could move easily from a genetically modified variety to other *Dioscorea* species.

***Dioscorea alata*.**
PHOTO CREDIT: Forest & Kim Starr/Wikimedia

2 SURVEY OF EXISTING GERMPLASM COLLECTIONS OF *DIOSCOREA* SPP.

A questionnaire (Annex 1) was sent to 105 addressees (Annex 2). Of those, 29 curators completed it and returned it to the coordinator. The information collected was processed by the coordinator (as data controller), in order to update the first global conservation strategy for yam (Crop Trust 2010). This data-processing operation was carried out as scientific research in the public interest. The personal and institutional data were stored for only four months without prejudice in accordance with to applicable regulations. The data were sent to the coordinator, and then transferred to the Crop Trust. In accordance with Regulation 2016/679 (GDPR) and local data protection law (in the EU), contributors have rights of access, modification, erasure and portability (when applicable) of personal data, and of limitation of and opposition to its processing, and they have the right to withdraw their consent at any time. Contributors also have the right to submit a complaint directly to the appropriate data protection supervisory authority.

2.1 GENERAL INFORMATION ON GERMPLASM COLLECTIONS

Up-to-date information on yam collections is difficult to obtain, especially in countries where yam is not a major crop. Much of the difficulty is that *ex situ* collections come and go quickly because limited resources are provided for their maintenance. These *ex situ* collections are very vulnerable to pests and diseases, natural disasters and civil unrest.

First, the present survey reveals a drastic reduction in the number of yam germplasm collections. According to FAO (2010, p. 259), in 2008, 99 *ex situ* collections were maintaining 15,903 accessions, whereas the present survey found only 31 *ex situ* collections maintaining 13,706 accessions. The names and addresses of the institutions that preserve germplasm are presented in Table 2.1.

The number of accessions of each yam species maintained in the 31 *ex situ* collections varies greatly (Table 2.2). The most represented species are the two major cultivated yams, *D. alata* (4,524 acc.) and *D. rotundata* (6,358 acc.). They are well preserved in most countries. Minor species are poorly represented in all collections, with the exception of *D. esculenta* (668 acc.) (Table 2.2). These figures clearly highlight the need to collect and store less represented species.

As expected, in West Africa, important *ex situ* collections exist in the major producing countries (Nigeria, Benin, Togo, Ghana, Côte d'Ivoire), with IITA hosting an international collection (5,839 acc.) that represents 42.6% of the total number of accessions maintained in *ex situ* collections in the world (13,706 acc.). Most collections are funded by governments or through institutions funded by public grants. Unfortunately, in many countries, the collections are not being used regularly by scientists or being distributed to farmers. This adds to their vulnerability because of the high costs involved in their management and maintenance. Very often, too few staff fully funded by their home institutions are involved in full-time maintenance and characterization work.

Few collections exist in Asia, where yams are minor crops. In India, Vietnam, the Philippines, Papua New Guinea, New Caledonia, Vanuatu and Fiji, rich and diverse collections are preserved and

are of utmost importance. Overall, Asian collections make up about 29.7% of the total number of accessions. Collections are much smaller in Indonesia now than they were in 2010, and would have disappeared from Malaysia; in Vietnam and the Philippines, the number of accessions is about the same as in 2010. More disappointing, however, is the number of collections that have disappeared from the Pacific island countries where yams are important crops and where diversity is substantial (Guarino and Jackson 1986; Jackson 1994). Some major collections have been abandoned (e.g. Solomon Islands), while others have been reduced substantially (e.g. Papua New Guinea). Fortunately, SPC (Suva, Fiji) runs a regional germplasm center that preserves some of these valuable Pacific genotypes *in vitro*.

It is possible that the first strategy surveyed only half of the *ex situ* collections maintained in the world, but, overall, the number of accessions has significantly increased in the major collections. Not only has the number of cultivars (farmers' varieties) in collections increased overall, but so too has the number of minor species and wild relatives (+718 acc.).

Nevertheless, a comparison of the data collected for the first global strategy in 2010 and the present survey (Table 2.3) indicates that significant efforts have been made over the past decade to collect and conserve yam genetic resources. The result is an increase of more than 6,000 accessions. The focus was on *D. alata* and *D. rotundata*.

Table 2.1 Major *Dioscorea* germplasm collections identified in August–September 2020.

Institution	Address	Curator	Owner	Year est.	No. of plants	Budget /year (USD)
Bangladesh Tuber Crops Research Centre (TCRC)	Tuber Crops Research Centre, Bangladesh Agricultural Research Institute Gazipur, 1701 Bangladesh www.bari.gov.bd	Harunor Rashid Tuber Crops Research Centre, Bangladesh Agricultural Research Institute, Gazipur Tel.: (+88) 49270178 james@bari.gov.bd	Government	2007	100	29,000
Benin Faculté des Sciences et Techniques, Université d'Abomey-Calavi (UAC)	Laboratoire de Biotechnologies, Ressources Génétiques et Amélioration des Espèces Animales et Végétales (BIORAVE), Dassa, P.O. Box 143 Benin	Alexandre Anagonou Dansi P.O. Box 143, FAST Dassa, UAC Tel.: (+229) 65813010 / 97276598 adansi2001@gmail.com	University	2001	4,600	52000
Brazil Universidad Federale de Amazonia (UFAM)	Av. Gal. Rodrigo O. J. Ramos, 6.200. Coroado. Manaus. 69080-900 Brazil www.fca.ufam.edu.br	Henrique dos Santos Pereira Rua Mem de Sá, 705. D. Pedro Manaus. Brazil Tel.: (+55) 92 999841721 Henrique.pereira.ufam@gmail.com, hpereira@ufam.edu.br	University	2015	500	5,700
Burkina Faso Institut de l'Environnement et de Recherches Agricoles (INERA)	Institut de l'Environnement et de Recherches Agricoles BP 8645, Ouagadougou 04 Burkina Faso www.inera.bf	Some Koussao 01 BP 476 Ouagadougou 01 Tel.: (+226) 76615894 / 71747167 koussao@hotmail.com	Government	2012	66	6,000
Cameroon Institut de Recherche Agronomique pour le Développement (IRAD)	IRAD P.O Box 2123 Yaoundé, Cameroon, 2123 www.irad.cm	Bouba Chrisian P.O Box 2123 Yaounde aoutaksa07@gmail.com	Government	2019	264	9,000

Institution	Address	Curator	Owner	Year est.	No. of plants	Budget /year (USD)
Colombia Universidad de Cordoba, Colombia (UCC)	University of Cordoba Carrera 6 No 76- 103 Monteria 230001 Colombia www.unicordoba.edu.co	Andres Alvarez Calle 40 No 14 - 58 Monteria, Colombia Tel.: (+57) 300 6787416 andresalvarez864@hotmail.com;andresalvarezs@correo.unicordoba.edu.co	Government	1998	3,100	5,400
Côte d'Ivoire Centre National de la Recherche Agronomique (CNRA)	CNRA 01 BP 1740 Abidjan 01 Côte d'Ivoire www.cnra.ci	Kouakou Amani Michel CNRA, BP 633 Bouaké Tel.: (+225) 02 02 11 11 amanimichelkouakou@gmail.com / Michel.kouakou@cnra.ci	Government		10,000	140,000
Cuba Instituto de Investigaciones de Viandas Tropicales (INIVIT)	Instituto de Investigaciones de Viandas Tropicales (INIVIT) Santo Domingo, Villa Clara 53 000 Cuba www.inivit.cu	Yuniel Rodríguez Apartado 6 Santo Domingo, Villa Clara Tel.: (+53) 52093067 geneticadioscorea@inivit.cu	Government	1970	125	52,000
Fiji Ministry of Agriculture (KRC)	Koronivia Research Station, Ministry of Agriculture, P.O Box 77, Nausori, Suva, Fiji www.agriculture.gov.fj	Savenaca Cuquma Koronivia Research Station KRC Tel.: (+679) 3477044 (office) 9700 939 (mobile) scuquma@gmail.com	Government	1980	10,000	11,750
France Institut de Recherches pour le Développement (IRD)	IRD, 911 avenue Agropolis Montpellier 34394, France www.ird.fr	Scarcelli Nora IRD, 911 avenue Agropolis Montpellier 34394 Tel.: +33(0) 4 67 41 61 65 nora.scarcelli@ird.fr	Government	2000	10	
Ghana (Bunso) Council for Scientific and Industrial Research (CSIR)	CSIR-Plant Genetic Resources Research Institute Bunso, BU 7, Ghana www.csir.pgrri.org.gh	Lawrence Aboagye Misa CSIR, Bunso P.O Box 7 Eastern Region, Ghana Tel.: (+233) 277766955 aboagyelawrencemisa@yahoo.com	Government	1964	277	34,803
Ghana (Kumasi) Council for Scientific and Industrial Research (CSIR)	CSIR-Crops Research Institute, Kumasi Postal Code: 00233 Ghana csir-cropsresearchinstitute.org	Emmanuel Otoo CSIR-Crops Research Institute, P.O. BOX 3785 Kumasi otooemmanuel@gmail.com	Government	1970		
Ghana (Tamale) Council for Scientific and Industrial Research (CSIR)	CSIR – Savanna Agricultural Research Institute Tamale, Box TL 52 Ghana https://sari.csir.org.gh/	Emmanuel Chamba CSIR – Savanna Agricultural Research Institute, Tamale Tel.: (+233) 558049744 echamba@gmail.com	Government	2015		10,200
Guadeloupe CRB Plantes Tropicales – Antilles (CRB, CIRAD, INRAE)	INRAE Antilles-Guyane, Domaine Duclos Petit-Bourg, 97170 France (Guadeloupe) http://intertrop.antilles.inra.fr/Portail/	Yoana Faure INRAE Antilles-Guyane, Domaine Duclos Petit-Bourg Tel.: (+590) 25 59 80 yoana.faure@inrae.fr	Government	1964	5,700	292,000
Haiti Direction Départementale Agricole du Sud Est (DDA/SE)	Direction Départementale Agricole du Sud Est (DDA/SE) Jacmel, 9110 Haïti	Ricot Scutt # 3 Rue Charlotin Marcadieu Jacmel, Tel.: (+509) 37 90 66 47 / 44 06 7028	Government		200	1,000

Institution	Address	Curator	Owner	Year est.	No. of plants	Budget /year (USD)
		ricotscutt@yahoo.fr				
India Indian Council of Agricultural Research (NBPGR)	ICAR-National Bureau of Plant Genetic Resources, Pusa Campus, New Delhi, 110 012 India www.nbpgr.ernet.in	Veena Gupta Division of Germplasm Conservation, ICAR- Pusa Campus, New Delhi Tel: (+91) 11 258026268 veena.gupta@icar.gov.in	Government	1986	3,000	6,300
India Central Tuber Crops Research Institute (CTCRI)	ICAR-CTCRI 695017 Thiruvananthapuram Kerala, India www.ctcri.org	M.N. Sheela Head of Crop Improvement 695017 / Thiruvananthapuram Kerala, India Tel.: (+91) 0471 2598551 sheelactcri@yahoo.co.in sheela.mn@icar.org	Government	1963	1,100	18,355
Indonesia Research Center for Plant Conservation, Indonesian Institute of Sciences (LIPI)	Jl. Surabaya-Malang Km.65, Purwodadi Pasuruan, 67163 Indonesia www.krpurwodadi.lipi.go.id	Fauziah Zulkarnain Sidosemi, Purwodadi Pasuruan Tel.: (+62) 856 4554 6215 fauziahkrp@gmail.com	Government	2011	150	4,020
Japan National Agriculture and Food Research Organization (NARO)	Genetic Resources Centre National Agriculture Food Research Organization http://www.naro.affrc.go.jp/	H. Kawaguchi 2-1-1 Kannondai, Tsukuba, Ibaraki 305-8602, Japan Tel.: +81-29-838-7467 Fax: (+81)-29-838-7054	Government			
La Réunion Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD)	CIRAD, UMR PVBMT, Station de Ligne-Paradis - 7 chemin de l'IRAT Saint Pierre 97410 Réunion (France) http://www.cirad.fr/	Marc Seguin 7 chemin de l'IRAT 97410 Saint-Pierre, Réunion (France) Tel.: (+262) (0)2 62 49 27 25 marc.seguin@cirad.fr	Government			
Madagascar Kew Madagascar Conservation Centre (KMCC)	Kew Madagascar Conservation Centre (KMCC) Antananarivo 101 Madagascar	Mamy Tiana Rajaonah KMCC, Antananarivo Tel: (+261) 340409552 mrajaonah.rbgkew@moov.mg	Research Institute	2015	200	
New Caledonia Agence pour le Développement Economique de la Nouvelle-Calédonie (ADECAL)	Pôle Terrestre ADECAL – Technopole Nouvelle-Calédonie Tel.: (+687) 44 12 20 / (+687) 87 44 33 www.technopole.nc	Méryl Jordan Centre des Tubercules Tropicaux, CTT Tribu de Wagap, Poindimié Tel.: (+687) 43 08 51, or 44 12 20 sebastien.blanc@adecal.nc meryl.jordan@adecal.nc	Government	1990	3,000	265,000
Nigeria International Institute of Tropical Agriculture (IITA)	International Institute of Tropical Agriculture Ibadan, 234 Nigeria www.iita.org	Michael Abberton IITA, Genetic Resources Center (GRC) Oyo Road, PMB 5320 Ibadan, Nigeria Tel.: (+234) 8039784482 m.abberton@cgiar.org	International Research Institute	1985	145,975	525,000
Nigeria National Root Crops Research Institute (NRCRI)	National Root Crops Research Institute, Umudike. Umuahia, PMB 7006. Nigeria www.nrcri.gov.ng	Ikoro Anyim Ikoro. Genetic Resources Unit, National Root Crops Research Institute, Umudike Umuahia Tel.: (+234) 8027315439	Government	1998	2,000	

Institution	Address	Curator	Owner	Year est.	No. of plants	Budget /year (USD)
		ikoromarshall@yahoo.com				
Pacific Secretariat of the Pacific Community (SPC)	Pacific Community Land Resources Division Centre for Pacific Crops and Trees (CePaCT) Suva, Fiji www.spc.int	Logotonu M. Waqainabete Programme Leader – Genetic Resources, 3 Luke St PMB, Nabua, Suva, Fiji. Tel.: (+679) 3379273 Mobile: (+679) 8629214 logow@spc.int/amits@spc.int	Regional Organization	2001	3,135	134,750
Papua New Guinea National Agricultural Research Institute (NARI)	National Agricultural Research Institute P.O. Box 4415, Lae, Morobe Province Papua New Guinea www.nari.org.pg	Janet Paofa NARI Southern Regional Centre Laloki, P.O. Box 1828 Port Moresby janet.paofa@nari.org.pg	Government	2000	700	
The Philippines The Philippines Root Crop Research and Training Center (PhilRootCrops)	PhilRootCrops Baybay City, Leyte, 6521-A The Philippines philrootcrops.vsu.edu.ph	Linda Vasquez Baybay City, Leyte, 6521-A Tel.: (+63) 053 563 7229 lindavasq@yahoo.com, philrootcrops@vsu.edu.ph	Government			
Sri Lanka Field Crops Research and Development Institute (FCRDI)	Department of Agriculture Mahailluppallama, 50270 Sri Lanka www.doa.gov.lk/ FCRDI/index.php/en/	Ravinda Senanayake 50270, Mahailluppallama Tel.: (+94) 252249132, 779027794 ravisena@gmail.com, fcrdimi@gmail.com	Government	2015	400	2,800
Togo Institut Togolais de Recherche Agronomique (ITRA)	Institut Togolais de Recherche Agronomique Tel.: (+228) 22 25 30 96 Lomé 1163 Togo itra@cafe.tg	Elom H.S. Kinglo ITRA / Ferme Semencière de Sotouboua / Qt : Watchalo Sotouboua Tel.: (+228) 91 86 67 55 elomkinglo@gmail.com	Government	1988	105	8,100
Vanuatu Vanuatu Agricultural Research and Technical Centre (VARTC)	VARTC, Saraoutou Station PO Box 231, Luganville, Vanuatu Tel.: (+678) 36420 www.vartc.vu	Floriane Lawac Head of Root Crops Section VARTC Tel.: (+678) 36420, 7334982 flhinano18@gmail.com	Government	1996	3,000	7,600
Vietnam National Plant Genebank Plant Resources Center (PRC)	Plant Resources Center Hanoi: 100000 Vietnam www.prc.org.vn	Le Van Tu Plant Resources Center (PRC) Hanoi Tel.: 84- 938988262 levantuht@gmail.com or kiennguyenvan8@gmail.com	Government	1992	2,760	50,000

Table 2.2 Number of accessions in each country collection by *Dioscorea* spp., from survey responses. Key: alata: ala; bulbifera: bul; cayenensis: cay; dumetorum: dum; esculenta: esc; japonica: jap; nummularia: num; oppositifolia: opp; pentaphylla: pen; rotundata: rot; trifida: tri; others: other; wild relatives: wild); * Information retrieved from institution's website; the questionnaire was not returned.

Country	ala	bul	cay	dum	esc	jap	num	opp	pen	rot	tri	other	wild	total
Bangladesh	15	4	0	0	0	0	0	0	0	0	0	0	0	19
Benin	10	0	12	6	0	0	0	0	0	1,089	0	0	31	1,148
Brazil	0	0	0	0	0	0	0	0	0	0	57	0	0	57
Burkina Faso	10	0	15	0	0	0	0	0	0	0	0	41	5	66
Cameroon	20	17	7	24	0	0	0	0	0	64	0	0	0	132
Colombia	118	1	2	0	2	0	0	0	0	25	4	2	0	154
Côte d'Ivoire	290	2	0	2	10	0	0	0	0	309	0	0	0	611
Cuba	106	3	9	0	2	0	0	0	0	5	1	0	0	126
Fiji	70	2	1	0	19	0	3	0	3	2	0	0	0	100
France	0	0	0	0	0	0	0	0	0	10	0	0	123	133
Ghana (Bunso)	50	4	0	5	8	0	0	0	0	10	0	0	0	77
Ghana (Kumasi)	85	20	0	51	0	0	0	0	0	48	0	0	0	204
Ghana (Tamale)	87	0	0	0	0	0	0	0	0	414	0	0	0	501
Guadeloupe	148	6	79	0	8	0	1	0	0	0	176	3	6	427
Haiti	39	2	6	0	1	0	0	0	0	4	2	0	0	54
India (Delhi)	119	6	0	0	6	0	2	5	13	15	0	0	74	235
India (Kerala)	646	6	0	0	222	0	0	35	31	158	0	135	54	1,151
Indonesia	50	2	0	0	9	0	0	0	1	0	0	20	0	82
IITA	1,252	70	85	77	21	0	0	0	0	3,901	0	0	433	5,839
Japan*	9	0	0	0	0	43	0	0	0	0	0	3	0	55
La Réunion	11	2	0	0	0	0	0	0	0	0	0	0	0	13
Madagascar	105	2	0	0	1	0	0	0	0	0	0	0	85	193
New Caledonia	265	2	4	0	5	0	0	0	1	0	0	2	0	279
Nigeria	30	100	3	5	21	0	0	0	0	160	0	0	0	319
Papua N Guinea	84	1	0	0	39	0	10	0	0	2	0	0	0	136
Pacific (SPC)	231	8	0	0	41	0	2	0	1	33	1	13	0	330
Philippines*	240	18	0	0	78	0	0	0	1	12	0	0	0	370
Sri Lanka	31	1	0	0	7	0	0	1	0	0	0	2	0	42
Togo	16	3	1	4	1	0	0	0	0	84	0	0	0	109
Vanuatu	237	24	2	0	47	0	10	0	1	13	1	6	0	341
Vietnam	150	6	0	0	120	0	0	0	0	0	0	0	0	276
Total	4,524	312	226	174	668	43	28	41	52	6,358	242	227	811	13,706

Table 2.3 Number of accessions maintained in *ex situ* collections per cultivated edible *Dioscorea* sp. Source: Data from the first global strategy for yam (Crop Trust 2010) and from the present survey (2020).

Species	First global strategy 2010		Present survey 2020		Variation
	No. of accessions	%	No of accessions	%	2010/2020 +/– acc.
D. alata	2,763	24.5	4,524	33.0	+ 1,761
D. bulbifera	164	2.1	312	2.3	+ 148
D. cayenensis	393	5.3	226	1.6	– 167
D. dumetorum	0	0	174	1.3	+ 174
D. esculenta	215	4.2	668	4.9	+ 453
D. japonica	0	0.7	43	0.3	+ 43
D. nummularia	81	0.3	28	0.2	– 53
D. oppositifolia	20	0	41	1.3	+ 21
D. pentaphylla	65	0.4	52	0.4	– 13
D. rotundata	3,631	26.5	6,358	46.4	+ 2,727
D. transversa	10	0.0	0	0.0	– 10
D. trifida	35	1.0	242	1.8	+ 207
Others/wild	320	35.0	1,038	7.6	+ 718
Total	7,697	100.00	13,706	100	+ 6,009

Table 2.4 Countries of origin of accessions maintained in the IITA international collection (August 2020). Country codes: BEN = Benin, BFA = Burkina Faso, CIV = Côte d'Ivoire, GNQ = Equatorial Guinea, GAB = Gabon, GHA = Ghana, GIN = Guinea, NGA = Nigeria, SLE = Sierra Leone, TZA = Tanzania, TGO = Togo.

Species	BEN	BFA	Congo	CIV	GNQ	GAB	GHA	GIN	NGA	SLE	TZA	TGO	Total	%
D. alata	377	5	9	107	1	4	83	0	239	25	1	401	1,252	21.4
D. abyssinica	90	0	0	1	0	0	0	0	0	0	0	0	91	1.6
D. bulbifera	3	2	7	0	2	12	2	1	17	4	0	20	70	1.2
D. burkilliana	292	0	6	0	0	0	0	0	0	0	0	0	298	5.1
D. cayenensis	14	0	3	6	0	0	15	0	40	0	0	7	85	1.5
D. dumetorum	7	0	2	0	0	2	4	0	46	0	0	16	77	1.3
D. esculenta	0	0	0	2	0	0	2	1	4	0	0	12	21	0.4
D. praehensilis	0	0	0	0	0	0	21	0	0	0	0	23	44	0.8
D. rotundata	1,130	5	4	145	3	1	165	29	1,535	5	0	879	3 901	66.8
Total	1,913	12	31	261	6	19	292	31	1,881	34	1	1 358	5,839	100

Most of these 31 collections are maintained only in the field. Very few countries have the means to duplicate their field collections using *in vitro* techniques (slowing growth by manipulation of

media, temperature or light, 25 °C, 12 h of light/day, transplanted once a year) as a complementary method of conservation. There are *in vitro* collections in Benin, Côte d'Ivoire, Ghana, Cuba, India (core collection), Vietnam, the Philippines and SPC (Fiji). In SPC, all accessions are maintained *in vitro* but there are no backup collections in the field.

True botanical seeds are rarely mentioned as part of conservation strategies, although NBPGR (India) uses seeds for preserving wild relatives. The breeding programs (Côte d'Ivoire, Ghana, Benin, IITA, CTCRI, VARTC and Guadeloupe) provide evidence that seeds can also be used for preservation of genes of interesting genotypes. Madagascar collects seeds of wild yams species, which are stored in SNGF (Silo National des Graines Forestières) for *ex situ* conservation.

At present, IITA (Nigeria) and SPC (Fiji) are the only institutions that maintain international collections of *Dioscorea* spp. IITA maintains accessions originating from 12 countries. SPC is a regional institution that maintains *in vitro* yam collections for eight Pacific island countries. Both collections are held under Article 15 of the ITPGRFA.

Most IITA accessions are of West African origin, with 5,152 from only three countries (Nigeria, Benin and Togo), accounting for more than 88% of the total number of accessions (5,839) (Table 2.4).

There is still a need to collect more accessions from Cameroon (IITA collected 90 accessions from Cameroon which are still in the process of being integrated into the collection), Ethiopia and other countries where *D. rotundata* is cultivated. For *D. alata*, accessions need to be collected from East Africa and Madagascar. These findings reveal a need to enrich this international collection with germplasm from other regions of Africa and Asia. This is especially true for a species as important as *D. alata*, which was introduced clonally into Africa from Southeast Asia (probably with plantains and taro) and which does not set seeds in farmers' fields. The high numbers of accessions for *D. alata* from Benin (377) and Togo (401) are surprising. As *D. alata* are often non-flowering, it is doubtful that the number represents different genotypes, a fact already remarked upon for Benin (Adoukonou-Sagbadja et al. 2014). It is known that the genetic base of clones distributed over wide geographic distances is narrow and that many accessions are probably duplicates of the same cultivar. A comprehensive survey of the allelic diversity of *D. alata* in Africa is therefore needed.

Generally, wild species are not well represented in the collections (Table 2.5). The IITA collection does contain wild representatives (433) of the Guinea yams (*D. abyssinica*, *D. burkilliana*, and *D. praehensilis*), but relatives of *D. alata* (*D. glabra*, *D. hamiltonii,* and *D. wightii*) are less represented. In Madagascar, *D. alata* cultivars and a unique set of endemic species are preserved (83 acc.) as they are endangered. In India, ICAR in New Delhi and CTCRI in Trivandrum, Kerala, preserve endemic wild species that have medicinal properties.

These wild species are not used for breeding purposes. In some cases, they belong to different taxonomic sections and are unlikely to be cross-compatible. Those belonging to the Enantiophyllum section do not present traits that are sufficiently attractive to convince breeders to conduct crosses. The variation existing within the two major species, for which breeding programs exist, is such that there is no need to search for useful genes in the wild reservoir. For example, resistance to anthracnose or tuber flesh with high DM content are traits present in *D. alata* accessions. The trait of tuber flesh with no oxidation exists in *D. rotundata* germplasm. Preservation of wild species is, therefore, done for the purpose of protecting endangered species rather than to protect genotypes of interest. Most wild species produce tubers with very poor shape and flesh quality.

Table 2.5 Wild *Dioscorea* species maintained in *ex situ* collections.

Wild species	IITA	UAC	IRD	ICAR	CTCRI	KMCC	LIPI	FCRDI	PRC	Total
D. abyssinica	91	15	103							209
D. acuminata						2				2
D. alatipes						1				1
D. antaly						9				9
D. arcuatinervis						1				1
D. analalavensis						1				1
D. bako						1				1
D. belophylla					2					2
D. bemarivensis						1				1
D. bemandry						1				1
D. bosseri						4				4
D. buckleyana						1				1
D. bulbifera				12					6	18
D. burkilliana	298	4								302
D. deltoidea				19						19
D. fandra						3				3
D. floribunda				1	1					2
D. glabra				6	2					8
D. hamiltonii				2	1					3
D. hispida				9	12		20			41
D. intermedia					1					1
D. irodensis						1				1
D. koyamae								1		1
D. maciba						9				9
D. orangeana						2				2
D. ovinala						1				1
D. praehensilis	44	12	20							76
D. pteropoda						4				4
D. pubera				1	5					6
D. pyrifolia				2						2
D. sambiranensis						21				21
D. sansibarensis						6				6
D. sativa								1		1
D. seriflora						1				1
D. serpenticola				1						1
D. soso						11				11
D. spicata				1	2					3
D. tomentosa				4	5					9
D. trichantha						2				2
D. vexans					1					1
D. wallichii				16	20					36
D. wightii					1					1
Total	433	31	123	74	53	83	20	2	6	827

2.2 MANAGEMENT OF THE COLLECTIONS

Germplasm management practices differ considerably between curators. Species identification, acquisition, classification, characterization, evaluation and distribution appear to be adequate at the national level. However, for more technical functions such as regeneration, documentation, storage, health control and safety duplication, which are often critical activities, some collections are facing serious difficulties.

Only a few collections have procedures for these activities, and only IITA has formal standard operating procedures (SOPs) that have been reviewed and audited externally. Most collections have good passport data (90–100%), including the name of the accessions and their place of origin, but poor characterization and evaluation data (Table 2.6). Most descriptions are based on qualitative traits, but agronomic performance and disease tolerance are rarely documented.

Table 2.6 Characterization and evaluation data available for all accessions.

Cultivated species	Total no. of accessions	% with passport data	No. of farmers' varieties	No. landraces selected for distribution	Breeding lines being evaluated	Improved varieties for distribution
D. alata	4 524	91	3,961	1,007	1,878	82
D. bulbifera	312	100	301	27	0	0
D. cayenensis	226	66	226	32	0	0
D. dumetorum	174	23	61	0	0	0
D. esculenta	668	99	668	111	0	3
D. japonica	43	100	43	43	0	0
D. nummularia	28	100	18	12	0	0
D. oppositifolia	41	71	41	41	0	0
D. pentaphylla	52	81	52	0	0	0
D. rotundata	6,358	96	4,634	2,023	2,309	111
D. trifida	242	86	242	0	0	0
Others / wild	1,038	17	0	0	0	0

All collections have been described using IPGRI descriptors, but duplicates have not been detected and removed. Quite often, a reduced set of descriptors is used. Very often, the collections have become too large with too many accessions to be maintained properly, as human resources are limited. Curators reported that mislabeling occurs occasionally.

Most countries maintain their collections in the field with an average of 4–5 duplicates per accession (Table 2.7). Most often, plants are grown on mounds at 1.0 × 1.0 m or 1.5 × 1.5 m spacing. The collections are replanted every year, sometimes on different sites. *In vitro* slow-growth conservation is done at 16–18 °C, with a 12 h photoperiod. In Benin, breeding materials are stored in net bags during the dry season for a short period before germination and replanting. In India, wild relatives collected from forests are conserved in shade net houses.

Facilities for *ex situ* conservation and storage are generally adequate for those collections that maintain tubers in storage rooms for the few months between two growing seasons. Storage conditions for tubers vary enormously, particularly with regard to temperatures and relative humidity in the store houses. Several collections reported that they do not have optimal facilities for storage of vegetative material and that their facilities need to be upgraded.

The major concern of germplasm curators is the erosion of their collections, both in the field *and in vitro*. Most curators reported having an *in vitro* backup collection of their accessions, either locally (India, Vietnam, the Philippines), within the IITA international collection for West African countries, or within the SPC, for Pacific island countries.

A substantial part of the collections from countries in West Africa are duplicated in the IITA collection. The *in vitro* slow growth of meristem-derived plantlets using controlled light and temperature and one or two episodes of subculturing per year allows medium-term conservation.

Table 2.7 Type of germplasm storage in major collections (>200 acc.).

Type	IITA acc.	CTCRI	Benin	Côte d'Ivoire	CSIR Ghana	CRB Guad	Nigeria	SPC	VARTC	PRC	CTT NC	ICAR
True botanical seeds	–	–	2,400	–	1,200	–	–	–	–	–	–	12
Maintained in the field*	5,839	2,857	800	611	173	135	319	–	409	270	279	–
In pots in screen house	–	119	–	–	–	16	–	31	–	–	–	62
In vitro slow growth	3,100	75	60	300	30	410	–	330	–	120	–	168
In vitro cryopreserved	–	–	–	–	–	–	–	–	–	–	–	6
Farmers' varieties	–	809	741	611	173	–	–	–	341	270	279	–
Breeding lines	859	1,841	450	>1,000	34	–	–	–	53	–	–	–
Wild relatives	433	119	31	–	–	6	–	–	–	6	–	–

* Includes wild relatives

For some species, meristem culture remains a constraint as some accessions are recalcitrant and, for some institutions, *in vitro* conservation is still a risky undertaking. One institution reported having lost almost its entire collection due to a power outage during a weekend; there was no field backup.

Cryobanking (conservation at very low temperature, generally in liquid nitrogen) is not yet deployed for yam. It is used only in ICAR (New Delhi). Two institutions are considering developing it (IITA and SPC). Various protocols have been suggested (Malaurie et al. 1993; Dumet et al. 2007). Cryobanking needs a regular supply of liquid nitrogen and occasional sample regeneration. However, cryobanking may be one of the most economical and efficient long-term storage options for selected, well-characterized and documented yam cultivars.

PHOTO CREDIT: JEFF HASKINS

2.3 CLASSIFICATION, CHARACTERIZATION AND DOCUMENTATION

Most of the collections have good passport data, and the species are identified. The IITA collection database indicates the twining direction of the stem, and 120 traits are described (Annex 3). The IITA characterization database (all species combined) is freely downloadable online. It shows that 443 accessions are male and 1,250 accessions are female; no data are recorded for ploidy levels. The database also shows that 3,173 accessions have been morphologically described, although incompletely. Of these, 1,619 accessions present cylindrical tuber shape, 856 are oval, 181 are oval-oblong, 232 are round, and 24 are irregular; the tuber shape is not described for 261.

Other country collections have been characterized using a smaller list of descriptors. However, characterization data are not available online, so it is difficult to know exactly which types of data are missing. However, it can be assumed that ploidy levels and sex have not been determined, given that they are not recorded for the international collections.

There is no dichotomous key based on morphological traits that is sufficiently accurate to stratify collections before molecular analysis to define a national core. The exceptions are those accessions from the IITA core collection and INRAE in Guadeloupe, for which incomplete molecular studies have been done but no elite subsets identified for each species. IITA has composed a core collection that includes six species.

There have been limited molecular studies carried out for current *ex situ* collections to identify genetic gaps in yam species diversity that might be filled from other collections around the world. However, as most cultivars were historically moved clonally from one country to another, the real diversity is probably much narrower than expected. There is very limited knowledge on the ploidy level and sex of accessions, and less than a fifth of the accessions have been characterized for these two essential traits.

Most accessions remain untested for yam pathogens; this is often due to a lack of resources as well as information on the pathogens likely to affect collections, especially viruses. Many collections are dependent on project funding for most research activities, which directly impact their operational efficiency.

Although most collections stated that they use computerized information systems to manage their collection data, it was often reported that electronic documentation was only partly completed. In general, passport data, which are often recorded using Microsoft Excel spreadsheets, are more completely computerized than data on characterization and agronomic evaluation, including resistance to diseases. Data associated with passport information, characterization, evaluation, management and photographs are recorded using a variety of tools, including database systems, spreadsheets or log books. However, completeness of this information varies, both within and between collections: some accessions are well documented while others are not. These data are kept with curators and are rarely available online. During the survey, it was found that only IITA characterization data was freely available online (see URL above).

The international Genesys database for yams is far from complete. In particular, it lacks data for collections in Asia (see Table 1.3). Those from SPC (Pacific) are included. The Genesys database is composed of data provided by partners that correspond to the same accessions as those reported in the present survey. Characterization and agronomic evaluation data are not included in the international databases at all, and only a few collections provide this type of information

through their own websites. For most collections, the only available information is on the number of accessions per *Dioscorea* species. As no information exists on ploidy levels and sex, improvement of these databases for these two essential traits, along with evaluation data, will contribute substantially to better management, conservation and use of yam germplasm.

According to the survey, most data are recorded in spreadsheets (e.g. Microsoft Excel), but a few institutions are looking at PGR focused SQL-based software, namely an open source platform initially developed by the USDA and the Crop Trust called GRIN(https://www.ars-grin.gov/Pages/Collections), to manage their accession information. More collections keep passport data (e.g. accession name, country of origin) in a database and/or spreadsheet. Regarding access and availability of information related to germplasm, in most cases, the data are publicly available to all on demand, but only IITA has a website from which the data can be freely downloaded. In some cases, if the data are not publicly available, they are still available upon request or through project reports. In Ghana, CSIR publishes information on their collection of roots and tuber crops on GBIF (Global Biodiversity Information Facility).

Generally, there is a need to support the use of a user-friendly genebank documentation system in collections and several collections are seeking new data management systems (e.g. GRIN).

2.4 HEALTH OF GERMPLASM

All curators who returned their questionnaires (29) report that their collections are affected by pests and diseases. All report that they need assistance to improve the health status of the collection; many also report a need to establish tissue culture and viral indexing facilities. When germplasm is distributed, it is rarely virus indexed (except that from IITA and SPC) and then only for a small subset of accessions.

Accessions must be free of pests and pathogens before they can be exchanged. Consequently, accessions need to be carefully monitored in field collections or during storage, but this is rarely the case because resources are limited. Specific protocols for detecting the major pathogens have been developed and vary by organism and host. They are required for accurate identification of most pathogens. Most countries apply the IPGRI descriptors for yams when scoring their *ex situ* field collections for pests and diseases.

A few curators from West Africa and the Pacific indicated that their collection has been partially or completely duplicated elsewhere because of the risks of pests and diseases in the field. It is not known in sufficient detail how many accessions of yam are currently safety duplicated. It will be necessary to update the level of safety duplication once the databases have been improved. Most curators are collaborating with quarantine officers to assess pest risk and to classify yam pathogens (mostly viruses) as regulated or non-regulated quarantine pests. Curators are demanding simple and cost-effective diagnostic tools for the rapid assessment of *in vitro* plantlets maintained in their own laboratory to allow the safe distribution of germplasm.

Most curators have selected for distribution cultivars that are being propagated on research stations, but the health status of these cultivars is often uncertain. Curators recognize the need for safe conservation and distribution of yam germplasm, and to build capacity to safeguard valuable yam germplasm from pests and pathogens. The build-up of pests and pathogens in research station fields is a problem. When new accessions are collected and inserted into the field collection, they are exposed to the inoculum existing in the collection. In many countries, the situation is complex, and there is a recognized need to develop reliable protocols for the production of pest-free planting materials.

The FAO/IBPGR Technical Guidelines for the Safe Movement of Yam Germplasm (Brunt et al. 1989) describe the procedures that minimize the risk of pest introductions. These guidelines are still valid but should be updated. Many new viruses have been isolated, described and documented in the past three decades. The currently recommended protocol is for tissue-cultured plantlets of an introduced accession to be grown in post-entry quarantine for six months (Brunt et al. 1989). Furthermore, visual examination of the plantlets, electron microscopy, and molecular testing should be conducted at three and six months. Specific tests are then carried out for known viruses, and nonspecific tests for unknown viruses, and only plants that index negatively should be distributed. This is a very laborious and lengthy procedure, and very few countries consider the introduction of such germplasm to be a priority. However, since these guidelines were developed, new molecular tools have allowed virologists to detect new viruses and new strains, all of which represent new potential threats to quarantine services.

Tuber-borne diseases and virus infections of tubers seriously restrict distribution of yam germplasm. Nineteen collections report problems in securing a sufficient health status for their germplasm. The eradication of viruses from tubers of cultivated yam material is a recurring need, because cleaned germplasm often gets reinfected when it is grown in the field.

Yam accessions should be transferred as sterile, pathogen-tested plantlets growing on tissue-culture medium. To date, it seems that transfer of such material has only been used for *D. rotundata* and *D. cayenensis* from West Africa and *D. alata* from the Pacific to Africa (Benin) and the Caribbean (Guadeloupe). The proposed technique is, however, hampered by the fact that very few partners have access to tissue culture laboratories. In practice, meristem tips should be cultured either in the country of origin or at an intermediate quarantine center. Ideally, *in vitro* plantlets should be tested for viruses in the country of origin or in an intermediate quarantine station. However, this recommendation limits the opportunities for such transfer of germplasm as very few institutions have *in vitro* laboratories. The result is that there is very limited movement of yam germplasm, if any, due to the difficulty of complying with phytosanitary regulations.

Nowadays, it is practically very difficult to import virus-free yam genotypes and the risk–benefit analysis does not make it attractive enough. In most countries (except five West African countries), yam are minor crops and, therefore, quarantine services are not inclined to take any risks with the introduction process. None of the curators reported any plans to introduce new genotypes *in vitro* from elsewhere. All curators believe that there is sufficient diversity in their collections to satisfy local needs and meet local demand.

A majority of countries restrict the introduction of yam material and follow the FAO/IBPGR technical guidelines (Brunt et al. 1989), which recommend that plants be virus-tested and transferred between countries as sterile tissue cultures. All curators know and accept this recommendation; however, as these countries have limited therapeutic capacities and the production of virus-free plants is technically complex, expensive and slow, international distribution is extremely limited. Consequently, further research to speed up the production of healthy germplasm is urgently needed.

To date, only part of the core sample of SPYN and the regional West Africa core collection have been virus-indexed and are available from SPC (Fiji) and IITA (Nigeria), respectively. Badnaviruses have proved a particular problem in the provision of healthy plants.

The present survey indicated that most countries recognize the need for regional well-equipped

virology and molecular diagnostics laboratories using ELISA and PCR (and more advanced tools such as genome sequencing as protocols are under development) to index plants for viruses, along with therapy and tissue culture facilities to remove infections. Some curators suggested that the protocols for yam virus diagnosis and cleaning need to be defined, to create a global standard operating procedure (SOP) for yam. The diversity of yam viruses in one region of the world might differ from that of other regions. For example, YMV is not found in the Pacific (Kenyon et al. 2003; Kenyon et al. 2008). However, as few studies have been carried out in most regions, much of the viral diversity remains uncharacterized.

Additional funding and international cooperation are needed to ensure that a globally recognized SOP is developed for yam pathogen testing. Further research into pathogen cleaning is also needed, and the discussion around which yam viruses are of quarantine risk, and which ones are not, is urgent, to dispel the existing uncertainty.

Yam viruses are now well known to the international community to pose a major risk to the international transfer of yams. Consequently, the safe movement of yam germplasm requires adequate virus-indexing procedures (Bömer et al. 2019) and virus-elimination procedures. However, some viruses may cause asymptomatic infections (Marais et al. 2020) or occur without economic cost, so defining which ones represent a threat might facilitate the distribution of accessions.

2.5 DISTRIBUTION OF GERMPLASM

Most distribution of germplasm occurs at the national level, from the research stations that hold the collections to partners in the same country (Table 2.8). All the institutes with major collections distribute yam tubers (minisetts or small tubers) within their country, albeit in small amounts. Only IITA and SPC distribute germplasm internationally, and again only in small amounts. The most common recipients are research scientists, including plant breeders. The survey suggests that distributions are in decline, because transfer of germplasm must be done under a Standard Material Transfer Agreement (SMTA) and institutes impose charges for processing requests and freight.

Most curators of collections indicated that their annual distribution of cultivars to local users was very low, and nil in many countries. A few provided figures of accessions distributed, and while most provided an estimate, but most did not provide data. Quite often, curators reported that germplasm was distributed for project-specific research and very few accessions were selected for this purpose. The very low number of distributed accessions indicates that germplasm is insufficiently used (Table 2.8). There are, however, large differences in distribution between collections, ranging from 0 to more than 50 accessions per year. Unfortunately, it is uncommon for users to provide evaluations of the requested germplasm to the collection from which it was obtained.

Yam germplasm can be distributed in the form of whole tubers, minisetts, rooted cuttings or *in vitro* plantlets. Eleven curators provided figures of accessions distributed per year. These data are difficult to analyze, as some collections may have interpreted accessions and number of plants as the same and, therefore, numbers vary greatly, from 0 to 500 per year (Table 2.9).

Nevertheless, several points can be made:

1. A number of collections indicated that their annual distribution of materials is for local users only. The demand from users outside the country was very low, or nil in many cases.
2. Demand is very low, including requests sent to regional or international genebanks such as IITA (Nigeria) and SPC (Pacific).
3. Only a few collections provided exact figures on the number of accessions and plants

distributed; most did not provide any information, indicating that very little was distributed.

4. A few collections reported that accessions were distributed for research projects. In these cases, many accessions are targeted to cover the diversity existing within the donor's collection.
5. The most frequent external users are local researchers, farmers, the public sector and, very rarely, yam breeders. The low use of accessions by yam breeders may simply be because there are less than 10 of them in the world.
6. Some germplasm was requested for biotechnological research and molecular fingerprinting.

Table 2.8 Distribution of material outside institutions during the past three years (2017-2019)

Type	Within the country	Outside the country	True seeds	Tubers	*In vitro*	Samples per shipment (kg)
Farmers' varieties	572	–	–	270	522	50
Breeders' varieties	500	256	–	500	–	50
Wild relatives	–	–	–	–	–	1–3
Others	–	–	–	–	–	–
Total	1,072	256	–	770	522	1–50

Table 2.9 Institutions that receive yam germplasm (av. no. per year)

Institution	Tubers	*In vitro* plantlets	True seeds	Other (specify)
University	230	75	–	–
Govt dept of agriculture	50	> 5,000	–	–
Research institute	500	514	–	–
NGOs	50	–	–	–

The most important factors limiting the distribution and use of accessions reported by the curators was the absence of local need and demand, the limited quantity of propagules available in their collections, the fact that the yam accessions are not certified virus-free and the lack of facilities to index the health status of yam germplasm. Limited resources was another factor reported as a major constraint in the distribution and use of yam germplasm, especially human resources and financial support. Bureaucracy and administrative constraints were also reported. The complexity of the Standard Material Transfer Agreement (SMTA) hinders distributions, as does the fact that not all countries have signed the ITPGRFA. Finally, not all the accessions in collections are wanted, as they are unlikely to be of economic importance for adoption as cultivars, and local cultivars are already meeting farmers' needs.

Some collections (especially IITA and SPC) that send germplasm attempt to monitor its performance through a feedback form sent to recipients. Any feedback received is documented in an internal system and is used to improve the institution's services. For evaluation data, feedback is usually stored in the format in which it is received. Evaluations are yet to be standardized or used to guide the selection of accessions for distribution. A challenge in this area is to develop a system for collecting evaluation data in an efficient, standardized and relatively straightforward manner.

SPC is implementing a new system of providing a maximum of 10–20 tissue-cultured plants per accession for free in line with international genebank thresholds. Additional plants requested by an importing country can be purchased at a cost of USD 4.00, excluding shipping and in-country biosecurity charges. SPC is now obliged to recover costs of production and germplasm distributed.

Very few curators have attempted to establish a quality management system or written procedures and protocols for acquisition (including collection, introduction and exchange), regeneration, replanting and subculturing, characterization, storage and maintenance, documentation (e.g. photos of the accessions tubers and leaves), health of germplasm, distribution and safety duplication. IITA has protocols for all these operations and should be requested to provide them to the Crop Trust to share with other collections.

2.6 SAFETY DUPLICATION OF GERMPLASM

Sporadic growth conditions due to irregular electricity supply or abiotic stresses in the field pose threats to the maintenance of most collections. Most curators realize this and consider it prudent to duplicate collections at a genebank with appropriate standards. IITA offers this option for several West African countries, as does SPC for Pacific island countries. IITA also conserves yam accessions from Vietnam (4 acc.), Costa Rica (40 acc.), the Philippines (128 acc.). The IITA *in vitro* collection is duplicated at IITA Cotonou (Benin).

In Brazil, Cuba, Guadeloupe, India, Vietnam and the Philippines, curators partly duplicate their field collections *in vitro* within their own institutions. The *in vitro* protocol for slow growth is based on 25 °C, 12 h photoperiod, with biannual subculturing. Côte d'Ivoire and Ghana duplicate their collections in the same way, to the extent that resources allow. In Guadeloupe, the conformity of *in vitro* and in vivo *D. alata* accessions was confirmed using molecular markers in 2017.

The erosion of *ex situ* field collections can be reduced when these collections are established in multiple sites across various agro-ecological zones, but this is rarely done. In most countries,

field collections are established on a single site. Ghana has three collection sites, but the number of accessions duplicated in each is unknown. When this duplication is done, for example for IITA in Benin, it provides the additional advantage of facilitating farmers' access to the germplasm.

In India, yam germplasm is conserved at the National Repository of Tuber Crops Germplasm at ICAR-CTCRI, Thiruvanathapuram, as well as in 14 tuber crop centers located in different states. Overall, 480 accessions are conserved under this system. CTCRI is the project coordinator (Table 2.10).

In South America, Asia and West Africa, wild *Dioscorea* populations are being destroyed by overharvesting. Collection of seeds and germplasm from these regions is vital to conserve what would otherwise be lost. However, there are no programs that aim to collect seeds from wild populations for long-term preservation, except in Madagascar where Royal Botanical Gardens, Kew (UK)-is-providing-assistance. More research is also needed to determine the best storage conditions for these seeds. In India, ICAR-NBPGR (New Delhi) is conserving dried seeds of wild species at –20 °C in vacuum-sealed three-layered aluminum pouches. Wild species are also maintained in mud pots in net houses (stored at 22 ± 2 °C with a 16/8 h photoperiod). Repotting and re-sowing follow every year.

There appears to be a need to duplicate all unique accessions in genebanks with high-standard *in vitro* conservation to prevent irreversible loss. However, these accessions are often identified by their passport data only, so duplicates might exist. Before duplicating collections, the first task is to identify duplicates in primary collections, which will reduce the number of accessions and thus make duplication more manageable.

At the moment, there are only two international hubs (i.e. genebanks) for *in vitro* safe duplication and the sanitation of yam germplasm at the regional level: IITA and SPC; the latter is not duplicated. These two have developed an *in vitro* (slow growth) system, but more research is needed on cryopreservation, especially on the stability of accessions following cryopreservation. ICAR in New Delhi is already using cryopreservation in liquid nitrogen at –196 °C, but IITA and SPC should develop it given their international mandates for germplasm conservation.

Table 2.10 Germplasm conserved in all coordinating centers for tuber crops across India.

Species	no. of Accessions	Location and (no. of accessions)
D. alata	284	Dholi, Bihar (9); Kovur, Andhra Pradhesh (32); Jorhat, Assam (15); Dapoli, Maharashtra (24); Kalyani, West Bengal (11); Ramnchi, Jharkhand (28); Jagadalpur, Chhattisgarh (63); Barapani, Meghalaya (2); Tripura (4); Navasari, Gujrat (16); Port Blair, Andamans and Nicobar (35) Imphal, Manipur (2); Palampur, Himachal Pradhesh (8); Udaipur, Rajastan (35)
D. esculenta	62	Dholi (5); Jorhat, Assam (4); Dapoli (14); Kalyani (27); Ramnchi (6); Jagadalpur (3); Navasari (2); Port Blair (1)
D. bulbifera	119	Dholi (2); Coimbatore (1); Dapoli (39); Kalyani (4); Jagadalpur (65); Port Blair (6); Imphal (2)
D. hispida	6	Jagadalpur (6)
D. pentaphylla	9	Jagadalpur (6); Palampur (3)

2.7 HUMAN RESOURCES

As most countries (except those in West Africa) consider yams to be minor species, they receive low priority in national programs. One of the recommendations made in the first global strategy for yam (Crop Trust 2010) was that the potential value of yam should be brought to the attention of policymakers at national, regional and international levels. It seems that in several countries where yams are grown (e.g. Bangladesh, China, India, Indonesia, Malaysia, Vietnam), crop statistics are not reported to the FAO database. This absence of statistics suggests that they are not surveyed at the national level because they are considered to be minor crops. However, not all countries in which yams are major crops have sufficient resources. As a result, IITA and SPC are often seen as the backup options for strengthening national germplasm conservation in West Africa and the Pacific, respectively.

The use of germplasm in breeding programs is also very limited because there are very few yam breeders. Most of the research is driven by scientific teams or donors from developed countries interested in academic research topics (e.g. phylogenies, diversity studies, MAS, genomics) rather than in basic applied research. More staff need to be assigned to the management of collections (Table 2.11), and existing staff need training to upgrade their skills. need training to upgrade their skills.

Table 2.11 Full-time staff working on *ex situ* collections

Staff	Scientists	Technicians	Assistants	Workers
IITA	1	9	0	5
KRC	1	3	3	20
UFM	2	1	0	1
FCRDI	1	1	0	2
INERA	5	5	2	3
CNRA	3	4	0	10
LIPI	2	3	0	1
PRC	3	1	1	1
CRB	2	2	0	0
VARTC	1	3	0	0
UAC	1	2	1	1
UCC	2	0.5	0	0.5
ITRA	1	2	0	0
INIVIT	1	1	1	0
CSIR	1	0	1	1
NBPGR	1	1	0	0
NARI	1	1	0	0
SPC	1	1	1	0
CSIR	2	3	3	3
NC	1	2	0	5
NRCRI	2	2	2	5

2.8 USE OF THE COLLECTIONS AND BREEDING

Few networks and partnerships related to yam have been established. There is a single international network, a regional network and a set of institutional partnerships coordinated by IITA. These networks are not formalized and meet on an ad hoc basis. Curators expressed interest in extending and broadening the networks in a new setting with more partners. In West Africa, several countries participate in the Genetic Resources Network for West and Central Africa (GRENEWECA) in collaboration with Bioversity International.

Support for capacity building and upgrading of seven collections in Africa, the Caribbean, Latin America and Asia was recommended by curators based on an analysis of their needs. Support should focus on characterization (ploidy and sex, tuber traits), documentation, conservation standards and rationalization. In Guadeloupe, the CRB is a member of The Plant pillar of Agro-BRC-RARe and Inter-TROP Network, two projects created to support the conservation and use of germplasm.

There appears to be an urgent need to evaluate all present accessions for traits of immediate interest to farmers (resistance to diseases, tuber quality) and to breeders (ploidy levels and sex). Once the relevant information is recorded, it would be useful to upgrade online documentation tools. Yam breeding capacity is limited, but it is crucial to invest in it to ensure that current diversity is fully utilized, in order to generate new and improved diversity to address current and future needs. Only in Nigeria, Benin, Ghana, Côte d'Ivoire, India, Guadeloupe and Vanuatu are the collections collaborating with breeding programs. Breeding *D. alata* for anthracnose resistance has been a goal in IITA, but, understandably, the emphasis has been on *D. rotundata* and *D. cayenensis*. At CTCRI in India, breeding of *D. alata* using local germplasm has continued in order to reduce local cultivars' susceptibility to anthracnose and to improve other important characteristics such as tuber shape. Several new hybrids have been produced, including *D. rotundata* lines that are bushy for unstacked cultivation, others that are early maturing and some with resistance to anthracnose, with the result that several cultivars have been released (ICAR-CTCRI 2019). Other hybrids are undergoing advanced trials in various agro-climatic zones to test their potential adoption by farmers. In Vanuatu, selected *D. alata* hybrids are being propagated and distributed due to their outstanding agronomic performance, especially regarding yield, tuber quality and resistance to anthracnose.

In most countries, however, breeding is not done on an ongoing basis. Crosses tend to be conducted as part of a particular research project or because a local scientist is convinced of the need. Hybrids are generated during a few seasons but the work stops when the project ends. At that point, the institutions become involved in the field evaluation of the hybrids and breeding activities are placed on standby, either because funding has stopped (end of the project) or because the scientist involved retired or was appointed to new functions. As there are very few yam breeders, most curators face practical difficulties in accurately assessing the extent of diversity in their collection and so may have limited knowledge about the allelic diversity, agronomic performance and breeding value of the germplasm that they conserve.

Among the 29 curators who returned the questionnaire, a few confirmed collaborating with an *in situ* conservation program. INIVIT is protecting *D. trifida* in Cuba. In India, ICAR is distributing selected accessions in tribal areas. CSIR is protecting endangered wild *Dioscorea* species in Ghana. In Madagascar, endemic *Dioscorea* species are present in protected areas. Finally, in Vietnam, PRC is a partner in an *in situ* conservation project in Huu Lung District, Lang Son Province.

2.9 POLICIES ON ACCESS TO COLLECTIONS

The most important constraint on the use of yam germplasm is the difficulty that curators and scientists face in obtaining materials from collections from other countries. This is due primarily to the viruses and quarantine issues described above, but also to very strict national policies. Current policies and legal restrictions on access to yam germplasm create real bottlenecks.

These administrative and legal procedures hinder breeders' efforts to ensure that genetic diversity contributes to the genetic improvement of yam. However, it is not only use by breeders that suffers: the restrictions also apply to obtaining germplasm for selection and distribution. For example, there are outstanding cultivars of *D. alata* that are rich in dry matter and so have the potential to produce a good fufu, which should be introduced into West Africa.

The International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) was created in 2004 to address the fair sharing of benefits arising from the use of crop germplasm. More than 150 countries are signatories. The objectives of the ITPGRFA are the conservation and sustainable use of plant genetic resources and the fair and equitable sharing of benefits derived from their use, in harmony with the Convention on Biological Diversity. The aim of the treaty is to promote international cooperation and exchange of germplasm. Countries that sign the ITPGRFA are agreeing to membership in a multilateral system to facilitate access. The multilateral system covers 64 crops and forages (referred to as "Annex 1 crops").

Yams and all *Dioscorea* species without distinction are included in Annex 1 of the ITPGRFA. In addition, all collections maintained by the CGIAR, including the IITA collection and the SPC collection, are included in the ITPGRFA under Article 15b. The governing body of the ITPGRFA has set out the conditions for access and benefit-sharing in a Standard Material Transfer Agreement (SMTA). The SMTA must be signed for each consignment (with each *Dioscorea* accession listed) that is sent from *ex situ* collections and received by researchers, breeders, farmers or NGOs.

Consequently, as yam falls under the ITPGRFA, all requests for yam germplasm from national collections require formal approval from the institute's administration and a signed SMTA. All countries with yam collections have signed and approved the Treaty (except Vanuatu and Vietnam; Nigeria has only signed it). In addition to an SMTA, users must obtain import permits and phytosanitary certificates from their biosecurity administrations. In many countries, the process for approving a request involves considerable bureaucratic procedure, resulting in delays in responding to a request.

In practice, countries with yam genetic resources are required to take measures to ensure that the germplasm within their jurisdiction is accessed in accordance with requirements for prior informed consent, and that mutually agreed terms have been established between them and the recipient country. This is the aim of the SMTA, which can be adapted depending on contractors' objectives and rules of consent. All yam curators understand that by signing the SMTA, they are committing to take measures to monitor the use of their genetic resources; there may be cases of alleged violation of the agreement where the parties need to collaborate, and the need for checkpoints along the value chain. However, because edible *Dioscorea* species are economically important in only five West African countries, only a few SMTAs are signed each year.

However, out of the 31 yam collections surveyed, 64.5% confirmed that their material is available for international distribution, whereas 19.4% of collections stated that their germplasm is not available for distribution outside the country and 16% did not respond to this question. Those that can distribute internationally use an SMTA for distribution (downloadable pdf) and for bilateral agreements. Exchange of germplasm occurs upon acceptance of the terms and conditions of the SMTA by the importing country. Only germplasm that has been tested and is virus-negative is available for distribution. Unfortunately, the number of countries officially requesting *Dioscorea* germplasm from IITA is very low.

2.10 FUTURE DEVELOPMENT OF YAM COLLECTIONS

Many collections reported adding new accessions over the past 10 years and having plans to collect more during the next decade, depending on their resources. Most, if not all, partners recognize that the lack of financial and human resources is the major constraint for the future development of their yam collections. They are struggling with very limited resources and cannot envisage new activities without extra financial support. Several partners also requested training and capacity building for virus identification, health checks, management and safety duplication.

Despite their desire to collect, expand and improve their present collections, most curators expressed concerns regarding the future. They were concerned about the constraints faced, even their capacity to replant and to maintain their existing collections in the field or *in vitro*. Curators recognized the need to develop a global strategy that would address shortfalls and gaps in the conservation of yam genetic resources and support informed use of the diversity, but were not confident that this was likely to happen.

Yam *in vitro* cultures in genebank at IITA Ibadan, Nigeria. PHOTO CREDIT: IITA

3 GLOBAL STRATEGY FOR THE CONSERVATION AND USE OF YAM

3.1 ELEMENTS OF THE GLOBAL STRATEGY: INSTITUTIONS AND OBJECTIVES

3.1.1 Institutions and key players

This global strategy acknowledges the geographic concentration of yam production as well as the origin of cultivated species. Africa accounts for more than 98% of the world production. Yams are crops of major importance in Nigeria, Ghana, Côte d'Ivoire, Benin and Togo. They support food security in Ethiopia, Cameroon, Chad, Central African Republic and a few other African countries. In Latin America, the Caribbean, Asia and the Pacific, yams are minor crops in terms of area planted and production, but they are highly esteemed and often sold at a high price or used as valuable medicinal plants. As expected, most institutions involved in yam germplasm conservation and use are located in major producing countries in Africa.

The international collection is located in IITA in Nigeria, which is by far the major yam-producing country. Nevertheless, other key players are located outside Africa, where they preserve unique germplasm of the greater yam (*D. alata*) and other Asian species of importance for African countries and the world (Table 3.1).

The overall objective of the proposed global strategy is the effective conservation of maximum yam diversity, permanently assured through an international network of *ex situ* collections that actively contribute to and benefit from common standards and techniques and the effective exchange of germplasm and information. IITA has the most important yam genetic resources, because of its total number of accessions and the high number of accessions for *D. rotundata*, *D. cayenensis* and wild related species. The IITA collection is therefore a priority for support in order to fully meet the Crop Trust's criteria for long-term assistance.

Table 3.1 Major institutions that preserve and use edible *Dioscorea* germplasm.

Species	Taxonomic section	Geographic origin	Key institutional players
D. alata	Enantiophyllum	Asia-Pacific	CTCRI, PRC, PhilRootCrops, NARI, VARTC, SPC, INRAE, INIVIT, CTT, FCRDI, LIPI, UCC, IITA, CNRA
D. cayenensis	Enantiophyllum	Africa	IITA, CNRA
D. rotundata	Enantiophyllum	Africa	IITA, UAC, CNRA, CSIR, CNRA
D. japonica	Enantiophyllum	Asia	NARO
D. oppositifolia	Enantiophyllum	Asia	–
D. nummularia	Enantiophyllum	Pacific	NARI, VARTC, SPC
D. esculenta	Combilium	Asia-Pacific	CTCRI, PRC, PhilRootCrops, NARI, VARTC, SPC
D. bulbifera	Opsophyton	Pantropical	IITA, CTCRI, PRC, PhilRootCrops, NARI, SPC
D. trifida	Macrogynodium	America	UFAM, CRB
D. dumetorum	Lasiophyton	Africa	IITA
D. pentaphylla	Lasiophyton	Asia-Pacific	NARI, VARTC, SPC

However, important collections now exist in Benin, Ghana, Côte d'Ivoire, Burkina Faso, Nigeria and Togo, all of which also need assistance. IITA could take the lead in Africa. Given the enormity of the task, it is proposed that the focus of the strategy remains on species known to have their center of origin in Africa: *D. cayenensis*, *D. dumetorum* and *D. rotundata*. It is very doubtful that for *D. alata*, *D. esculenta* and other Asian species, genotypes would have developed from seedlings that resulted from spontaneous crosses between two distinct genotypes grown in Africa.

This local phenomenon could possibly occur for *D. bulbifera*, as its origin is considered to be pantropical. Consequently, for *D. alata*, another institution should take the lead and then liaise with IITA and national institutions for the potential introduction of genotypes into Africa.

In Asia, three countries (India, the Philippines and Vietnam) indicated that yam should be supported, although it is considered to be a minor crop in these countries. This priority was given based on several criteria, including diversity, importance as a food crop, importance of regional and/or international collections, and usefulness in marginal areas, subsistence agriculture and food security for smallholders. India, the Philippines and Vietnam are therefore identified in the strategy as countries that could lead the coordination of the conservation of yam within Asia

Dioscorea oppositifolia is an orphan crop. It is cultivated mostly in China and Taiwan, but no responses were received from partners in those countries, so it is difficult to determine whether any institutions have an *ex situ* collection.

Papua New Guinea, Vanuatu and New Caledonia, with technical support from SPC (Suva, Fiji) for *in vitro* conservation and cryobanking, can assemble a large proportion of the diversity in the Pacific. In the Caribbean, collections in Cuba, Haiti and Guadeloupe have assembled significant diversity, and also require support. The UFAM collection in Brazil is unique for *D. trifida*, an important species in America and the Caribbean. These yam collections in Asia, Latin America and the Pacific are identified as those of greatest importance and in need of priority support outside Africa.

3.1.2 Rationale for the strategy

The greater yam (*D. alata*) and the Guinea yam (*D. cayenensis* and *D. rotundata*), which are by far the most important species economically, are considered the priorities in this global strategy. However, minor yam species should not be neglected given their importance for food security. The proposed strategy does not identify themes as priorities, nor does it attempt to formulate for each theme a list of recommendations aimed at addressing the main challenges faced by curators. This approach was used to develop the first global strategy, many of the recommendations in which are still valid today (Crop Trust 2010). The present strategy outlines a roadmap with activities to be undertaken in a particular order. This strategy acknowledges the financial constraints faced by curators and attempts to develop a system to optimize the use of existing resources while identifying the needs for external financial resources.

Considering the current trends reported by curators in the survey, conservation activities should receive priority over characterization activities. Otherwise, by the time the characterization work is completed, many conservable genotypes would have disappeared. There are clear indications that germplasm erosion is already underway in a few countries. However, to improve the efficiency of conservation, it is necessary to select conservable accessions and cull out duplicates, thus optimizing time, labor and financial resources. There are clear indications that collections are disappearing because of insufficient funding. Conservation and characterization of yam are two enormous

complementary tasks that are highly demanding in terms of cost and human labor. The fact that yams are clonally propagated increases these factors. However, if the characterization work focuses on a few essential traits, then the work could be reduced, which would lead to improvements in conservation. The rationale described in Section 1 of this strategy is summarized in the following.

Within each cultivated *Dioscorea* species, there are many cultivars known under different names in different countries, but the real number of different genotypes is probably far lower than the number of accessions preserved in germplasm collections. This is due to the sexual biology of yam. For example, *D. alata* has been reported to be unknown in the wild because it was thought sterile and unable to produce seeds in farmers' fields (Burkill 1935). As the plant is dioecious with variable ploidy levels, the chances of having two fertile male and female plants with synchronization of their flowering are extremely low. Opportunities for producing seedlings (and new genotypes) are very infrequent, and most cultivars have been dispersed over very wide geographic distances and diversified morphologically through the accumulation of somatic mutations. The genetic base of *D. alata* is narrow in most countries where it has been clonally introduced (Lebot et al. 1998, Arnau et al. 2017; Sharif et al. 2020).

As a result, *ex situ* collections include large numbers of duplicates (Vandenbroucke et al. 2016), and maintenance of collections will be improved if the duplicates are identified and removed. The situation might be somewhat different for the Guinea yam (*D. cayenensis* and *D. rotundata*) because cultivars can exchange genes with wild relatives (Scarcelli et al. 2019). Another probable reason why duplicates are conserved is that, when farmers select interesting genotypes, these are shared and exchanged, or stolen and distributed. Improved, comprehensive characterization of yam collections will ultimately facilitate germplasm conservation, but there is an urgent need to downsize the collections.

The situation is comparable to the potato. Following its creation in Lima, Peru, in 1970, the International Potato Center (CIP) assembled a collection of more than 15,000 accessions from nine Latin American countries. Subsequently, duplicates were identified and the total number was reduced to 3,527 accessions, including 552 diploids, 128 triploids, 2,836 tetraploids and 11 pentaploids (Huaman et al. 1997). This hierarchical structuring of the potato diversity was an essential milestone in germplasm conservation and use (Bradshaw and Bonierbale 2010).

A similar approach could be used for yam, but, as *Dioscorea* spp. are dioecious, sex and ploidy level are the major traits to consider for hierarchical structuring. It could be argued that these two traits are too cumbersome and/or complex to be characterized, which is why this essential information is lacking in most collections. However, ploidy levels can be determined using flow cytometry, and sex can be determined using GBS. Sex of flowering genotypes can be determined in field collections. This will reduce the number of non-flowering genotypes for which genomic tools will be used for sex determination. This work is probably time consuming and will need optimized protocols, but once it is done, collections can be re-organized into ploidy groups and subgroups, which will pave the way toward identification of duplicates and to downsizing—the key for better conservation.

Top priority should be given to determining the ploidy level, in order to organize the existing diversity in germplasm collections into ploidy groups. If the identification of sex appears to be too cumbersome or laborious, or constrained by financial and/or technical means, then within each ploidy group, further stratification could be done

based on tuber shape and tuber quality[1]. As yam is a tuber crop, these two traits are essential for germplasm characterization.

3.1.3 Structure of the strategy

This global strategy proposes a threefold approach:

1. **To stratify *D. alata*, *D. rotundata* and *D. cayenensis* germplasm based on ploidy and sex and to detect duplicates:** Yam collections should be re-organized into groups based on ploidy level and then by sex within each group (e.g. 2× *alata* females, 2× *alata* males, 3× *alata* females, 3× *alata* males, 4× *alata* females, 4× *alata* males and higher ploidy levels if detected). Duplicates could then be detected using molecular markers. The same should apply to *D. cayenensis* and *D. rotundata* collections (although the existence of tetraploids for these species has not been confirmed). The aim of this process is to use a rational subdivision of the large number of accessions maintained in *ex situ* collections, to ease the detection of duplicates, to reduce the total number of accessions and to improve their conservation. If the size of most collections could be reduced, they would be better characterized agronomically and better conserved, leading to an increased use of suitable genotypes in breeding programs and/or for direct distribution to farmers. DNA fingerprinting will allow the detection of duplicates and/or somatic mutants. Once sex has been identified, more research should be undertaken on flowering-induction techniques. *Dioscorea* spp. are perennial species in the wild and, therefore, permanent collections should be established within agroforestry systems where selected accessions will not be harvested on an annual basis (regular vegetative propagation is a form of rejuvenation). Physiologically older plants have increased potential for flowering. Diploids are much more frequent than tri- and tetraploids, so the diploids group will need further stratification. Tuber shape (and uniformity and tendency to branch) as well as tuber quality (flesh oxidization) are traits that might be considered to guide further stratification into subgroups.

2. **To compose elite subsets for each *Dioscorea* species (major and minor species) comprising elite cultivars. Elite cultivars** (approximately 10% of the total number of accessions) are selected based on their yield, tuber shape, tuber quality and tolerance to major diseases. In most countries, these elite cultivars are already known and/or can be identified easily. They are often the most widely planted and traded cultivars. These elite subsets should be transferred to a regional or international genebank, DNA fingerprinted to identify duplicates (ploidy levels and sex) and sanitized (freed of viruses) to facilitate their distribution. They should be preserved *in vitro* and in a cryobank. Most, if not all, of these elite cultivars tend to have high ploidy levels (often associated with agronomic performance) and are probably non-flowering. Their sterility is not a constraint for their inclusion in a elite subset, as the priorities for these genotypes are their conservation, sanitation and distribution. There are probably fewer than 100 of these elite cultivars for *D. alata*, and maybe more for *D. cayenensis* and *D. rotundata*; the number is much lower for the minor yam species. A catalogue, similar to that created for other major species (e.g. "Yamlogue"), should be published online, with photos.

3. **To collect, exchange and preserve true seeds from wild relatives and selected cultivars** to broaden the genetic base of existing collections for future use in breeding programs. *Dioscorea* spp. plants are susceptible to infection by a range

[1] Gueye, B. (IITA) argued that using tuber quality (rather than sex) would be better for stratification, providing still to use very informative quality parameters such as flesh oxidization (proposed), starch content and others. (Personal communication, Gueye, B. 2021)

of viruses and strains. Their sanitation is an expensive, long-term activity that requires expertise and financial means. In many countries, as yams are economically considered to be minor crops, the risk–benefit analysis does not favor the demand and importation of sanitized genotypes. Given the low demand, international distribution of germplasm is extremely limited, if not close to nil. However, it has been shown that breeding programs can benefit from the introduction of suitable genes (i.e. resistance to anthracnose, female plants) under the form of true botanical seeds introduced from distant geographic origins following official guidelines (Brunt et al. 1989). These seeds can speed up improvement strategies (Lebot et al. 2019a). This approach is cost efficient and it bypasses the virus constraints. This approach has already been used with practical results for *D. alata* and *D. rotundata*. Once female plants are identified, polycross blocks can be established with selected genotypes, and true botanical seeds can be produced in large quantities for international exchange and to broaden the genetic base. This approach, based on the geographic distribution of allelic diversity, could contribute to the future adaptation of yam to climatic changes. A further constraint, however, is getting these seeds to yam breeders, because further recombinations will be needed, and there are very few yam breeders.

3.1.4 Specific objectives

This threefold approach aims at assessing the diversity of accessions for inclusion in the conservation program of each country and internationally. The objective is to reduce the number of accessions to be conserved without losing valuable genes. Ploidy level and sex are the two important basic criteria for diversity analysis and conservation of dioecious edible *Dioscorea* species and their wild relatives. Ploidy levels can be determined to a large extent with field experience, but flow cytometry (and/or GBS) can be used to ascertain the classification. By structuring the yam gene pool diversity in this hierarchical manner, it will become easier for curators to detect duplicates, downsize collections and optimize management. Such germplasm collections are also directly accessible to yam breeders. From a breeding point of view, only diploids and tetraploids are useful, as triploids are sterile. Exceptional hexaploids and other higher levels (e.g. *D. nummularia*) can be useful as cultivars, but only a few may be fertile. Although triploids are not useful for breeding purposes, sex is a useful discriminant trait for classifying the various triploid accessions.

At the field level, within the same species and ploidy level (and ideally within the two sex groups), curators can classify accessions using quantitative discriminating traits such as tuber shape and tuber quality (and/or flesh color and oxidation). They can then reclassify the collection by considering all possible useful traits, screen out those that are similar, and then study the selected ones for further detailed observation. Most institutions have adopted a conservation strategy based on *ex situ* field collections supplemented and supported by *in vitro* conservation. A loss in one bank can be replaced from another bank. Through useful characterization, collections will be rationalized and hopefully downsized, easing the *in vitro* conservation work as well. Finally, for each *Dioscorea* species, groups of accessions embodying the total available yam diversity will be identified and held in hubs (i.e. genebanks) and in field collections. If held only in national *ex situ* field collections or in the wild, *Dioscorea* germplasm could be threatened by pests and diseases, wild pigs, deforestation or overexploitation of natural resources (e.g. for saponins).

The first global strategy (2010) recommended developing more collaborative conservation initiatives between collections in different institutions. Better interaction with yam germplasm users and with the research

community will help yam collections to ensure that well-characterized material is accessible, but viruses and exchange policies will remain major constraints to the exchange of germplasm. At the global level, better access to yam germplasm and associated information can be achieved by forming a global information system that links data from IITA's international collection and data from national collections. This global information system would provide regular updates on the availability of new germplasm.

To ease this process, yam health testing methods should be regularly improved and updated, especially with regard to viruses, and the available technology transferred to national *in vitro* laboratories (where they exist) to facilitate the safe local exchange of germplasm, within each country. It is also necessary to revise the Technical Guidelines for the Safe Movement of Yam Germplasm (Brunt et al. 1989), in particular, to update the information on virus indexing to determine the phytosanitary status of the germplasm for research, conservation and basic plant breeding purposes.

Significant progress could occur if field collections are granted access to the necessary indexing expertise in their country of origin to minimize the risk of transferring virus-infected material. Where necessary, training in approved indexing methodologies should be given. An accreditation system for indexing laboratories would increase confidence in the regional movement of yam germplasm. At the moment, it seems that very little germplasm from Asia is imported into Africa, despite the obvious need to broaden the genetic base. However, this task is not straightforward, given government restrictions on germplasm export or sharing. For many years, it has been impossible for IITA to obtain yam germplasm from countries in Asia.

Ideally, true botanical seeds are preferred for the transfer of yam germplasm. Not only they are considered to be safe, but they also allow the rapid introduction of allelic diversity into a country's breeding population. Unblemished seeds should be selected from plants that appear healthy and then are fumigated and treated with fungicide. On arrival in the recipient country, these seeds should be germinated and the seedlings grown in post-entry quarantine in a research station, for at least one crop cycle. This recommendation made by Brunt et al. (1989) remains valid and, considering the need for adaptation to climatic changes, this recommendation should be a priority for broadening the genetic base. This procedure has been followed in a few countries that introduced seeds for their breeding programs; 20 years after their introduction, it is confirmed that this approach is safe and extremely efficient for introducing useful genes (Lebot et al. 2019b).

3.2 PRIORITY ACTIVITIES AND TIMELINE

It is necessary to: systematically determine the ploidy levels of all accessions within all species in all collections; group them into diploids, triploids, tetraploids and higher levels of ploidy within each species; subdivide the ploidy groups into sex groups (males and females, with plants predominantly male or female included in the corresponding unique sex group) and analyze the variation within each group; subdivide the subgroups into subsets based on geographic origin, tuber shape, flesh color and quality (flesh oxidation).

This kind of stratification, combined with DNA fingerprinting, will make it possible to identify duplicates and efficiently downsize the collections, while preserving the useful diversity. Downsizing will improve conservation and use, and will also make it easier to identify any gaps that require filling.

Following is an outline of the priority conservation and use activities:

1. Conservation

1.1. Stratification

- Carry out molecular characterization of germplasm to rationalize collections based on species, ploidy levels and sex (cytometry, chromosome counting and GBS).
- Identify duplicates to downsize the international collection and national collections and improve *ex situ* conservation through better characterization of accessions.
- Provide short-term support to national programs for *ex situ* field collection maintenance or *in vitro* conservation of base collections.

1.2. Elite subsets

- Conduct research to develop a reliable cryopreservation protocol for yam to preserve a elite subset of each species.
- Validate international elite subsets for each species using standardized molecular markers to identify duplicates.
- Ensure safety duplication of yam elite subsets in different hubs (i.e. genebanks).

1.3. Seed conservation

- Research induction of flowering.
- Research true botanical seed conservation for selected elite genotypes.
- Collect true botanical seeds and develop long-term storage techniques for wild relatives.

2. Characterization and evaluation

2.1. Ploidy level groups

- After rational stratification based on ploidy and sex, conduct characterization, evaluation and selection of germplasm currently available, for further stratification based on geographic origins within countries.

2.2. Morphological and tuber quality subgroups

- Reorganize collections into subgroups, especially among diploids, based on maturity, tuber shape, oxidation, flesh color; investigate relationships among genotypes, chemotypes and organoleptic properties.

3. Exchange of germplasm

- Set up optimized virus-cleaning protocols according to virus–host interaction.
- Develop virus-indexing capacity within regions.
- Exchange "clean" material within and outside regions.
- Convene a virtual meeting (and/or email discussion group) to update safe transfer guidelines.
- Monitor sanitized selected yam clones after field release.

4. Breeding, genetic improvement and use

- Ensure sustainability of breeding programs in Africa, India, Vanuatu and Guadeloupe.
- Support the development of user-friendly online training tools (e.g. short videos) on yam breeding.
- Develop the international exchange of true seeds between these programs.
- Strengthen coordination among conservation and breeding programs in West Africa.

- Develop a catalogue of elite cultivars and selected improved yam hybrids (Yamlogue).
- Establish an international network on yam to facilitate exchange of information.
- Several of these activities can be conducted simultaneously, but priority should be given to the rationalization of the collections, which could contribute to downsizing the number of accessions and therefore easing their conservation. It is estimated that four years will be needed to achieve this work plan.

Table 3.2 provides a timeline for these activities on a semester basis for four years.

Table 3.2 Gantt chart, timeline (two semesters per year).

Priority activity	2022.1	2022.2	2023.1	2023.2	2024.1	2024.2	2025.1	2025.2
Stratification:								
Characterization of ploidy and sex								
Identification of duplicates and downsizing								
Support of national *ex situ* & *in vitro* activities								
Elite subset:								
Research on cryopreservation								
DNA fingerprinting of elite subset candidates								
Support to hubs (i.e. genebanks) for maintenance of elite subsets								
Seed conservation:								
Research on flowering induction								
Research on true botanical seeds conservation								
Collection of true seeds of WR and cultivars								
Characterization and evaluation:								
Evaluation of ploidy level groups								
Characterization of tuber shape and quality								
Exchange of germplasm:								
Virus-indexing capacity development								
Exchange of clean materials								
Update of safe transfer guidelines								
Monitoring of sanitized yams in the field								
Genetic improvement:								
Support of breeding programs								
Development of international exchange of seeds								
Strengthening of coordination between breeders								
Establishment of international yam network								

3.3 GAP FILLING

For *D. alata*, the areas of distribution and diversity are vast, ranging from India to China to Melanesia. Many cultivars are not preserved in collections. Any that were collected in the 1970s and 1980s have since disappeared from collections. There are no reported *ex situ* collections for *D. alata* in Bangladesh, Myanmar, Thailand, Cambodia, Lao PDR or China. There is a need for better geographic coverage, but this would result in:

- the transfer of accessions to a certified laboratory and the development of complex sanitation techniques to remove all viruses probably present;
- legal issues regarding the ownership of the cultivars; and
- an excessive burden on existing collections in the region and/or on the international collection if these materials were to be transferred once sanitized.

Rationalization and downsizing of the collections is a priority to clarify what is missing before launching new collecting trips. Priority should be given to female tetraploids.

For *D. cayenensis* and *D. rotundata*, several countries in Africa have already been identified for further collecting (Cameroon, Ethiopia). Countries such as the Central African Republic and South Sudan should also be included. For these species, too, there is a need to rationalize collections and identify duplicates. It is currently hypothesized that most are diploids, but this assessment was based on a rather small number of accessions compared to the total number preserved *ex situ*. Therefore, there is a need to look for more females, especially tetraploids, if they exist. Polyploidy breeding is probably interesting for the Guinea yam as well (not only for *D. alata*). Better documentation of wild relatives is required, and there is still a need for taxonomic clarification and review before new samples are preserved, to avoid further confusion regarding the relationships between wild and cultivated species.

For minor yam species: *D. trifida* needs further collecting in northern Brazil and in the Guianas. *Dioscorea nummularia* needs to be collected in Indonesia, Papua New Guinea, Solomon Islands and Vanuatu. *Dioscorea oppositifolia* and *D. japonica* cultivars need to be collected in China, Japan and Taiwan, and described.

3.4 INFORMATION SHARING

All curators use IPGRI descriptors for the morphological descriptions of their accessions. Once recorded, the passport and characterization data are entered into Microsoft Excel spreadsheets. These files are not circulated and/or exchanged (except for the IITA database, which is freely downloadable). Many yam collections are not systematically documented, and only limited characterization and evaluation data are available. These data remain scattered across distant research stations and institutions. This lack of information prevents curators from rationalizing their collections, identifying duplicates, understanding general characteristics and optimizing the use of yam diversity.

One option for facilitating access to data held across a range of databases and harmonization of the data is the Crop Ontology Portal, which provides access to multi-crop passport data, anatomy, development stages and agronomic traits. The aim is to provide harmonized breeders' trait names, measurement methods, scales and standard variables for many crops, including *Dioscorea* spp. The yam ontology was created by IITA. The yam ontology is a harmonized and structured list of 119 traits[2], some of which correspond to the descriptors (Annex 3). The yam ontology integrates the phenotypic, genotypic and

[2] www.cropontology.org/ontology/CO_343

environmental data associated with a given trait, and can be easily completed and improved online. However, it seems that, since this tool's creation in 2017, very few breeders and curators have contributed to it. This is understandable, given that a major constraint reported by curators in the survey was their limited means.

There are two related databases. The first is AgroPortal. The AgroPortal content is automatically retrieved by FAIRsharing.org and the Map of Data Standards.

The other database is YamBase, which contains breeding data for yams, including phenotypic and genotypic data, as well as trial metadata from breeding programs in Africa (59,746 entries for "accessions" and 531 entries for "trials," but only two entries for images). So far, a total of 196 yam scientists have logged in. The database requires regular updating, but it seems that the initial enthusiasm has faded away. Curators seem to have more urgent priorities.

There is a need for more information on taxonomy, ploidy levels, sex characterization, evaluation, health status, availability and agronomic performance. Complete passport data are needed to confirm the identity of the accessions, but, in many countries, this work is incomplete. Without such data, conservation and use are pointless, as the value of the accessions cannot be known and the information cannot be shared. For each country, the absence of accurate records on the use of the accessions makes it difficult to evaluate the usefulness of the whole *ex situ* collection and thus to justify its management costs. Therefore, all country collections need local germplasm management systems that document each step, from acquisition to distribution, including regeneration and health testing. Monitoring acquisition, maintenance, distribution and health testing is critical for collection management. The system has to be standardized.

This indicates a need to develop a Yam Germplasm Information System (YGIS) with the objective of collecting and sharing publicly available information from all yam collections (31 so far). YGIS should contain passport data, botanical classification, ploidy, sex, morpho-taxonomic descriptors, photographs, georeferenced information and genetic fingerprints based on molecular markers.

YGIS would serve the following groups:

- collection curators who require a global system for data sharing, comparison and managing data on their own collection
- researchers and breeders who select accessions for experiments and other uses
- general users looking for reference information on the characteristics and uses of cultivars.

The overall objective of YGIS would be to ensure that country databases are sufficiently reliable, freely accessible and downloadable. Efforts should be made to simplify the flow of data being shared and to facilitate the exchange of data between collections. YGIS should also make it possible for users to import/export data into/from electronic spreadsheets and print summary information on accessions for the Yamlogue. YGIS would have to be extremely easy to use; if not, users will, again, fail to share and use it. Considering the limited means available, it might be as simple as a website where curators could upload their Excel spreadsheets in the short term, at least to duplicate and save their data.

3.5 CAPACITY BUILDING

Efficient yam germplasm management will depend on the availability of expertise. Therefore, capacity building is important, particularly the sharing of technical knowledge and expertise. The feedback from the questionnaire survey suggests

that funding, lack of human resources and capacity building are the most urgent needs for improving the current situation in countries' *ex situ* collections. There is an obvious need to train and build capacity in the use of methodologies, standards and best practices that contribute to improved management of yam collections. Equally important is to ensure that adequate skills and equipment, including *in vitro* laboratories and other equipment, are available for germplasm conservation activities. Most curators in the survey saw this as a priority. There is also a need for full-time curators and breeders to ensure continuity of the collections, but as yams are minor crops in many countries, these demands are difficult to justify. Specific equipment is needed for ploidy level assessment (flow cytometers) as well as *in vitro* labs and the maintenance of screen houses to back up field collections and for optimization of cryopreservation techniques.

It is possible to strengthen regional networks by stimulating exchange between curators. However, in-person meetings might not be the ideal solution, as they are expensive, have a high carbon footprint and might not be cost efficient. Very often, the return on investment for in-person meetings is poor. Alternatives should be investigated. However, it might be necessary to develop technical training in management of plant genetic resources and increase capacity building for virus indexing and for ploidy-level determination using cytometry and cytology techniques. It would be interesting to improve information technology capacity (software and hardware) and ensure the completeness of a geographic information system with data on all available accessions. As most distribution occurs locally within countries, field collections should have access to the necessary indexing expertise to minimize the risk of transferring virus-infected material to virus-free regions within the same country. Where necessary, training in approved indexing methodologies should be given to optimize the safety of local propagation and national distribution.

There is obviously a need for more exchange of disease-free material between countries within regions, especially in Africa, in order to enable breeders to speed up the breeding process and adapt yam to climatic changes. Yam programs and collections need to acknowledge this major constraint and design their activities accordingly, based on the introduction of allelic diversity via botanical seeds rather than a few *in vitro* clean and sanitized genotypes whose sex and ploidy are often unknown.

In order to develop this approach, an international yam network could help strengthen countries' capacity, by optimizing plant conservation and true seed multiplication strategies. Such an approach should be developed with national authorities, regional and international agricultural research institutes and other relevant organizations. The overall objective is to strengthen the capacity of curators for achieving the cost-effective long-term conservation and management of *ex situ* collections that are rich in allelic diversity and to facilitate access to yam germplasm in breeding programs.

3.6 ENHANCED USE

The ultimate beneficiaries of yam germplasm are farmers, communities, the processing industry and consumers. The major constraint on use comes from the presence of viruses. Many elite cultivars could be rapidly identified and could be propagated and distributed to farmers, with a potentially major positive impact. When 'Florido' was introduced in Côte d'Ivoire in the 1970s (from USDA in Mayaguez, Puerto Rico), farmers widely adopted it, but at that time, viruses and intellectual property rights were not constraints. Other elite cultivars (from *D. alata*, *D. cayenensis*, *D. rotundata*, *D. esculenta*, *D. bulbifera*) could be introduced in

West African countries, where they would most likely have a positive impact.

The main source of yam accessions available for distribution internationally is the IITA collection. IITA holds the most comprehensive set of *D. cayenensis* and *D. rotundata* diversity with a guaranteed health status, but only small samples can be provided. For other *Dioscorea* spp., the diversity is elsewhere and is not directly transferable to West Africa. Badnaviruses are a major impediment to the international transfer of *D. alata* germplasm (Kenyon et al. 2008). Sanitation of all infected genotypes is a priority but is a very expensive process. Continued research into viruses and virus therapy is required. In particular, it is necessary to shorten virus cleaning procedures and indexing times, keep indexing protocols up to date and efficiently manage badnavirus-infected accessions.

If qualified laboratories cannot certify to a country that the yam material has been tested and is free of viruses, then biosecurity authorities will not permit importation; this creates a technical bottleneck. For some minor species, *especially D. esculenta*, removing all viruses is difficult, and it is doubtful that it can be easily done with existing resources. The potential threats of quarantine and non-quarantine yam viruses should be discussed. If, in the future, yam germplasm is requested but laboratories cannot clean the accessions, then a decision will have to be made regarding the sharing of germplasm based on the need to quarantine the virus.

Information on virus indexing must be updated, in order to determine the phytosanitary status of germplasm for research, conservation, breeding and, most importantly, distribution purposes. The FAO/IBPGR Technical Guidelines for the Safe Movement of Yam Germplasm (Brunt et al. 1989) should be revised in partnership with plant health laboratories and specialist pathologists in order to increase ownership and acceptance of these standards among stakeholders. An accreditation system for regional indexing laboratories would increase confidence in the regional movement of yam germplasm. There is therefore a need for a global standard operating procedure (SOP) for cleaning and testing of yam viruses. Existing diagnostic methods are scattered across various publications and various institutes. These methods need to be consolidated, and a globally recognized germplasm testing protocol needs to be synthesized and validated by the institutes working on yams. With new technologies, new viruses are being discovered; it is important to determine if any of these viruses are significant. Most countries now believe that it is highly risky to import yam from other countries.

Health testing and sanitation are costly and very lengthy procedures for collections. Technical alternatives and options need to be explored to improve the cost-efficiency of the indexing process. In recent decades, very little research has been conducted to develop new therapies, compared to the numerous descriptive studies aimed at characterizing new viruses and strains using new powerful molecular tools. As far as yam virology is concerned, there is a clear imbalance between academic research (descriptive) and applied research (problem solving). Partners should acknowledge this and look for practical alternatives; otherwise, more studies will be published with limited practical implications, which will not lead to improvements in the field.

There is a need to clarify the legal status of germplasm in some national collections and to overcome legal and practical barriers to free exchange. Increasing the involvement of farmers, seed systems and multiplication centers in consultation processes would accelerate the process. However, quality control mechanisms are also needed, to ensure that national collections are fully and safely accessible, namely by establishing quality management systems in these collections. Better identification of users and their

needs can be achieved through follow-up surveys sent by curators to recipients of germplasm and through increased collaboration among breeders, researchers and national collections. Other key users of yam germplasm are scientists, who are often based in universities or countries far from the collections and who want access to biologically well-defined accessions for new studies and for generating new knowledge.

3.7 *IN SITU* STRATEGIC ACTION PLAN

Following are the priority strategic actions for enhancing and promoting *in situ* conservation and on-farm management. These actions are based on the analysis of the major constraints and obstacles for yam genetic resources discussed in Section 1.6.2 on *in situ* conservation.

1. Inventory of yam diversity in farmers' fields and in the wild. There is not enough information about the genetic diversity of cultivated and domesticated cultivars of yam and their wild relatives in most of the range states. This calls for a systematic survey to inventory the yam diversity in farmers' fields and in the wild across the range states. Any inventory should also include all associated knowledge, including farmers' indigenous knowledge on *in situ* management and wild diversity located within protected areas.

2. Development of an early warning monitoring system for tracking the loss of yam genetic diversity from farmers' fields and in the wild. As described in Sections 1 and 2, there is a general lack of data on the extent of diversity of traditional yam cultivars in farmers' fields in most countries. In addition, numerous factors are eroding the diversity of yam, especially wild relatives. There is thus an urgent need to establish a monitoring system to track changes in the genetic diversity of yams on farms and in the wild, in order to deploy conservation measures (both *in situ* and *ex situ*) for their safeguard. It is recommended that an early warning monitoring system be established at the global level. The *in situ* conservation monitoring system for root, tuber and banana crops currently in development by the Alliance of Bioversity and CIAT could provide such a platform for monitoring yam diversity globally.

3. Global *in situ* conservation planning for the safeguard of yam wild relatives. It is recommended that a global conservation planning exercise be carried out to determine key priority sites that would be targets for detailed *in situ* conservation interventions, including the creation of genetic reserves for yam conservation.

4. Capacity building. Most countries where yam is indigenous lack the technical capacity for *in situ* conservation. Enhancing the capacity of stakeholders who manage protected areas or natural areas is thus critical for ensuring the sustainable conservation and use of yam genetic resources. Local universities need to be supported to establish specific courses on *in situ* conservation and taxonomy.

5. Support of research on yam genetic diversity. Much remains unknown about the ecology, distribution patterns and taxonomy of yam genetic resources. Research in these areas should be supported to increase our knowledge about yam genetic resources, so that a better informed conservation strategy and implementation plan can be developed.

6. Strengthening partnerships for yam *in situ* conservation. The strengthening of linkages among key stakeholders (government institutions, nongovernment institutions, farmers, local communities, traders and other stakeholders) involved in conservation is essential for the successful implementation of any conservation plan. Participation of the various stakeholders in *in situ* management must be sought. The development of a participatory *in situ* conservation strategy will be needed to improve linkage and coordination among institutions involved in conservation activities.

7. Education and public awareness. The lack of support for *in situ* conservation and on-farm management of yam genetic diversity is often due to poor understanding of the importance of conserving yam genetic diversity among various stakeholder groups (policymakers, protected area managers, farmers, local communities, traders and local authorities). In particular, there is a need for strong advocacy to policymakers to create an enabling environment for implementing activities aimed at conservation of yam genetic resources. In addition, strategies are required regarding information, education and communication, in order to enhance awareness and public action on conservation and use of diversity appropriate for each stakeholder group.

8: Use it or lose it: Enhancements to the value chain to sustain the conservation of local genetic resources of yams. To sustain local diversity of yams on farms, there is a need to stimulate the cultivation and marketing of local yam cultivars along the value chain. The presence of markets will encourage rural communities to conserve and maintain their food crop diversity both on farms and in wild habitats. This could involve the development of local community-based seed supply, product development and marketing systems, development of niche markets and creation of incentive mechanisms for the conservation and use of local diversity.

3.8 NETWORKING

There is no international network for yam genetic resources. As only 31 yam collections together contain a large part of the global yam gene pool, the number of partners interested in a global strategy is rather limited. These partners would form the basis for a yam network for conservation. The systems in place in different countries could be substantially improved through the improvement of critical activities such as regeneration, documentation, storage, health control and safety duplication. At the moment, very few collections can conduct these activities to international standards. In West Africa, several countries reported their participation in the project GRENEWECA (Halewood et al. 2014), but this network focused on species other than yam. The development of a global strategy will be possible only if it is based on a "YamNet," that is, an international network for yam conservation and use. This network could bring together the institutions that participated in this survey and strengthen partnerships via the exchange of information and germplasm. Although yam is primarily grown and produced in Africa, it is of utmost importance to have an international network with partners located outside Africa (where the areas of origin of several species are located). A YamNet would help in facilitating partnerships for increased exchange of well-characterized accessions and improved evaluation in a range of environments. The incentive for national collections to join the network is the assurance that their collections will be safely backed up and documented when they share their materials with the international collection (IITA), regional hubs and other partners. The ultimate objective is to increase the focus on the value and use of their collections' diversity.

3.9 ACCESS AND BENEFIT-SHARING POLICIES

To fulfil the objectives of the Convention on Biological Diversity and the Nagoya Protocol on Access and Benefit-sharing, yam *ex situ* collections must acquire new accessions legally and share benefits from the use of these accessions fairly and equitably with their providers. All yam collections are now facing the challenge of working out how to conduct their conservation work in agreement with new international laws and regulations related to access and benefit-sharing. This could be a problem for the very few

yam collections that source accessions from outside their area; it does not pose a problem for most collections, as they are composed of local yam cultivars and accessions originating only from their own country.

In fact, IITA (Nigeria) and SPC (Fiji) are the only securely funded diverse collections that are safely distributing yam germplasm internationally. All others are national collections. A registered collection is a germplasm collection that has demonstrated the capacity to apply internationally standardized procedures for exchanging germplasm (and related information), to supply accessions to other parties with documentation providing evidence that these accessions have been collected in accordance with applicable legislation, and to keep accurate records of all yam accessions. The FAO has put in place a process to facilitate domestic implementation of access and benefit-sharing for genetic resources. These guidelines are freely accessible online (FAO 2019). For crops included in the ITPGRFA, the trend is toward more-formalized exchange practices, through an SMTA.

Much of the work of yam collections should focus on gaining access to and exchanging accessions to enrich collections, or on securing accessions by distributing them to various geographic sites or hubs. However, most of the work is presently done locally by national collections, with very little international exchange of germplasm. The exceptions are IITA's international collection in Ibadan, Nigeria, and the SPC's regional germplasm center in Suva, Fiji, but even for these two collections, international distribution is somewhat limited because of low demand.

It is possible that, once the elite subsets have been assembled, characterized and sanitized, countries will request new cultivars, but it is difficult to anticipate the extent of the demand. Demand will probably be limited because there are so few yam breeding programs in national systems, and those programs are not robust. The absence of such programs is an important constraint on the demand for new germplasm in West Africa. It is doubtful that the international exchange of accessions and cultivars will intensify in the near future. One of the main findings of the present survey is that the distribution of yam germplasm is extremely limited because accessions have accumulated viruses of quarantine importance (Kenyon et al. 2003; Kenyon et al. 2008). New viruses or new strains have been identified and documented in international journals, but very few institutions have invested time and effort in developing rapid and cost-efficient protocols for sanitizing genotypes and certifying them free of viruses. Some genotypes have almost no international demand. Very few countries are planning to introduce yam genotypes from countries that do not have the means to sanitize them, as facilities are lacking in most yam-growing countries.

This major phytosanitary barrier is exacerbated by the fact that available tissue culture techniques are not sufficiently efficient to produce certified virus-free germplasm. To make matters worse, very often the accessions maintained in *in vitro* collections are poorly characterized. Therefore, should one of the very few yam breeders be interested in importing a particular genotype into their country, the first traits they would need to know before importing are ploidy level and sex. Without the systematic characterization of these traits, no accession is worth exchanging, as indicated by a risk–benefit analysis.

3.10 IMPLEMENTATION, GOVERNANCE AND FUNDING

IITA will play a major role in the implementation and governance of the Global Strategy for the Conservation and Use of Yam. However, as the strategy entails numerous and varied activities in relation to a great number of species, others will

need to share the burden. Furthermore, for species that originate from Asia (*D. alata*, *D. bulbifera*, *D. esculenta*, *D. japonica*, *D. nummularia*, *D. oppositifolia*) and America (*D. trifida*), there is a need for an international network and partnership to strengthen the conservation and use of yam genetic resources.

Flow cytometry: Ideally, all yam accessions should be analyzed for ploidy levels using a flow cytometer. Chromosome counts should be done on a few accessions which could be used as standards. The indicative cost of a flow cytometer is approximately EUR 22,000 (including accessories; see www.sysmex-partec.com). Some cytometers are portable and have a Pelican (flight) case so they can be moved between countries within the same region, depending on the number of accessions to be analyzed. Scientists can travel to neighboring countries with their samples of fresh leaves (depending on quarantine regulations). It is estimated that, to complete this work rapidly, seven cytometers would be needed (one for the Caribbean and Brazil, three for West Africa, one for India, one for Southeast Asia and one for Melanesia). Partners will need to undertake a three-day training with a yam cytometry expert before the work can be safely conducted. The training would take place in Europe, which will necessitate long-distance travel for about 30 partners. Partners would then be able to take the cytometers home with them, but tax exemption procedures will have to be discussed before then.

DNA fingerprinting: For GBS analyses, the average cost is around EUR 25 per sample (including extraction and the preparation of libraries for sequencing). For yam, this work is cumbersome (Sharif et al. 2020). There are two alternatives for DNA fingerprinting: genotyping with microsatellite markers (around 10 markers are needed) at a cost of approximately EUR 10 per sample, or SNP fingerprinting (20–30 markers) with a comparable cost. Ideally, about 20% of the accessions identified as potential candidates for inclusion in the elite subset should be fingerprinted because a high proportion of duplicates is expected. The objective is to assemble an elite subset that represents approximately 10% of the total number of accessions (1,370 acc.).

Development of cleaning and indexing procedures: As soon as possible, the responsibility for conducting simple tests should be transferred to partners, after appropriate training, to analyze *in situ* their accessions and detect the major viruses present. This could be done as early as the first year in an institution with relevant expertise, with the responsibility then transferred to partners in the field.

Production of true seeds: Partners should learn yam floral biology and how to produce true botanical seeds in order to exchange allelic diversity and to conduct research locally on seed preservation. This training can be completed by organizing a short course (a few days) in IITA, which has the necessary expertise.

3.11 CONDITIONS FOR SUCCESS AND INDICATORS

This global strategy could be implemented smoothly if partners are sincere and willing to exchange their germplasm to secure the geographic distribution of allelic diversity. The approach described in this strategy will contribute to the long-term conservation of significant diversity in all participating countries in a cost-efficient manner, so long as there are no bureaucratic obstacles to exchange. In order to make sure that partners are willing to share and exchange, a consortium agreement should be signed, detailing obligations of each participating country base on a win-win deal: countries agree to share their germplasm in exchange for support for implementing the global strategy (flow cytometry,

DNA fingerprinting, virus indexing and training). Potential quantitative indicators to monitor the proper implementation of this global strategy over the next four years are: the number of accessions passed in flow cytometry with ploidy level determined, the number of accessions fingerprinted with DNA markers, the number of elite cultivars sanitized and inserted into the elite subset, the number of duplicates identified and removed from collections, and the establishment of a functional yam network, YGIS and Yamlogue.

Table 3.3 Tentative budget for implementing the global strategy for the conservation and use of yam genetic resources (in EUR)

Item	Year 1	Year 2	Year 3	Year 4	Total
Equipment (7 flow cytometers with Pelican case)	154,000	–	–	–	154,000
Training in cytometry (flights, accommodation, expert)	130,000	–	–	–	130,000
DNA fingerprinting of 2,740 acc. with SSR + expertise	68,000	–	–	–	68,000
Development of virus cleaning (and indexing tests)	200,000	–	–	300,000	500,000
Training in true seeds (flights, accommodation, expert)	–	–	120,000	–	120,000
Networking, YGIS, Yamlogue	20,000	20,000	20,000	20,000	80,000
Research on cryopreservation	40,000	40,000	40,000	–	120,000
Total	612,000	60,000	180,000	320,000	1,172,000

REFERENCES

Abang, M.M., Winter, S., Green, K.R., Hoffmann, P., Mignouna, H.D. and Wolf, G.A. 2002. Molecular identification of Colletotrichum gloeosporioides causing yam anthracnose in Nigeria. Plant Pathology 51, 63–71. https://doi.org/10.1046/j.0032-0862.2001.00655.x

Abang, M.M., Fagbola, O., Smalla, K. and Winter, S. 2005. Two genetically distinct populations of Colletotrichum gloeosporioides Penz. Causing anthracnose disease of yam (Dioscorea spp.). Journal of Phytopathology (Berlin) 153(3), 137–142. https://doi.org/10.1111/j.1439-0434.2005.00942.x

Abang, M.M., Asiedu, R., Hoffmann, P., Wolf, G.A., Mignouna, H.D., Winter, S. 2006. Pathogenic and genetic variability among Colletotrichum gloeosporioides isolates from different yam hosts in the agroecological zones in Nigeria. Journal of Phytopathology (Berlin) 154(1): 51–61. doi:10.1111/j.1439-0434.2005.01060.x

Abraham, K. 2002. Genetic potential of sexually propagated seedlings of greater yam, Dioscorea alata L. Journal of Root Crops 28(2): 21–25.

Abraham, K, Nair, P.G. 1990. Floral biology and artificial pollination in Dioscorea alata L. Euphytica 48: 45–51. doi:10.1007/BF00028959

Abraham, K., Nair, P.G. 1991. Polyploidy and sterility in relation to sex in Dioscorea alata L. (Dioscoreaceae). Genetica 83: 93–97. doi:10.1007/BF00058525

Abraham, K., Nemorin, A., Lebot, V., Arnau, G. 2013. Meiosis and sexual fertility of autotetraploid clones of greater yam Dioscorea alata L. Genetic Resources and Crop Evolution 60(3): 819–823. doi:10.1007/s10722-013-9973-4

Abraham, K., Sreekumari, M.T., Sheela, M.N. 2006. Breeding significance of seedling and clonal tuber shapes in greater yam. Journal of Root Crops 32(1): 72–77.

Adoukonou-Sagbadja, H., Missihoun, A.A., Sedah, P., Dagba, R.A., Kinhoegbe, G., Ahanhanzo, C., Agbangla, C. 2014. Genetic variability of accessions of yam (Dioscorea alata L.) introduced in Benin from the South Pacific Islands. Journal of Applied Biosciences 73: 5966–5978.

Agre, P., Asibe, F., Darkwa, K., Edemodu, A., Bauchet, G., Asiedu, R., Adebola, P., Asfaw, A. 2019. Phenotypic and molecular assessment of genetic structure and diversity in a panel of winged yam (Dioscorea alata) clones and cultivars. Scientific Reports 9: 18221. doi:10.1038/s41598-019-54761-3

Akimoto, M., Shimamoto, Y., Morishima, H. (1999). The extinction of genetic resources of Asian wild rice, Oryza rufipogon Griff.: a case study in Thailand. Genetic Resources and Crop Evolution, 46(4), 419-425.

Akoroda, M.O. 1983. Floral biology in relation to hand pollination of white yam. Euphytica 32: 831–838. doi:0.1007/BF00042164

Akoroda, M.O., Okonmah, L.U. 1982. Sett production and germplasm maintenance through vine cuttings in yams. Tropical Agriculture 59(4): 311–314.

Akoroda, M.O., Wilson, J.E., Cheda, H.R. 1981. Artificial pollination, pollen viability and storage in white yam. In: Terry, E.R., Oduro, K.A., Caveness, F. (eds.). Tropical root crops, research strategies for the 1980s. Ottawa, Canada: IDRC. pp. 189–194.

Altoveros, N.C, Borromeo, T.H. 2007. The State of the Plant Genetic Resources for Food and

Agriculture of the Philippines (1997 - 2006). Bureau of Plant Industry.

Available at https://www.fao.org/pgrfa-gpa-archive/phl/docs/countryreport2.pdf?

Andriamparany J.N. 2015. Diversity, local uses and availability of medicinal plants and wild yams in the Mahafaly region of south-western Madagascar. PhD dissertation, University of Kassel, Germany.

Araki, H., Harada, T., Yakuwa, T. 1983. Some characteristics of interspecific hybrids between Dioscorea japonica and Dioscorea opposita. Journal of the Japanese Society for Horticultural Science 52: 153–158. doi:10.2503/jjshs.52.153

Arnau, G., Abraham, K., Sheela, M.N., Chaïr, H., Sartie, A., Asiedu, R. 2010. Yams. In: Bradshaw, J.E. (ed.). Root and tuber crops: handbook of plant breeding. New York: Springer Verlag. pp: 127–148.

Arnau, G., Bhattacharjee, R., Sheela, M.N., Chaïr, H., Malapa, R., Lebot, V., Abraham, K., Perrier, X., Petro D., Penet, L., Pavis, C. 2017. Understanding the genetic diversity and population structure of yam (Dioscorea alata L.) using microsatellite markers. PLoS ONE 12(3): e0174150. doi:10.1371/journal.pone.0174150

Arnau, G., Némorin, A., Maledon, E., Abraham, K. 2009. Revision of ploidy status of Dioscorea alata L. (Dioscoreaceae) by cytogenetic and microsatellite segregation analysis. Theoretical and Applied Genetics 118(7): 1239–1249. doi:10.1007/s00122-009-0977-6

Asfaw, A., Agre, P., Nwachukwu, C., Olasanmi, B., Obidiegwu, J., Nwachukwu, E., Adebola, P., De Koeyer, D. 2020. Sample preservation and plant sex prediction in white Guinea yam (Dioscorea rotundata Poir.) seedlings. Preprint doi:10.20944/preprints202002.0187.v1

Asiedu, R., Sartie, A. 2010. Crops that feed the world 1. Yams. Yams for income and food security. Food Security 2: 305–315. doi:10.1007/s12571-010-0085-0

Avula, B., Wang, Y.H., Wang, M., Ali, Z., Smillie, T.J., Zweigenbaum, J., Khan, I.A. 2014. Characterization of steroidal saponins from Dioscorea villosa and D. cayenensis using ultrahigh performance liquid chromatography/electrospray ionization quadrupole time-of-flight mass spectrometry. Planta Medica 80: 321–329.

Babil, P.K., Irie, K., Shiwachi, H., Tun, Y.T., Toyohara, H., Fujimaki, H. 2010. Ploidy variation and their effects on leaf and stoma traits of water yam (Dioscorea alata L.) collected in Myanmar. Tropical Agriculture and Development 54(4): 132–139.

Babil, P.K., Yasuhara, D., Sagaguchi, K., Iwashina, T., Irie, K., Shiwachi, H., Toyohara, H., Fujimaki, H. 2012. Recurring somaclonal variation as a factor of intra-specific diversity observed in Dioscorea alata L. Tropical Agriculture and Development 56(2): 71–79.

Beinart, W., Beinart, R. 2019. 'From elephant's foot … to cortisone': Boots pure drug company and Dioscorea sylvatica in South Africa, c. 1950–1963. South African Historical Journal 71(4): 644-675. doi:10.1080/02582473.2019.1668837

Bhattacharjee, R., Gedil, M., Sartie, A., Otoo, E., Dumet, D., Kikuno, H., Kumar, P.L., Asiedu, R. 2011. Dioscorea. In: Kole, C. (ed.). Wild crop relatives: genomic and breeding resources. Industrial crops. Berlin: Springer-Verlag. pp. 71–96. doi:10.1007/978-3-642-21102-7_4

Bömer, M., Rathnayake, A.I., Visendi, P., Sewe, S.O., Sicat, J.P.A., Silva, G., Kumar, P.L., Seal, S.E. 2019. Tissue culture and next-generation sequencing: A combined approach for detecting yam (Dioscorea spp.) viruses.

Physiological and Molecular Plant Pathology. 105: 54–66. doi:10.1016/j.pmpp.2018.06.003

Bömer, M., Turaki, A., Silva, G., Kumar, P., Seal, S. 2016. A sequence-independent strategy for amplification and characterisation of episomal badnavirus sequences reveals three previously uncharacterised yam badnaviruses. Viruses 8: 188.

Boussalem, M., Arnau, G., Hochu, I., Arnolin, R., Viader, V., Santoni, S., David, J. 2006. Microsatellite segregation analysis and cytogenetic evidence for tetrasomic inheritance in the American yam Dioscorea trifida and a new basic chromosome number in the Dioscoreae. Theoretical and Applied Genetics 113: 439–451. doi:10.1007/s00122-006-0309-z

Bradshaw, J.E., Bonierbale, M. 2010. Potatoes. In: Bradshaw, J.E. (ed.). Root and tuber crops: handbook of plant breeding. Springer. pp. 1–52.

Brunt, A.A., Jackson, G.V.H., Frison, E.A. (eds.). 1989. FAO/IBPGR technical guidelines for the safe movement of yam germplasm. Rome, Italy: Food and Agriculture Organization of the United Nations/International Board for Plant Genetic Resources.

Burkill, I.H. 1935. A dictionary of the economic products of the Malay Peninsula. London, UK: Crown Agents.

Burkill, I.H. 1960. Organography and evolution of Dioscoreaceae, the family of yams. Journal of the Linnean Society 56(367): 319–412.

Cable, W.J., Wilson, J.E. 1984. Dioscorea nummularia Lam.: the primary edible yam of Western Samoa. In: Proceedings of the 6th Symposium of the ISTRC. Lima, Peru: International Potato Center (CIP). pp. 599–605.

Cabrera, J.M., Kosky, R.G., Cuellar, E.E. 2011. Effect of liquid media culture systems on yam plant growth (Dioscorea alata L. 'Pacala Duclos'). Biotechnology Agronomy Society Environment 15(4): 515−521.

Caddick, L.R., Wilkin, P., Rudall, P.J., Hedderson, T.A.J., Chase, M.W. 2002. Yams reclassified: a recircumscription of Dioscoreaceae and Dioscoreales. Taxon 51: 103–114.

Camus, P., Lebot, V. 2010. On-farm assessment of clonal introduction of root crops diversity in Vanuatu, Melanesia. Experimental Agriculture 46(4): 541–559. doi:10.1017/S0014479710000591

Chaïr, H., Duroy, P.O., Cubry, P., Sinsin, B., Pham J.L. 2011. Impact of past climatic and recent anthropogenic factors on wild yam genetic diversity. Molecular Ecology doi:10.1111/j.1365-294X.2011.05041.x

Chaïr, H., Perrier, X., Agbangla, C., Marchand, J.L., Dainou, O., Noyer, J.L. 2005. Use of cpSSRs for the characterization of yam phylogeny in Benin. Genome 48(4): 674–684. doi:10.1139/g05-018

Chaïr, H., Sardos, J., Supply, A., Mournet, P., Malapa, R., Lebot, V. 2016. Plastid phylogenetics of Oceania yams (Dioscorea spp., Dioscoreaceae) reveals natural interspecific hybridization of the greater yam (D. alata). Botanical Journal of the Linnean Society 180(3): 319–333. doi:10.1111/boj.12374

Chandrasekara, A., Kumar, T.J. 2016. Roots and tuber crops as functional foods: a review on phytochemical constituents and their potential health benefits. International Journal of Food Science. doi:10.1155/2016/3631647

Chen, M.F., Tsai, J.T., Chen, L.J., Wu, T.P., Yang, J.J., Yin, L.T., Yang, Y.L., Chiang, T.A., Lu, H.L., Wu, M.C. 2014. Antihypertensive action of allantoin in animals. BioMed Research International vol. 2014, article ID 690135, 6 p. doi:10.1155/2014/690135.

Cheng, Y., Dong, C., Huang, C., Zhu, Y. 2015. Enhanced production of diosgenin from Dioscorea zingiberensis in mixed culture solid state fermentation with Trichoderma reesei and Aspergillus fumigatus. Biotechnology and Biotechnological Equipment 29(4): 773–778. doi:10.1080/13102818.2015.1032352

Cormier, F., Lawac, F., Maledon, E., Gravillon, M.C., Nudol, E., Mournet, P., Vignes, H., Chaïr, H, Arnau, G. 2019a. A reference high-density genetic map of greater yam (Dioscorea alata L.). Theoretical and Applied Genetics 132(6): 1733–1744. doi:10.1007/s00122-019-03311-6

Cormier F., Mournet, P., Causse, S., Arnau, G., Maledon, E., Gomez, R.M., Pavis, C., Chaïr, H. 2019b. Development of a cost-effective single nucleotide polymorphism genotyping array for management of greater yam germplasm collections. Ecology and Evolution 9(10): 5617–5636.

Coursey, D.G. 1967. Yams: an account of the nature, origins, cultivation and utilisation of the useful members of the Dioscoreaceae. Tropical Agriculture Series. London, UK: Longmans.

Couto, R.S., Martins, A.C., Bolson, M., Lopes, R.C., Smidt, E.C., Braga, J.M. 2018. Time calibrated tree of Dioscorea (Dioscoreaceae) indicates four origins of yams in the Neotropics since the Eocene. Botanical Journal of the Linnean Society XX: 1–17.

Crop Trust. 2006. Global strategy for the *Ex situ* of Potato Bonn, Germany: Global Crop Diversity Trust. Available at https://cdn.croptrust.org/wp/wp-content/uploads/2017/02/Potato-Strategy-FINAL-30Jan07.pdf (accessed 11 November 2020).

Crop Trust. 2010. Towards a global strategy for the conservation and use of yam. Bonn, Germany: Global Crop Diversity Trust. Available at https://cdn.croptrust.org/wp/wp-content/uploads/2017/07/Yam-conservation-strategy-Part-1-and-2.pdf (accessed 11 November 2020).

Crop Trust. 2020. Yam. Bonn, Germany: Global Crop Diversity Trust. Available at https://www.croptrust.org/crop/yam/? (accessed 11 November 2020).

Crop Wild Relatives Occurrence Data Consortia. 2018. A global database for the distributions of crop wild relatives. Version 1.12. CIAT. Occurrence dataset available at https://doi.org/10.15468/jyrthk (accessed 22 September 2020 via GBIF.org).

Cruz, V.M.V., Ramirez, D.A. 1999. Variation in morphological characters in a collection of yams (Dioscorea spp.). Philippines Journal of Crop Sciences 24: 27–35.

Daïnou, O., Agbangla, C., Berthaud, J., Tostain, S. 2002. Le nombre chromosomique de base des espèces de Dioscorea constituant la section Enantiophyllum pourrait être égal à x = 20. Quelques preuves. Annales des Sciences Agronomiques du Bénin 3: 21–43.

Dansi, A., Dantsey-Barry, H., Dossou-Aminon, I., N'Kpenu, E.K., Agré, A.P., Sunu, Y.D., Kombaté, K., Loko, Y.L., Dansi, M., Assogba, P., Vodouhè, R. 2013. Varietal diversity and genetic erosion of cultivated yams (Dioscorea cayenensis Poir - D. rotundata Lam complex and D. alata L.) in Togo. International Journal of Biodiversity and Conservation 5(4): 223–239.

Dansi, A., Mignouna, H.D., Pillay, M., Zok, S. 2001. Ploidy variation in the cultivated yams (Dioscorea cayenensis–Dioscorea rotundata complex) from Cameroon as determined by flow cytometry. Euphytica 119: 301–307. doi:10.1023/A:1017510402681

Dansi, A., Mignouna, H.D., Zoundjihékpon, J., Sangare, J., Asiedu, R., Quin, M.F. 1999. Morphological diversity, cultivar groups and possible descent in the cultivated yams

(Dioscorea cayenensis-rotundata) complex in the Benin Republic. Genetic Resources and Crop Evolution 46: 371–388. doi:10.1023/A:1008698123887

Dansi, A., Mignouna, H.D., Zoundjihékpon, J., Sangare, A., Ahoussou, N., Asiedu, R. 2000. Identification of some Benin Republic's Guinea yam (Dioscorea cayenensis/Dioscorea rotundata complex) cultivars using Randomly Amplified Polymorphic DNA. Genetic Resources and Crop Evolution 47: 619–625.

Darkwa, K., Agre, P., Olasanmi, B., Iseki, K., Matsumoto, R., Powell, A., Bauchet, G., De Koeyer, D., Muranaka, S., Adebola, P., Asiedu, R., Terauchi, R., Asfaw, A. 2020c. Comparative assessment of genetic diversity matrices and clustering methods in white Guinea yam (Dioscorea rotundata) based on morphological and molecular markers. Scientific Reports. doi:10.1038/s41598-020-69925-9

Darkwa, K., Agre, P., Olasanmi, B., Kolade, O., Mournet, P., Lopez-Montes, A., Dekoeyer, D. Adebola, P., Kumar, L.P., Asiedu, R., Asfaw, A. 2020b. A SNP-based linkage map and QTL identification for resistance to yam anthracnose disease (YAD) in water yam (Dioscorea alata). Research Square doi:10.21203/rs.3.rs-26806/v1

Darkwa, K., Olasanmi, B., Asiedu, R., Asfaw, A. 2020a. Review of empirical and emerging breeding methods and tools for yam (Dioscorea spp.) improvement: status and prospects. Plant Breeding 139: 474–497. doi:10.1111/pbr.12783

Darwin Initiative. 2018. Conserving Madagascar's yams through cultivation for livelihoods and food security. Edinburgh: UK, Darwin Initiative. Available at https://www.darwininitiative.org.uk/assets/uploads/2018/06/6.-Conserving-Madagascars-yams-FINAL.pdf (accessed 12 November 2020)

Degras, L.M. 1993. The yam: a tropical root crop. London, UK: MacMillan Press Ltd.

Deshpande, H.A., Bhalsing, S.R. 2014. Plant-derived novel biomedicinal: diosgenin. International Journal of Pharmacognosy and Phytochemical Research 6(4): 780–784.

Dumet, D., Ojuderie, O., Kikuno, H. 2007. Yam in vitro genebanking. IITA genebank manual series. Ibadan, Nigeria: IITA. Available at: https://cropgenebank.sgrp.cgiar.org/images/file/learning_space/iita_yam_manual.pdf (accessed 11 November 2020).

Dumont, R., Dansi, A., Vernier, P., Zoundjihékpon, J. 2006. Biodiversity and domestication of yams in West Africa: traditional practices leading to Dioscorea rotundata Poir. Nancy, France: Editions Quae, Cirad-IPGRI.

Egesi, C.N., Asiedu, R., Egunjobi, J.K., Bokanga, M. 2003. Genetic diversity of organic properties in water yam (Dioscorea alata L.). Journal of the Science of Food and Agriculture 83: 858–865. doi:10.1002/jsfa.1343

Egesi, C.N., Asiedu, R., Ude, G., Ogunyemi, S., Egunjobi, J.K. 2006. AFLP marker diversity in water yam (Dioscorea alata L.). Plant Genetic Resources: Characterization and Utilization 4(3): 181–187. doi:10.1079/PGR2006121

Essad, S. 1984. Variation géographique des nombres chromosomiques de base et polyploïdie dans le genre Dioscorea à propos du dénombrement des espèces transversa Brown, pilosiuscula Bert. et trifida L. Agronomie 4(7): 611–617.

FAOSTAT. 2020. Yam producing countries statistics for 2018. Available at www.fao.org/faostat/en#data/QC/ (accessed 11 August 2020).

Food and Agriculture Organization of the United Nations (FAO). 2009. The state of plant genetic resources for food and agriculture: country

report of Papua New Guinea. Available at: www.fao.org/3/i1500e/Papua%20New%20Guinea.pdf (accessed 11 November 2020).

Food and Agriculture Organization of the United Nations (FAO). 2010. The second report on the state of the world's plant genetic resources for food and agriculture. Rome, Italy: FAO.

Food and Agriculture Organization of the United Nations (FAO). 2019. ABS Elements: Elements to facilitate domestic implementation of access and benefit-sharing for different subsectors of genetic resources for food and agriculture – with explanatory notes. Rome, Italy: FAO. Licence: CC BY-NC-SA 3.0 IGO.

Food and Agriculture Organization of the United Nations (FAO). 2019b. The Staterof the World's Biodiversity for Food and Agriculture. Rome, Italy: FAO.

Fullagar, R., Field, J., Denham, T., Lentfer, C. 2006. Early and mid-Holocene tool use and processing of yam (Colocasia esculenta): yam (Dioscorea sp.) and other plants at Kuk Swamp in the highlands of Papua New Guinea. Journal of Archaeological Science 33(1): 595–614. doi:10.1016/j.jas.2005.07.020

Gamiette, F., Bakry, F., Ano, G. 1999. Ploidy determination of some yam species (Dioscorea spp.) by flow cytometry and conventional chromosome counting. Genetic Resources and Crop Evolution 46: 19–27. doi:10.1023/A:1008649130567

GBIF.org. GBIF occurrence download. Available at https://doi.org/10.15468/dl.8r2nb8 (accessed 21 September 2020).

Genesys. 2020. International database of plant genetic resources. Available at www.genesys-pgr.org/ (accessed 6 August 2020).

Girma, G., Bhattacharjee, R., Lopez-Montes, A., Gueye, B., Ofodile, S., Franco, J., Abberton, M. 2017. Re-defining the yam (Dioscorea spp.) core collection using morphological traits. Plant Genetic Resources 16(3): 193–200. doi:10.1017/S1479262117000144

Girma, G., Hyma, K.E., Asiedu, R., Mitchell, S.E., Gedil, M., Spillane, C. 2014. Next-generation sequencing based genotyping, cytometry and phenotyping for understanding diversity and evolution of guinea yams. Theoretical and Applied Genetics 127(8): 1783–1794. doi:10.1007/s00122-014-2339-2

Girma, G., Natsume, S., Carluccio, A.V., Takagi, H., Matsumura, H., Uemura, A., Muranaka, S., Takagi, H., Stavolone, L., Gedil, M., Spillane, C., Terauchi, R., Tamiru, M. 2019. Identification of candidate flowering and sex genes in white Guinea yam (D. rotundata Poir.) by SuperSAGE transcriptome profiling. PLoS ONE 14(9): e0216912. doi:10.1371/journal.pone.0216912

Girma, H., Spillane, C., Gedil, M. 2015. DNA barcoding of the main cultivated yams and selected wild species in the genus Dioscorea. Journal of Systematics and Evolution 9999: 1–10. doi:10.1111/jse.12183

Govaerts, R., Wilkin, P., Saunders, R.M.K. 2007. World checklist of Dioscoreales, yams and their allies. London, UK: The Board of Trustees of the Royal Botanic Gardens, Kew.

Graham-Acquaah, S., Ayernor, G.S., Bediako-Amoa, B., Saalia, F.K., Afoakwa, E.O. 2014. Spatial distribution of total phenolic content, enzymatic activities and browning in white yam (Dioscorea rotundata) tubers. Journal of Food Science and Technology 51(10): 2833–2838. doi:10.1007/s13197-012-0760-6

Green, K.R., Simons, S.A. 1994. 'Dead skin' on yams (Dioscorea alata) caused by Colletotrichum gloeosporioides. Plant Pathology 43: 1062–1065. doi:10.1111/j.1365-3059.1994.tb01660.x

Guarino, L., Jackson, G.V.H. 1986. Describing and documenting root crops in the South Pacific.

Suva, Fiji: FAO RAS/83/001 Field Document No. 12.

Halewood, M., Baidu-Forson, J.J., Clancy, E., Vodouhe, R.S. (eds.). 2014. Cooperating to make the best use of plant genetic resources in west and central Africa: a regional imperative. Rome, Italy and Dakar, Senegal: Bioversity International and CORAF/WECARD.

Heargreaves, S., and Wilkin P. 2019. Tubers in Trouble. RBG Kew website. url: https://www.kew.org/read-and-watch/tubers-in-trouble.

Hegde, S. G., Nason, J. D., Clegg, J. M., and Ellstrand, N. C. 2006. The evolution of California's wild radish has resulted in the extinction of its progenitors. Evolution, 60(6), 1187-1197.

Hamon, P., Touré, B. 1990. The classification of the cultivated yams (Dioscorea cayenensis-rotundata complex) of West Africa. Euphytica 47: 179–187. doi:10.1007/BF00024240

Honfozo, L., Adinsi, L., Bouniol, A., Adetonah, S., Forsythe, L., Kleih, U., Hounhouigan, J.D., Fliedel, G., Akissoe, N.H. 2020. Boiled yam end-user preferences and implications for trait evaluation. International Journal of Food Science and Technology. doi:10.1111/ijfs.14707

Horrocks, M., Nunn, P.D. 2006. Evidence for introduced yam (Colocasia esculenta) and lesser yam (Dioscorea esculenta) in Lapita-era (c. 3050–2500 cal. yr. BP) deposits from Bourewa, south-west Viti Levu Island, Fiji. Journal of Archaeological Science 34(5): 739–748. doi:10.1016/j.jas.2006.07.011

Hsu, K.L.,Tsai, J.M., Chen, M.Y., Ku, H.M., Liu, S.C. 2013. Molecular Phylogeny of Dioscorea (Dioscoreaceae) in East and Southeast Asia. Blumea 58: 21-27 http://dx.doi.org/10.3767/000651911 3X669022

Huamàn, Z., Golmirzaie, A., Amoros, W. 1997. The potato. In: Fucillo, D., Sears, L., Stapleton, P. (eds.). Biodiversity in trust: conservation and use of plant genetic resources in CGIAR centres. Cambridge, UK: Cambridge University Press. pp. 21–28.

Hunter, D., and Heywood, V. H. 2011. Crop Wild Relatives: A Manual of in situ Conservation. Earthscan.

Idohou, R., Assogbadjo, A.E., Fandohan, B., Gouwakinnou, G.N., Kakai, R.L.G., Sinsin, B., Maxted, N. 2013. National inventory and prioritization of crop wild relatives: case study for Benin. Genetic Resources and Crop Evolution 60: 1337–1352 doi:10.1007/s10722-012-9923-6

Indian Council of Agricultural Research-Central Tuber Crops Research Institute (ICAR-CTCRI). 2019. Annual report 2018–2019. Thiruvananthapuram, Kerala, India: ICAR-CTCRI. Available at www.ctcri.org/publications/annual-report/CTCRI%20Annual%20Report%202018-19.pdf (accessed 3 September 2020).

International Plant Genetic Resources Institute and International Institute of Tropical Agriculture (IPGRI/IITA). 1997. Descriptors for yam (Dioscorea spp.). Ibadan, Nigeria and Rome, Italy: IPGRI and IITA.

International Union for Conservation of Nature (IUCN). 2001. IUCN Red List categories and criteria. Gland and Cambridge: IUCN Species Survival Commission, IUCN.

IPBES 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany.

Jackson, G.V.H. 1994. Yam and yam genetic resources in the Pacific and Asia. A report

prepared for the Australian Centre for International Agricultural Research and the International Plant Genetic Research Institute. Canberra, Australia: Anutech Pty Ltd.

Jesus, M., Martins, A.P.J., Gallardo, E., Silvestre, S. 2016. Diosgenin: recent highlights on pharmacology and analytical methodology. Journal of Analytical Methods in Chemistry ID 4156293, 16 p. doi:10.1155/2016/4156293.

John, J.L., Courtney, W.H., Decoteau, D.R. 1993. The influence of plant growth regulators and light on microtuber induction and formation in Dioscorea alata L. cultures. Plant Cell, Tissue and Organ Culture 34: 245–252. doi:10.1007/BF00029713

Kell, S., Qin, H., Chen, B., Ford-Lloyd, B., Wei, W., Kang, D., Maxted, N. 2015. China's crop wild relatives: diversity for agriculture and food security. Agriculture, Ecosystems and Environment 209: 138–154.

Kenyon, L., Lebas, B.S.M., Seal, S.E. 2008. Yams (Dioscorea spp.) from the South Pacific Islands contain many novel badnaviruses: implications for international movement of yam germplasm. Archives of Virology 153: 877–889. doi:10.1007/s00705-008-0062-5

Kenyon, L., Shoyinka, S.A., Hughes, J., Odu, B.O. 2003. An overview of viruses infecting Dioscorea yams in sub-Saharan Africa. In: Proceedings of a conference on plant virology, 4–8 June 2001. Ibadan, Nigeria: IITA. pp. 423–439. Available at https://hdl.handle.net/10568/96505 (accessed 11 November 2020).

Kiang, Y.T., Antonovics, J., Wu, L., 1979. The extinction of wild rice (Oryza perennis formasana) in Taiwan. Journal of Asian Ecology 1: 1–9.

Kikuno, H., Kumar, P.L., Asiedu, R., Bhattacharjee, R., Gedil, M., Sartie, A., Otoo, E., Dumet, D. 2011. Dioscorea. In: Kole, E. (ed.). Wild crop relatives: genomic and breeding resources industrial crops. Berlin Heidelberg: Springer. pp. 71–96.

Kim, G.B., Na, C.S., Song, C.H., Kim, J.S., Kim, S.J., Kang, H.S. 2015. Antidiabetic effects of yam (Dioscorea batatas) and its active constituent, allantoin, in a rat model of streptozotocin-induced diabetes. Nutrients 7: 8532–8544. doi:10.3390/nu7105411.

Khoury, C., Sotelo, S. Amariles, D. 2019. The plants that feed the world: baseline information to underpin strategies for their conservation and use. International Treaty on Plant Genetic Resources for Food and Agriculture (Rome) Project 2018 – 2019

Kobbe, S., Kübler, D., Ratovonamana, Y., Fricke, R., Andriamparany, J.N., Brinkmann, K., Götter, J., Rakotomalala, D., Wesselow, M. 2017. SuLaMa—participatory research to support sustainable land management on the Mahafaly Plateau in southwestern Madagascar. Final report (01.01.2011–31.12.2016).

Kouam, E.B., Avana-Tientcheu, M.L., Lekeumo, V.D., Akitio, H.M., Khasa, D.P., Pasquet, R.S. 2018. Agro-ecological distribution of the phenotypic diversity of aerial yam (Dioscorea bulbifera L.) in Cameroon using multivariate analysis: prospect for germplasm conservation and improvement. Open Agriculture 3: 190–206. doi:10.1515/opag-2018-0020

Kumar, S., Das, G., Shin, H.-S., Patra, J.K. 2017. Dioscorea spp. (a wild edible tuber): a study on its ethnopharmacological potential and traditional use by the local people of Similipal Biosphere Reserve, India. Frontiers in Pharmacology 8: 52. doi:10.3389/fphar.2017.00052

Kung, T.L., Lin, K.H. and Lin, S.F. (2016) Genetic diversity of Dioscorea japonica germplasm in Taiwan revealed by inter-simple sequence repeat DNA markers. Plant Genetic Resources: Characterization and Utilization 14(3), 211–218. https://doi.org/10.1017/S147926211500026X

Kwon, Y.K., Jie, E.Y., Sartie, A., Kim, D.J., Liu, J.R., Min, B.W., Kim, S.W. 2015. Rapid metabolomics discrimination and prediction of dioscin content from African yam tubers using Fourier transform-infrared spectroscopy combined with multivariate analysis. Food Chemistry 166: 389–396. doi:10.1016/j.foodchem.2014.06.035

Laly, J., Gbemavo, D.S.J.C., Gbaguidi, A.A., Dossou-Aminon, I., Dansi, A. 2019. Dioscorea dumetorum (Kunth) Pax, a neglected and underutilized yam species in Benin: folk classification and post-harvest conservation. Genetic Resources and Crop Evolution 66: 965–979 doi:10.1007/s10722-019-00762-0

Lebas, B.S.M. 2002. Diversity of viruses infecting Dioscorea species in the South Pacific. PhD dissertation. University of Greenwich, UK.

Lebot, V. 2003. Yam: cultivar selection for disease resistance and commercial potential in Pacific Islands. Montpellier, France: CIRAD. Available at https://agritrop.cirad.fr/513977/1/ID513977.pdf (accessed 11 November 2020)

Lebot, V. 2020. Tropical root and tuber crops: cassava, sweet potato, yams and aroid. 2nd edition. Wallingford, UK: CABI.

Lebot, V., Faloye, B., Okon, E., Gueye, B. 2019a. Simultaneous quantification of allantoin and steroidal saponins in yam (Dioscorea spp.) powders. Journal of Applied Research on Medicinal and Aromatic Plants 13:100200, 8 p. doi:10.1016/j.jarmap.2019.02.001

Lebot, V., Abraham, K., Kaoh, J., Rogers, C., Molisalé, T. 2019b. Development of anthracnose resistant hybrids of the greater yam (Dioscorea alata L.) and interspecific hybrids with D. nummularia Lam. Genetic Resources and Crop Evolution 66(4): 871–883. doi:10.1007/s10722-019-00756-y

Lebot, V., Malapa, R., Molisalé, T., Marchand, J.L. 2006. Physico-chemical characterization of yam (Dioscorea alata L.) tubers from Vanuatu. Genetic Resources and Crop Evolution 53(6): 1199–1208. doi:10.1007/s10722-005-2013-2

Lebot, V., Malapa, R., Abraham, K. 2017. The Pacific yam (Dioscorea nummularia Lam.): an under-exploited tuber crop from Melanesia. Genetic Resources and Crop Evolution 64(1): 217–235. doi:10.1007/s10722-016-0475-z

Lebot, V., Malapa, R., Abraham, K., Molisalé, T., Gueye, B., Waki, J., Van Kien, N. 2018b. Secondary metabolites content may clarify the traditional selection process of the greater yam cultivars (Dioscorea alata L.) Genetic Resources and Crop Evolution 65: 1699–1709.

Lebot, V., Malapa, R., Molisalé, T. 2018a. Development of HP-TLC method for rapid quantification of sugars, catechins, phenolic acids and saponins to assess yam (Dioscorea spp.) tuber flour quality. Plant Genetic Resources: Characterization and Utilization 17(1): 62–72. doi:10.1017/S1479262118000333

Lebot, V. ,Malapa, R. 2012. Application of near infrared reflectance spectroscopy to the evaluation of yam (Dioscorea alata) germplasm and breeding lines. Journal of the Science of Food and Agriculture 93(7), 1788–1797. https://DOI: 10.1002/jsfa.6002

Lebot, V., Trilles, B., Noyer, J.L., Modesto, J. 1998. Genetic relationships between Dioscorea alata L. cultivars. Genetic Resources and Crop Evolution 45(6): 499–509.

Liu, T., Li, H., Fan, Y., Man, S., Liu, Z., Gao, W., Wang, T., 2016. Antioxidant and Antitumor Activities of the Extracts from Chinese Yam (Dioscorea opposite Thunb.) Flesh and Peel and the Effective Compounds. Journal of Food Science 81 (6): 1553-1564.

Lopez-Montes, A., Bhattacharjee, R., Tessema, G. 2012. Yam breeding at IITA: achievements, challenges, and prospects. Available at http://r4dreview.iita.org/index.php/2012/05/14/yam-breeding-at-iita-achievementschallenges-and-prospects/ (accessed 18 March 2019).

Magwé-Tindo, J., Wieringa, J.J., Sonké, B., Zapfack, L., Vigouroux, Y., Couvreur, T.L.P., Scarcelli, N. 2018. Guinea yam (Dioscorea spp., Dioscoreaceae) wild relatives identified using whole plastome phylogenetic analyses. Taxon 67(5): 905–915. doi:10.12705/675.4.

Magwé-Tindo, J., Zapfack, L., Sonké, B. 2015. Diversity of wild yams (Dioscorea spp., Dioscoreaceae) collected in continental Africa. Biodiversity and Conservation 25: 77–91. doi:10.1007/s10531-015-1031-4

Mahalakshmi, V., Ng, Q., Atalobhor, J., Ogunsola, D., Lawson, M., Ortiz, R. 2007. Development of a West African yam Dioscorea spp. core collection. Genetic Resources and Crop Evolution 54: 1817–1825. doi:10.1007/s10722-006-9203-4

Malapa, R. 2005. Description de la diversité de Dioscorea alata L. du Vanouatou à l'aide de marqueurs agro-morphologiques et moléculaires (AFLP). Relations avec les autres espèces de la section Enantiophyllum. PhD dissertation. Ecole nationale Supérieure Agronomique de Rennes, France.

Malapa, R., Arnau, G., Noyer, J.L., Lebot, V. 2005. Genetic diversity of the greater yam (Dioscorea alata L.) and relatedness to D. nummularia Lam, D. transversa Br. as revealed with AFLP markers. Genetic Resources and Crop Evolution 52(7): 919–929. doi:10.1007/s10722-003-6122-5

Malaurie, B., Pungu, O., Dumont, R., Trouslot, M.F. 1993. The creation of an in vitro germplasm collection of yam (Dioscorea sp.) for genetic resources preservation. Euphytica 65: 113–122. doi:10.1007/BF00022573

Marais, A., Umber, M., Filloux, D., Gomez, R.M., Faure, C., Pavis, C., Julian, C., Roumagnac, P., Acina-Maranbole, I., Bonheur, L., Theil, S., Contreras, S., Candresse, T., Teycheney, P.Y. 2020. Yam asymptomatic virus 1, a novel virus infecting yams (Dioscorea spp.) with significant prevalence in a germplasm collection. Archives of Virology doi:10.1007/s00705-020-04787-0

Martin, F.W., Rhodes, A.M. 1977. Intraspecific classification of Dioscorea alata. Tropical Agriculture (Trinidad) 54: 1–13.

Maurin, O., Muasya, A.M., Catalan, P., Shongwe, E.Z., Viruel, J., Wilkin, P., van der Bank, M. 2016. Diversification into novel habitats in the Africa clade of Dioscorea (Dioscoreaceae): erect habit and elephant's foot tubers. BMC Evolutionary Biology 16: 238. doi:10.1186/s12862-016-0812-z

Mignouna, H.D., Mank, R.A., Ellis, T.H.N., van den Bosch, N., Asiedu, R., Abang, M.M., Peleman, J. 2002a. A genetic linkage map of water yam (Dioscorea alata) based on AFLP markers and QTL analysis for anthracnose resistance. Theoretical and Applied Genetics 105: 726–735. doi:10.1007/s10681-010-0338-1

Mignouna, H.D., Mank, R.A., Ellis, T.H.N., van den Bosch, N., Asiedu, R., Ng, S.Y.C., Peleman, J. 2002b. A genetic linkage map of Guinea yam (Dioscorea rotundata Poir.) based on AFLP markers. Theoretical and Applied Genetics 105: 716–725. doi:10.1007/s00122-002-0911-7

Mignouna, H.D., Abang, M.M. and Asiedu, E. 2007. Yams. In: Kole, C. (ed.) Genome Mapping and Molecular Breeding in Plants. Vol. 3. Pulses, Sugar and Tuber Crops. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 271–296.

Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being. Washington, D.C.: Island Press.

Mizuki, I., Tani, N., Ishida, K., Tsumura, Y. 2005. Development and characterization of microsatellite markers in a clonal plant, Dioscorea japonica, Thunb. Molecular Ecology Notes 5: 721–723. doi:10.1111/j.1471-8286.2005.01020.x

MusaNet 2016. Global Strategy for the Conservation and Use of Musa Genetic Resources. Boversity International, Montpellier, France.

Muthamia, Z.K., Nyende, A.B., Mamati, E.G., Ferguson, M.E., Wasilwa, J. 2014. Determination of ploidy among Yam (Dioscorea spp.) landraces in Kenya by flow cytometry. African Journal of Biotechnology 13(3): 394–402. doi:10.5897/AJB2013.12496

Nair, N.G., Chandrababu, S. 1994. A slow growth medium for in vitro conservation of edible yams. Journal of Root Crops 20: 68–69.

Nemorin A., David, J., Maledon, E., Nudol, E., Dalon, J., Arnau, G. 2013. Microsatellite and flow cytometry analysis to help understand the origin of Dioscorea alata polyploids. Annals of Botany 112(5): 811–819. doi:10.1093/aob/mct145

Norman, P.E., Agre A.P., Danquah, A., Tongoona, P.B., Danquah, E.Y., De Koeyer, D., Ikeogu, U.N., Asiedu, R., Asfaw, A. 2020. Paternity assignment in white Guinea yam (Dioscorea Rotundata) half-sib progenies from polycross mating design using SNP markers. Plants 9: 527; doi:10.3390/plants9040527

Nwadili, C.O., Augusto, J., Bhattacharjee, R., Athenkeng, J., Lopez-Montes, A., Onyeka, T.J., Kumar, P.L., Asiedu, R., Bandyopadhyay, R. 2017. Comparative reliability of screening parameters for anthracnose resistance in Water Yam (Dioscorea alata). Plant Disease 101: 209–216. doi:10.1094/PDIS-06-16-0924-RE

Obidiegwu, J., Loureiro, J., Ene-Obong, E., Rodriguez, E. Kolesnikova-Allen, M., Santos, C., Muoneke, C., Asiedu, R. 2009. Ploidy level studies on the Dioscorea cayenensis /Dioscorea rotundata complex core set. Euphytica 169: 319–326. doi:10.1007/s10681-009-9960-1

Odu, B.O., Hughes, J.d'A., Asiedu, R., Ng, Q., Shoyinka, S.A. and Oladiran, O.A. 2004a. Responses of white yam (Dioscorea rotundata) cultivars to inoculation with three viruses. Plant Pathology 53, 141–147. http://dx.doi.org/10.1111/j.0032-0862.2004.00997.x

Odu, B.O., Asiedu, R., Hughes, J.,d'A., Shoyinka, S.A. and Oladiran, O.A. 2004b. Identification of resistance to yam mosaic virus (YMV), genus potyvirus in white Guinea yam (Dioscorea rotundata Poir.). Field Crops Research 89, 97–105. http://dx.doi.org/10.1016/j.fcr.2004.01.009

Odu, B.O., Asiedu, R., Shoyinka, S.A., Hughes, J.D.'A. 2006. Screening of water yam (Dioscorea alata L.) genotypes for reaction to viruses in Nigeria. Journal of Phytopathology 154: 716–724. doi:10.1111/j.1439-0434.2006.01180.x

Onyeka, T.J., Petro, D., Etienne, S., Jacqua, G. and Ano, G. 2006a. Optimizing controlled environment assessment of levels of resistance to yam anthracnose disease using tissue culture-derived whole plants. Journal of Phytopathology 154(5), 286–292. http://dx.doi.org/10.1111/j.1439-0434.2006.01095.x

Onyeka, T.J., Petro, D., Ano, G., Etienne, S. and Rubens, S. 2006b. Resistance in water yam

(Dioscorea alata) cultivars in the French West Indies to anthracnose disease based on tissue culture-derived whole-plant assay. Plant Pathology 55(5), 671–678. https://doi.org/10.1111/j.1365-3059.2006.01436.x

Otegbayo, B., Madu, T., Oroniran, O., Chijioke, U., Fawehinmi, O., Okoye, B., Tanimola, A., Adebola, P., Obidiegwu, J. 2020. End-user preferences for pounded yam and implications for food product profile development. International Journal of Food Science and Technology doi:10.1111/ijfs.14770

Otoo, E. 2017. Yam breeding in Ghana. Journal of Agricultural Science 9(10): 132–136. doi:10.5539/jas.v9n10p122

Ovono, P., Kevers, C., Dommes, J. 2007. Axillary proliferation and tuberisation of Dioscorea cayenensis–D. rotundata complex. Plant Cell, Tissue and Organ Culture 91(2): 107–114. doi:10.1007/s11240-007-9238-z

Padhan, B., Mukherjee, A.K., Mohanty, S.K., Lenka, S.K., Panda, D. 2019. Genetic variability and inter species relationship between wild and cultivated yams (Dioscorea spp.) from Koraput, India based on molecular and morphological markers. Physiology and Molecular Biology of Plants 25: 225–1233. doi:10.1007/s12298-019-00691-3

Pengelly, A., Bennett, K. 2011. Appalachian plant monographs: Dioscorea villosa L., wild yam. Available at https://bearalchemy.com/wild-yam-monograph/

Phillips, S., Bridon, R.W., Brunt, A.A., Hull, R. 1999. The partial characterization of badnavirus infecting the greater Asiatic or water yam (Dioscorea alata). Journal of Phytopathology 147: 265–269.

Polycarp, D., Afoakwa, E.O., Budu, A.S., Otoo, E. 2012. Characterization of chemical composition and anti-nutritional factors in seven species within the Ghanaian yam (Dioscorea) germplasm. International Food Research Journal 19(3): 985–992.

Price, E.J., Bhattacharjee, R., Lopez-Montes, A., Fraser, P.D. 2017. Metabolite profiling of yam (Dioscorea spp.) accessions for use in crop improvement programs. Metabolomics 13(11): 144.

Price, E.J., Bhattacharjee, R., Lopez-Montes, A., Fraser, P.D. 2018. Carotenoid profiling of yams: clarity, comparisons and diversity. Food Chemistry 259: 130–138. doi:10.1016/j.foodchem.2018.03.066

Price, E.J., Wilkin, P., Sarasan, V., Fraser, P.D. 2016. Metabolite profiling of Dioscorea (yam) species reveals under-utilized biodiversity and renewable sources for high-value compounds. Scientific Reports 6: 29136. doi:10.1038/srep29136

Rakotondratsimba, H.M. 2008. Etudes ethnobotaniques, biologiques et éco géographiques des Dioscorea spp sauvages d'Ankarafantsika en vue de leur conservation. PhD dissertation. Université d'Antannanarivo, Madagascar.

Sardos, J., Muller S., Duval, M.F., Noyer, J.L., Lebot, V. 2015. Root crops diversity and agricultural resilience: a case study of traditional agrosystems in Vanuatu (Oceania). Agriculture and Human Values 33(3): 721–736. doi:10.1007/s10460-015-9657-0

Sartie, A., Asiedu, R., Franco, J. 2012. Genetic and phenotypic diversity in a germplasm working collection of cultivated tropical yams (Dioscorea spp.). Genetic Resources Crop Evolution 59: 753–1765. doi:10.1007/s10722-012-9797-7

Sastrapradja, S. 1982. Dioscorea alata: its variation and importance in Java, Indonesia. In: Miège, J., Lyonga, S.N. (eds.). Yams. Ignames. Oxford, UK: Clarendon Press. pp. 45–49.

Scarcelli, N., Chaïr, H., Causse, S., Vesta, R., Couvreur, T.L.P., Vigouroux, I. 2017. Crop wild relative conservation: wild yams are not that wild. Biological Conservation 210: 325–333.

Scarcelli, N., Couderc, M., Baco, M.N., Egah, J., Vigouroux, Y. 2013. Clonal diversity and estimation of relative clone age: application to agrobiodiversity of yam (Dioscorea rotundata). BMC Plant Biology 13: 178 http://www.biomedcentral.com/1471-2229/13/178.

Scarcelli, N., Cubry, P., Akakpo, R., Thuillet, A.-C., Obidiegwu, J., Baco, M.N., Otoo, E., Sonké, B., Dansi, A., Djedatin, G., Mariac, C., Couderc, M., Causse, S., Alix, K., Chaïr, H., François, O., Vigouroux, Y. 2019. Yam genomics supports West Africa as a major cradle of crop domestication. Science Advances 5(5): eaaw1947. doi:10.1126/sciadv.aaw1947

Scarcelli, N., Tostain, S., Mariac, C., Agbangla, D., Berthaud, J., Pham, J.L. 2005a. Genetic nature of yams (Dioscorea sp.) domesticated by farmers in Benin (West Africa). Genetic Resources and Crop Evolution 53(1): 121–130. doi:10.1007/s10722-004-1950-5

Scarcelli, N., Dainou, O., Agbangla, C., Tostain, S., Pham, J.L. 2005b. Segregation patterns of isozyme loci and microsatellite markers show the diploidy of African yam Dioscorea rotundata (2n=40). Theoretical and Applied Genetics 111(2): 226–233. doi:10.1007/s00122-005-2003-y

Scarcelli, N., Tostain, S., Vigouroux, Y., Agbangla, C., Dainou, O., Pham, J.L. 2006. Farmers' use of wild relative and sexual reproduction in a vegetatively propagated crop: the case of yam in Benin. Molecular Ecology 15(9): 2421–2431. doi:10.1111/j.1365-294X.2006.02958.x

Scarcelli, N., Tostain, S., Vigouroux, Y., Luong, V., Baco, M.N., Agbangla, C., Daïnou, O., Pham, J.L. 2011. Genetic structure of farmer-managed varieties in clonally-propagated crops. Genetica 139: 1055–1064. doi:10.1007/s10709-011-9607-8

Schols, P., Wilkin, P., Furness, C.A., Huysmans, S., Smets, E. 2005. Pollen evolution in yams (Dioscorea: Dioscoreaceae). Systematic Botany 30: 750–758.

Seal, S., Turaki, A., Muller, E., Kumar, P.L., Kenyon, L., Filloux, D., Galzi, S., Lopez-Montes, A., Iskra-Caruana, M.L. 2014. The prevalence of badnaviruses in West African yams (Dioscorea cayenensis-rotundata) and evidence of endogenous pararetrovirus sequences in their genomes. Virus Research 186: 144–154. doi:10.1016/j.viruses.2014.01.007

Sharif, B.M., Burgarella, C., Cormier, F., Mournet, P., Causse, S., Nguyen, K.V., Kaoh, J., Rajaonah, M.T., Senanayake, R.L., Waki, J., Bhattacharjee, B., Badara, G., Pachakkil, B., Arnau, G., Chaïr, H. 2020. Genome-wide genotyping elucidates the geographical diversification and dispersal of the polyploid and clonally propagated yam (Dioscorea alata). Annals of Botany XX: 1–10. doi:10.1093/aob/mcaa122

Song, Z., Zhu, W., Rong, J., Xu, X., Chen, J., Lu, B. R. 2006. Evidences of introgression from cultivated rice to Oryza rufipogon (Poaceae) populations based on SSR fingerprinting: implications for wild rice differentiation and conservation. Evolutionary Ecology, 20(6), 501-522.

Sonibare, M.A., Asiedu, R., Albach, D.C. 2010. Genetic diversity of Dioscorea dumetorum (Kunth) Pax using Amplified Fragment Length Polymorphisms (AFLP) and cpDNA. Biochemical Systematics and Ecology 38(3): 320–334. doi:10.1016/j.bse.2010.01.012

Soto Gomez, M., Pokorny, L., Kantar, M.B., Forest, F., Leitch, I.J., Gravendeel, B., Wilkin, P., Graham, S.W., Viruel, J. 2019. A customized nuclear target enrichment approach for developing a

phylogenomic baseline for Dioscorea yams (Dioscoreaceae). Applications in Plant Sciences 7(6): e11254. doi:10.1002/aps3.112543

Sugihara, Y., Darkwa, K., Yaegashi, H., Natsume, S., Shimizu, M., Abe, A., Hirabuchi, A., Ito, K., Oikawa, K., Tamiru-Oli, M., Ohta, A., Matsumoto, R., Paterne, A., De Koeyer, D., Pachakkil, B., Yamanaka, S., Muranaka, S. Takagi, H., White, B., Asiedu, R., Innan, H., Asfaw, A., Adebola, P., Terauchi, R. 2020. Genome analyses reveal the hybrid origin of the staple food crop white Guinea yam. BioRyxv Preprint. doi:10.1101/2020.07.14.202564

Sukal, A.C., Kidanemariam, D.B., Dale, J.L., Harding, R.M., James, A.P. 2019. Assessment and optimization of rolling circle amplification protocols for the detection and characterization of badnaviruses. Virology 529, 73–80. doi:10.1016/j.virol.2019.01.013

Sukal, A.C., Kidanemariam, D.B., Dale, J.L., Harding, R.M., James, A.P. 2020. Characterization and genetic diversity of Dioscorea bacilliform viruses present in a Pacific yam germplasm collection. Plant Pathology 69(3): 576–584. doi:10.1111/ppa.13133

Sukal, A., Kidanemariam, D., Dale, J., James, A., Harding, R. 2017. Characterization of badnaviruses infecting Dioscorea spp. in the Pacific reveals two putative novel species and the first report of Dioscorea bacilliform RT virus 2. Virus Research 238: 29–34. doi:10.1016/j.virusres.2017.05.027

Summerhayes, G.R., Leavesley, M., Fairbairn, A., Mandui, H., Field, J., Ford, A, Fullagar, R. 2010. Human adaptation and plant use in Highland New Guinea 49,000 to 44,000 years ago. Science Reports 330: 78–81.

Takagi, H., Ishiga, Y., Watanabe, S., Konishi, T., Egusa, M., Akiyoshi, N., Matsuura, T., Mori, I.C., Hirayama, T., Kaminaka, H., Shimada, H., Sakamoto, A. 2016. Allantoin, a stress-related purine metabolite, can activate jasmonate signaling in a MYC2-regulated and abscisic acid-dependent manner. Journal of Experimental Botany 67(8): 2519–2532.

Tamiru, M., Becker, H.C., Maass, B.L. 2007. Genetic diversity in yam germplasm from Ethiopia and their relatedness to the main cultivated Dioscorea species assessed by AFLP markers. Crop Science 47(4): 1744–1750. doi:10.2135/cropsci2006.11.0719

Tamiru, M., Becker, H.C., Maass, B.L. 2008. Diversity, distribution and management of yam landraces (Dioscorea spp.) in Southern Ethiopia. Genetic Resources and Crop Evolution 55:115–131. doi:10.1007/s10722-007-9219-4

Tamiru, M., Natsume, S., Takagi, H., White, B., Yaegashi, H., Shimizu, M., Urasaki, N. 2017. Genome sequencing of the staple food crop white Guinea yam enables the development of a molecular marker for sex determination. BMC Biology 15: 86. doi:10.1186%2Fs12915-017-0419-x

Tamiru, M., Yamanaka, S., Mitsuoka, C., Babil, P., Takagi, H., Lopez-Montes, A., Sartie, A., Asiedu, R., Terauchi, R. 2015. Development of genomic simple sequence repeat markers for yam. Crop Science 55: 2191–2200. doi:10.2135/cropsci2014.10.0725

Terauchi, R., Terachi, T., Tsunewaki, K. 1991. Intraspecific variation of chloroplast DNA in Dioscorea bulbifera L. Theoretical and Applied Genetics 81: 461–470. doi:10.1007/BF00219435

Thouvenel, J.C., Dumont, R. 1990. Perte de rendement de l'igname infectée par le virus de la mosaique en Côte d'Ivoire. L'Agronomie Tropicale 45: 125–129.

Trèche, S. 1998. Valeur nutritionnelle des ignames. In: Berthaud, J., Bricas, N, Marchand, J.L. (eds) L'igname, plante séculaire et culture d'avenir.

Proceedings of International Symposium. Montpellier, France: CIRAD. pp. 305–331.

Tuivavalagi, P. 2010. Country report on the State of Plant Genetic Resources for Food and Agriculture: Country report Samoa; FAO ..

Ude, G.N., Igwe, D.O., McCormick, J., Ozokonkwo-Alor, O., Harper, J., Ballah, D., Aninweze, C., Chosen, O., Okoro, M., Ene, C., Chieze, V., Unachukwu, M., Onyia, C., Acquaah, G., Ogbonna, J., Das, A. 2019. Genetic diversity and DNA barcoding of yam accessions from southern Nigeria. American Journal of Plant Sciences 10: 179 –207.

Umber, M., Gomez, R.-M., Gélabale, S., Bonheur, L., Pavis, C., Teycheney, P.Y. 2016. The genome sequence of Dioscorea bacilliform TR virus a member of the genus Badnavirus infecting Dioscorea spp., sheds light on the possible function of endogenous Dioscorea bacilliform viruses. Archives of Virology 162: 517–521. doi:10.1007/s00705-016-3113-3

Umber, M., Filloux, D., Gélabale, S., Gomez, R.M., Marais, A., Gallet, S., Gamiette, F., Pavis, C., Teycheney, P.Y. 2020. Molecular viral diagnosis and sanitation of yam genetic resources: implications for safe yam germplasm exchange. Viruses 12: 1101. doi:10.3390/v12101101

Urbino, C., Boussalem, M., Pinel, A., Fargette, D., Dubern, J. 1998. Les virus de l'igname: caractérisation immunologique et moléculaire du virus de la mosaïque de l'igname. In: Berthaud, J., Bricas, N, Marchand, J.L. (eds.). L'igname, plante séculaire et culture d'avenir. Proceedings of International Symposium. Montpellier, France: CIRAD. pp. 205–211.

Vandenbroucke, H., Mournet, P., Vignes, H., Chaïr, H., Malapa, R., Duval, M.F., Lebot, V. 2016. Somaclonal variants of yam (Colocasia esculenta Schott) and yam (Dioscorea alata L.) are incorporated into farmers' varietal portfolios in Vanuatu. Genetic Resources and Crop Evolution 63(3): 495–511. doi:10.1007/s10722-015-0267-x

Van Treuren, R., Engels, J.M.M., Hoekstra, R., van Hintum, T.J. 2009. Optimization of the composition of crop collections for ex situ conservation. Plant Genetic Resources 7(2): 185–193.

Vincent, H., Wiersema, J., Kell, S., Fielder, H., Dobbie, S., Castañeda-Álvarez, N.P. Guarino, L., Eastwood, R., León, B., Maxted, N. 2013. A prioritized crop wild relative inventory to help underpin global food security. Biological Conservation 167: 265–275. doi:10.1016/j.biocon.2013.08.011

Viruel, J., Forest, F., Paun, O., Chase, M.W., Devey, D., Couto, R.S., Segarra-Moragues, J.G., Catalàn, P., Wilkin, P. 2019. A nuclear Xdh phylogenetic analysis of yams (Dioscorea: Dioscoreaceae) congruent with plastid trees reveals a new Neotropical lineage. Botanical Journal of the Linnean Society XX: 1–15.

Viruel, J., Segarra-Moragues, J.G., Raz, L., Forest, F., Wilkin, P., Sanmartin, I., Catalan, P. 2016. Late Cretaceous–early Eocene origin of yams (Dioscorea, Dioscoreaceae) in the Laurasian Palaearctic and their subsequent Oligocene–Miocene diversification. Journal of Biogeography 43, 750–762. https://doi.org/10.1111/jbi.12678

Wheeler, G.S., Pemberton, R.W., Raz, L. 2007. A biological control feasibility study of the invasive weed-air potato Dioscorea bulbifera L. (Dioscoreaceae) and effort to increase biological control transparency and safety. Natural Areas Journal 27(3): 269–279. doi:10.3375/0885-8608(2007)27

Wilkin, P., Burrows, J., Burrows, S., Muthama Muasyna A., van Wyk, E. 2010. A critically endangered new species of yam (Dioscorea strydomiana Wilkin, Dioscoreaceae) from

Mpumalanga, South Africa. Kew Bulletin 65: 421–433. doi:10.1007/s12225-010-9227-y

Wilkin, P., Thapyai, C., Chayamarit, K. 2007. Lectotypification of Dioscorea L. (Dioscoreaceae) names from Thailand. Kew Bulletin 62: 251–258.

Wilson, J.E. 1982. Progress in the breeding of yam, Dioscorea spp. In: Miège, J., Lyonga, S.N. (eds.). Yams. Ignames. Oxford, UK: Oxford University Press. pp. 17–22.

Wireko-Manu, F.D., Ellis, W.O., Oduro, I., Asiedu, R., Maziya-Dixon, B. 2011. Physicochemical and pasting characteristics of water yam (D. alata) in comparison with pona (D. rotundata) from Ghana. European Journal of Food Research and Review 1(3): 149–158. http://ir.knust.edu.gh/bitstream/123456789/11174/1/1322825635-WirekoManuetal_2011EJFRR659.pdf

Wu, Z.G., Li, X.X., Lin, X.C., Jiang, W., Tao, Z.M., Nitin, M., Fan, C.Y., Bao, X.Q. 2014. Genetic diversity analysis of yams (Dioscorea spp.) cultivated in China using ISSR and SRAP markers. Genetic Resources and Crop Evolution 61: 639–650

Wu, W., Chen, C., Zhang, Q., Zaheer Ahmed, J., Xu, Y., Huang, X., Xie, J., Xia, W., Huang, D. 2019. A comparative assessment of diversity of greater yam (Dioscorea alata) in China. Scientia Horticulturae 243 2019. 116–124. doi:10.1016/j.scienta.2018.08.016

Xia, W., Zhang, B., Xing, D., Li, Y., Wu, W., Xiao, Y., Sun, J., Dou, Y., Tang, W., Zhang, J., Huang, X., Xu, Y., Xie, J., Wang, J., Huang, D. 2019. Development of high-resolution DNA barcodes for Dioscorea species discrimination and phylogenetic analysis. Ecology and Evolution 9: 10843–10853. doi:10.1002/ece3.5605

Yasuoka, H. 2013. Dense wild yam patches established by hunter-gatherer camps: beyond the wild yam question, toward the historical ecology of rainforests. Human Ecology 41: 465–475. doi:10.1007/s10745-013-9574-z

Yoon, K.D., Kim, J. 2008. Preparative separation of dioscin derivatives from Dioscorea villosa by centrifugal partition chromatography coupled with evaporative light scattering detection. Journal of Separation Science 31: 2486–2491.

Zhang, Y., Xu, Y., Qi, Y., Xu, L., Song, S., Yin, L., Tao, X., Zhen, Y., Han, X., Ma, X., Liu, K., Peng, J. 2017. Protective effects of dioscin against doxorubicin-induced nephrotoxicity via adjusting FXR-mediated oxidative stress and inflammation. Toxicology 378: 53–64.

Zoundjihékpon, J. 1993. Biologie de la reproduction et génétique des ignames cultivées de l'Afrique de l'Ouest, Dioscorea cayenensis-rotundata. PhD dissertation. Université Nationale de Côte d'Ivoire, Abidjan, Côte d'Ivoire.

Zoundjihékpon, J., Hamon, S., Tio-Ouré, B., Hamon, S. 1994. First controlled progenies checked by isozymic markers in cultivated yams, Dioscorea cayenensis-rotundata. Theoretical and Applied Genetics 88: 1011–1016. doi:10.1007/BF00220809

Zulu, D., Ellis, R.H., Culham, A. 2019. Collection, consumption and sale of lusala (Dioscorea hirtiflora) – a wild yam – by rural households in Southern Province, Zambia. Economic Botany 73: 47–63.

ANNEXES

ANNEX 1. A SURVEY TO BUILD A GLOBAL CONSERVATION STRATEGY FOR YAMS

The Global Crop Diversity Trust is helping to develop strategies for the conservation of crop diversity. The Trust has commissioned CIRAD to coordinate the development of a global conservation strategy for yams. This questionnaire is for people caring for major yam collections to help develop that strategy. The Trust will base its support for the conservation of yam genetic resources on this strategy, once developed and adopted. As a key curator of a yam collection(s), please complete the questionnaire. CIRAD is keen to ensure your active participation in the development of the global yam conservation strategy and will keep you informed of progress and consult you until it is completed.

1. General:

Name and address of organisation holding/maintaining yam collections:
1. Address:
2. City:
3. Postal Code:
4. Country:
5. Web site:

Curator in charge of the yam collection:
6. Name:
7. Address:
8. City:
9. Telephone:
10. Email:

Is the organisation holding the yam collection:
A - an independent organisation : ( )
B - part of a larger organisation : ( ) name and address of the larger organisation:

Is the organisation holding the collection part of a government agency? yes ( ) no ( )
If no, what type of organisation is it?

Who is financing the conservation of the collection, and to what extent (% age)?
11. Government : %
12. Private sector: %
13. International or regional organisation/agency: %
14. Other funding agencies (specify): %
15. Is the institution in charge of the collection the legal owner of the collection? yes ( ) no ( )
16. If no, who is the owner (state if no owner is recognised)?

Details on the collection:
17. Year the collection was established:

What is the maximum capacity of the collection in terms of existing infrastructure?
- In the field: number of plants:
- In the lab: number of plantlets:
- What are the average annual costs for maintaining the collection?

- Staff:
- General maintenance of infrastructure:
- Inputs (field and lab costs):
- Other:

Origin of the collection. Please state how many countries are represented in the collection: ( )

Geographic coverage of the collection (quantify %age of collection from different countries):
- Home country: %
- Neighbouring countries: %
- Countries in other regions: %
- Unknown : %

Present size of the collection. Number of accessions (landraces) for each species:

Species	Total number of accessions	% with passport data	Number of farmers' varieties	No. landraces selected for distribution	Breeding lines being evaluated	Improved varieties for distribution
D. alata						
D. bulbifera						
D. cayenensis						
D. dumetorum						
D. esculenta						
D. japonica						
D. nummularia						
D. oppositifolia						
D. pentaphylla						
D. rotundata						
D. trifida						
D. transversa						
Others (specify)						
Wild relatives:						
D.						
D.						
D.						
Total						

2. Management of the collection

Has the collection been enlarged during the last 10 years with new germplasm? Yes ( ) No ( )
If yes, how many new accessions have been included of the following:
- Related wild species: ( )
- Farmers' varieties: ( )
- Breeders' varieties: ( )

How was the newly obtained germplasm acquired?
- Collecting in own country : ( )
- Collecting in other countries : ( )
- Introduction from other institutes or private organisations in country : ( )
- Introduction from other countries : ( )

- Other sources, please specify:

Are there important gaps in the collection? yes ( ) no ( )

- If so, what are they:

Do you plan to fill these gaps in the next 10 years? yes ( ) partly ( ) no ( )

- If yes or partly, how:
- If no, what are the main reasons why not:
- Do you plan new collecting missions in the next 10 years? yes ( ) no ( )

Type of germplasm Stored (more than one option for the same type of material is possible):

Type	Total No. accessions	Storage facilities conditions: description
True botanical seeds		
Maintained in the field		
In pots in screen house		
In vitro slow growth		
In vitro cryopreserved		
Farmers' varieties		
Breeding lines		
Wild relatives		
Others		
Total		

Do you apply tests to control the quality of stored germplasm? Yes ( ) No ( ) What tests?
If yes, do you check whether the *in vitro* plantlets are true-to-type: Yes ( ) No ( )
Please explain how these tests are done:

How is the collection replanted or re-cultured:

Type of germplasm	Replanting period in months	time	True seeds	Tubers in field	*In vitro*	Cryopreserved
Farmers' varieties						
Breeding lines						
Related wild relatives						
Total						

3. Identification (classification) and characterization (description)

Is the collection taxonomically identified? yes ( ) partially ( ) no ( )
If partially, please state the percentage NOT identified: %
Do you have assistance of a taxonomist to identify the germplasm? Yes ( ) occasionally ( ) No ( )

Type of germplasm	% acc. with Passport data	% acc. with Ploidy levels	% acc. with Sex (M / F)	% Morpho-Agro described	% fingerprinted with DNA markers	% acc. data computerized
Farmers' varieties						
Breeders' varieties						

Wild relatives
Total

Do you use a computerized information system for the management of the collection? yes ( ) no ( )
If yes, what software do you use for documentation? What data have been computerised?
In case the collection is not computerised, are there plans to do so in the future?

- No plans : ( )
- Computerisation planned within next 1 year : ( )
- Is information on the yam collection accessible through the Internet? yes ( ) partly ( ) no ( )
- If yes/partly, please provide URL:

Are data of the collection included in other databases?

- National: yes ( ) partly ( ) no ( )
- Regional: yes ( ) partly ( ) no ( )
- International: yes ( ) partly ( ) no ( )
- If yes/partly, specify the database:

4. Health of germplasm

Is the collection affected by diseases that can restrict germplasm distribution? Yes ( ) No ( )
If yes, which types of diseases are causing this restriction?

- Seed-borne diseases : ( )
- Infection of tubers : ( )

If *in vitro* samples are distributed within the country are they virus indexed? Yes ( ) No ( )
If *in vitro* samples are distributed outside the country are they virus indexed? Yes ( ) No ( )
Are there facilities for eradication of these diseases in your institution? Yes ( ) limited ( ) no ( )
Do you need assistance to improve the health status of the collection? Yes ( ) limited ( ) no ( )
If yes, what type of assistance is required?

5. Distribution

Have you distributed material outside your institute during the last 3 years ? Yes ( ) No ( )

Type	Within the country	Outside the country	True seeds	Tubers	*In vitro*	Samples per shipment
Farmers' varieties						
Breeders' varieties						
Wild relatives						
Others						
Total						

Are you distributing more material now than 10 years ago? more ( ) the same ( ) less ( )
Do you expect to distribute more material in 10 years' time than now? more ( ) the same ( ) less ( )
Do you keep records of the distribution? Who are the institutions receiving materials:

Institution	Tubers	*In vitro* plantlets	True seeds	Other (specify)
University				
Dept of Agriculture				

Research institute
NGOs

Do you request and get any feed back from the recipients? Yes ( ) No ( ) If yes, what use is made of the information received:
How are the services of the collection publicized to users and how effective are these methods in terms of increased use of the collection? High impact ( ) Medium impact ( ) Low impact ( )

- Scientific publications : ( )
- Institutional reports : ( )
- Extension Leaflets : ( )
- Oral presentations : ( )
- Group visits to the collection : ( )
- Other : ( )

Have any requests for material been refused? If yes, specify:
How do the users of the germplasm influence the management of the collection?

- Through feedback on the material : ( )
- Through formal consultations : ( )
- Through participation in the governing body of the genebank : ( )

6. Safety duplication

Are the accessions safety-duplicated in another genebank? Yes ( ) fully ( ) partly ( ) no ( )
If yes/partly, please specify where the germplasm is safety-duplicated, what part (%) of the collection and under what storage conditions:
Is there any germplasm of other collections safety-duplicated at your facilities? yes ( ) no ( )
If yes, can you specify the name of the holder and the number of accessions duplicated?

7. General management

How many staff are working on the collection (full-time staff equivalents)? <1, 1-2, 3-5, >5

Staff	In the field:	In the laboratory:
Scientists		
Technicians		
Assistants		
Filed workers		

Have you established a quality management system or written procedures and protocols for:

- Acquisition (including collecting, introduction and exchange) : ( )
- Regeneration/Replanting and/or sub-culturing : ( )
- Characterisation : ( )
- Storage and maintenance : ( )
- Documentation : ( )
- Health of germplasm : ( )
- Distribution : ( )
- Safety duplication : ( )

In case you have written procedures and protocols, can you provide the Trust with this information or include a copy of it? yes : ( ) no : ( )
Does the existing capacity in numbers and skills of staff meet the needs of the collection in the

long term? If no, please describe what is needed?

8. Utilisation of the collection

For what purposes is the collection used?

- Research activities (e.g. taxonomy, diversity, evolution studies, etc.) : ( )
- Characterisation, Evaluation for agronomic traits (production and quality) : ( )
- Screening for biotic and abiotic stress resistances : ( )
- Conventional plant breeding : ( )
- Participatory plant breeding : ( )
- Biotechnology (e.g. gene isolation, molecular studies, genomics, etc.) : ( )
- Distribution to farmers : ( )
- Return of germplasm to country of origin : ( )

Do you have a systematic program to evaluate the collection for agronomic and other traits?
Yes ( ) No ( ) If yes, list the most important traits the collection is evaluated for?
Do you have collaboration with an *in situ* conservation programme: Yes ( ) No ( )
If yes/planned, give details:
Do you collaborate (or have you collaborated in the past 10 years) in (a) plant genetic resources network(s) as a collection holder (specify if collaboration is ongoing)? Yes ( ) No ( )
If yes, please indicate what kind of network:

9. Policies with regard to access of the collection

What is your policy regarding distribution of germplasm?

- Distribution only to users in your country : ( )
- Distribution only to users in certain countries : ( )
- Distribution to users in all countries : ( )

Conditions of distribution:

- Distribution to any user, without further conditions : ( )
- Distribution to any after signing of an MTA (Material Transfer Agreement) : ( )
- Distribution only on a mutually agreed exchange basis : ( )
- Other conditions, please specify:

Cost for distribution of germplasm:

- No cost, distribution gratis to all users : ( )
- No cost, but reciprocal exchange of material required : ( )
- Costs charged to some users (e.g. private sector) or some countries only : ( )
- Request to contribute for processing and shipping; specify amount: ( )
- Request to pay for each requested accession; specify amount: ( )
- Other, please specify:

10. Future developments regarding the yam collection

Will the collection be enlarged with new material or rationalized in the next 10 years?

- collection will remain approximately the same size : ( )
- collection will be expanded to a limited extent (5-10 %) ( )
- collection will be substantially increased (> 20%) ( )
- collection will be reduced due to duplication and internal rationalisation : ( )
- collection will be reduced as a result of lack of funding or facilities : ( )

Are there any constraints for the maintenance of the collection? Yes ( ) No ( )
If yes, what type of constraints do you face

- Insufficiently trained staff : ( )
- Capacity to replant/maintain the collection in field and/or *in vitro* limited : ( )
- Facilities for optimal maintenance of the collection not satisfactory : ( )
- Others, please state:

Will some of the above constraints result in a loss of germplasm? Yes ( ) No ( )
What is the most important constraint, which contribute to genetic erosion of the collection?

11. Further remarks

Do you have any further remarks or suggestions? Please feel free to comment on the need for such a Global Strategy and do not hesitate to be critical. Your contribution will be highly appreciated!

Many thanks!

Please return the completed questionnaire, no later than 15th September 2020 to:
Dr Vincent Lebot (CIRAD) Email: lebot@vanuatu.com.vu

ANNEX 2. LIST OF ADDRESSEES

Country	Institution	Name	email
Bangladesh	Tuber Crops Research Centre BARI	Director	dir.tcrc@bari.gov.bd
Bangladesh	Tuber Crops Research Centre BARI	Chief Scientist	cso.tcrc@bari.gov.bd
Bénin	UAC	Alexandre Dansi	adansi2001@gmail.com
Bénin	Bioversity International	Arman B. Omondi	b.a.omondi@cgiar.org
Brazil	INPA, Manaus	Charles Clement	cclement@inpa.gov.br, charlesr.clement@yahoo.com.br
Brazil	Federal University of Amazonas	Henrique DS Perreira	henrique.pereira.ufam@gmail.com
Brazil	University of Sao Paulo	Elisabeth Ann Veasey	eann.veasey@gmail.com
Burkina Faso	INERA	Some Koussao	koussao@hotmail.com
Burundi	Bioversity International	Bioversity office	JP.Kanyaruguru@cgiar.org
Cameroon	Bioversity International	Marius Ekue	m.ekue@cgiar.org
Cameroun	IRAD	Walter Leke	walter.leke@fullbrightmail.org, walterleke0@gmail.com
China	Institute of Vegetables and Flowers, Bejing	Haiping Wang	wanghaiping@caas.cn
China	Bioversity International	Bioversity office	bioversity-caas@cgiar.org
China	Zhejiang Institute of the Subtropical Crops	Zhi Gang Wu	wuzhigang177@126.com
China	Institute of Crop Germplasm Resources of Hainan	Jianqiu Ye	yejianqiu2006@126.com
Colombia	University of Cordoba	Hernando Rivera-Jiménez	hriveraj@gmail.com
Colombia	University of Cordoba	Andres Alvarez	andresalvarez864@hotmail.com
Congo	Bioversity International	Baly Kabike	IITA-Bukavu@cgiar.org, B.Kabike@cgiar.org
Costa Rica	University of Costa Rica	Francisco Saborío	francisco.saborio@ucr.ac.cr
Costa Rica	Bioversity International	Bioversity office	bioversity-costarica@cgiar.org
Côte d'Ivoire	Centre national de la Recherche Agronomique	Kouakou Amani Michel	amanimichelkouakou@gmail.com
Côte d'Ivoire	Centre national de la Recherche Agronomique	Dibi Konan Brice	dibikonan@yahoo.fr
Cuba	INIVIT, Santa Clara	Sergio Rodriguez	sergio@inivit.cu
Cuba	INIVIT, Santa Clara	Marylis Jeminez	geneticamx@inivit.cu
Cuba	INIVIT, Santa Clara	Alfredo Morales Rodriguez	alfremr88@gmail.com
Fiji	Ministry of Agriculture	Mereia Fong	mereia.fong@govnet.gov.fj
Fiji	Ministry of Agriculture	Savenaca Cuquma	savenaca.cuquma@agriculture.gov.fj
Fiji	Secretariat of the Pacific Community SPC	Logotonu Waqainabete	logow@spc.int
France	CIRAD	Hana Chaïr	hana.chair@cirad.fr

Country	Institution	Name	email
France	Institut de Recherche pour le Développement	Nora Scarcelli	nora.scarcelli@ird.fr
Ghana	CSIR	Lawrence Aboagye	aboagyelawrencemisa@yahoo.com
Ghana	CSIR-SARI	Emmanuel Chamba	echamba@gmail.com
Ghana	CSIR-CRI	Emmanuel Otoo	otooemmanuel@gmail.com
Guadeloupe	CIRAD	Michel Roux Cuvelier	michel.roux-cuvelier@cirad.fr
Guadeloupe	CIRAD	Gemma Arnau	gemma.arnau@cirad
Guadeloupe	INRAE	Yoana Faure	yoana.faure@inrae.fr
Guam	Deapartment of Agriculture	Danko Taborosi	taborosi9@gmail.com
Haiti	MARNDR	Ricot Sctutt	ricotscutt00@hotmail.com, ricotscutt@yahoo.fr
Haiti	MARNDR	Jean Denis Sardou	s.jean-denis@avsf.org
Hawaii	Tropical Plant Genetic Resources USDA, Hawaii	Tracie Matsumoto	tracie.matsumoto@usda.gov
India	CTCRI, Trivandrum, Kerala	Archana Mukherjee	archanapsm2@rediffmail.com
India	ICAR National Bureau of Plant Genetic Resources	Kuldeep Singh	nbpgr@icar.gov.in
India	ICAR National Bureau of Plant Genetic Resources	Kuldeep Singh	kuldeep.singh4@icar.gov.in
India	ICAR National Bureau of Plant Genetic Resources	Veena Gupta	Veena.Gupta@icar.gov.in
India	ICAR National Bureau of Plant Genetic Resources	Veena Gupta	vgupta1123@rediffmail.com
India	CTCRI, Trivandrum, Kerala	Sheela MN	sheelactcri@yahoo.co.in
India	CTCRI, Trivandrum, Kerala	K. Abraham	abrahamk@rediffmail.com
Indonesia	Institute of Bioctechnology Bogor	Made Sri Prana	msprana_bio@yahoo.com
Indonesia	Purwodadi Botanic Garden-Institute of Sciences	Fauziah Zulakarnain	fauziahkrp@gmail.com
Indonesia	Indonesian Center for Genetic Resources Research	Dodin Koswanudin	dodinkoswanudin@gmail.com
Jamaica	CARDI	Gregory Robin	gregrobin7@gmail.com
Japan	NARO	Makato Kawase	setariakawase@gmail.com
Japan	National Museum of EthnoBiology, Osaka	Peter Mathews	pjm@minpaku.ac.jp, researchcooperative@gmail.com
Kenya	Bioversity International	Bioversity office	bioversity-kenya@cgiar.org
La réunion	CIRAD	Jean Pierre Labouisse	jean-pierre.labouisse@cirad.fr
Madagascar	FOFIFA	Vaohangy Andrianavalona	andrivoah@yahoo.com
Madagascar	FOFIFA	Arsene Rakotondravao	rakotondravao_arsene@yahoo.com
Malaysia	Bioversity International	Bioversity office	bioversity-apo@cgiar.org
Malaysia	Agricutural Research and Development Institute	Mohd Shukri Mat Ali	mshukri@mardi.gov.my
Myanmar	Ministry of Agricuture	contact	contact@e-moali.gov.mm

Country	Institution	Name	email
New Caledonia	Institut Agronomique Néo Calédonien	Julien Drouin	drouin@iac.nc
New Caledonia	Institut Agronomique Néo Calédonien	Audrey leopold	leopold@iac.nc
New Caledonia	Agence pour le Développement de la N Calédonie	Sylvia Cornu Mecky	sylvia.cornumercky@adecal.nc
New Caledonia	Institut Agronomique Néo Calédonien	Laurent Lhuillier	lhuillier@iac.nc
New Caledonia	Agence pour le Développement de la N Calédonie	Sébastien Blanc	sebastien.blanc@adecal.nc
New Caledonia	Agence pour le Développement de la N Calédonie	Meryl Jordan	meryl.jordan@adecal.nc
New Caledonia	Agence pour le Développement de la N Calédonie	Olivier Ratiarson	olivier.ratiarson@adecal.nc
Nicaragua	University of Nicaragua	Guillermo Reyes	greyes@ci.una.edu.ni
Nigeria	NRCRI	Joseph Onyeka	jonyeka@yahoo.com
Nigeria	IITA	David DeKoeyer	D.DeKoeyer@cgiar.org
Nigeria	NRCRI, Nigeria	Charles Amadi	okeyamadi2003@yahoo.com
Nigeria	IITA, Ibadan	Robert Asiedu	R.asiedu@cgiar.org
Nigeria	IITA, Ibadan	Michael Abberton	M.abberton@cgiar.org
Nigeria	IITA, Ibadan	Badara Gueye	B.gueye@cgiar.org
Nigeria	IITA, Abuja	Patrick Adebola	P.Adebola@cgiar.org
Nigeria	IITA, Abuja	Asrat Amele	A.Amele@cgiar.org
Nigeria	IITA, Abuja	Norbert Maroya	N.maroya@cgiar.org
Nigeria	IITA, Abuja	Beatrice Aighewi	B.aighewi@cgiar.org
Nigeria	NRCRI	Jude Obidiegwu	ejikeobi@yahoo.com
Nigeria	EBSU	Happiness Oselebe	h.oselebe@gmail.com
Nigeria	NRCRI	Ikoro Aniyim Ikoro	ikoromarshall@yahoo.com
Papua N Guinea	NARI National Agricultural Research Institute	Sim Sar	sim.sar@nari.org.pg
Papua N Guinea	NARI National Agricultural Research Institute	Birte Komolong	birte.komolong@nari.org.pg
Peru	Bioversity International	Marleni Ramirez	m.ramirez@cgiar.org
Peru	Bioversity International	Natalia Maravi	n.maravi@cgiar.org
Philippines	PhilRootCrops, BayBay, Leyte	Linda Vasquez	lindavasq@yahoo.com, philrootcrops@vsu.edu.ph
Philippines	PhilRootCrops, BayBay, Leyte	Dilberto Ferraren	bertocaferr@yahoo.com
Pohnpei	Federated States of Micronesia	Konrad Englberg	konrad.englberger@gmail.com
Pohnpei	Department of Agriculture	Adelino Lorens	lorensadelino@gmail.com
Pohnpei	Department of Agriculture	Mark Kotska	mkostka1771@gmail.com
Puerto Rico	University of Puerto Rico, Mayaguez Campus	Merari Feliciano-Rivera	merari.feliciano@upr.edu
Samoa	Ministry of Agriculture	Danny Hunter	tilafono@gmail.com
Sri Lanka	Department of Agricultue	Ravinda Senanayake	ravisena@gmail.com
Sri Lanka	Department of Agriculture	Samanthi Wasala	samanthiwasala@yahoo.com

Country	Institution	Name	email
Taiwan	Taiwan Agricultural Research Institute (TARI)	Len-Chie Wen	icwan@tari.gov.tw
Taiwan	Taiwan Agricultural Research Institute rootcrops	Kan-Shu Chen	kschen@dns.caes.gov.tw
Tanzania	Bioversity International	Rose Taremwa	r.taremwa@cgiar.org
Thailand	King Mongkut's Institute of Technology, Bangkok	Keith Thompson	keiththompson28@yahoo.
Thailand	Faculty of Natural Resources and Environment	Chirdsak Thapyai	chirdsakt@nu.ac.th
Togo	Université de Lomé	Damigou Bamite	bdamigou@gmail.com
Togo	Institut Togolais de Recherches Agronomiques	Kombaté Koffi	koffiprosper@gmail.com
Tonga	Ministry of Agriculture	Elisaiea Ika	elisaia.ika@gmail.com
Uganda	Bioversity International	Bioversity office	bioversity-uganda@cgiar.org
Vanuatu	Vanuatu Agricultural Research Technical Centre	Floriane Lawac	flhinano18@gmail.com
Vietnam	National Plant Genebak, PRC, Hanoi	Kien NoguyenVan	kiennguyenvan8@hotmail.com

ANNEX 3: DESCRIPTORS LIST FOR YAM (IITA)

1. Days to emergence (Unit: days.)
2. Stem length (Unit: cm.)
3. Internode number
4. Young stem colour
    1 – Purple
    2 - Colours other than Purple, marron and red
    3 – Red
    4 – Maroon
5. Absence/presence of waxiness
    1 – Absent
    2 - Present
6. Absence/presence of wings
    1 - Present
    2 - Absent
7. Absence/presence of hair
    1 - Absent
    2 - Present
8. Absence/presence of spines
    1 - Absent
    2 - Present
9. Colored spots at the base of spine
    1 - Absent
    2 - Present
10. Barky patches
    1 - Absent
    2 - Present
11. Plant type
    1 - Climbing
    2 - Shrub-like
    3 - Dwarf
12. Bearing type
    1 - Thick foliage
    2 - Intermediate
    3 - Stripped off
13. Vigor of entire plant
    1 - High
    2 - Intermediate
    3 - Low
14. Twining habit
    1 - Present
    2 - Absent
15. Layering habit
    1 - Absent
    2 - Present
16. Twining direction
    1 – Anticlockwise
    2 – Clockwise
17. Stem height 8 weeks after planting
    1 - Short
    2 - Medium
    3 - Long
18. Stem number per hill
19. Internode number up to 1st branching
20. Stem diameter measured 15cm from the base Unit: cm.
21. Internode length Unit: cm.
22. Branching at 16 weeks after planting
    1 - Many
    2 - Few
23. Adult stem color
    1 – Green
    2 - Dark green
    3 - Dark Green
    4 - DARK GREEN
    5 – Purple
    6 - Light green
    7 - Light Green
24. Adult Hairiness
    1 - Dense
    2 - Sparse
25. Adult waxiness
    1 - Absent
    2 - Present
26. Adult wings
    1 - Present
    2 – Absent
27. Rugosity
    1 – Absent
    2 - Present

28. Striation
    1 - Absent
    2 - Present
29. Cataphyll
    1 - Absent
    2 - Present
30. Hair type
    1 - Others
    2 - Simple
    3 - T-shaped
    4 - Stellate
31. Cataphyll position
    1 – Both
    2 - Alternate
    3 - Opposite
32. Spininess
    1 - Many/entire stem
    2 - Few/entire stem
    3 - Few/basal
    4 - Many/basal
33. Spine shape
    1 - Curved downward
    2 – Straight
    3 - Curved upward
34. Spine length
    1 – Long
    2 - Intermediate
    3 – Short
35. Coalescent spines
    1 – Absent
    2 – Present
36. Coloured spots at spine base
    1 - Absent
    2 - Present
37. Color of spots at spine base
    1 - Red
    2 - Colours other than Maroon, purple and red
    3 - Purple
    4 - Maroon
38. Surviving plants 4 weeks after planting
39. Leaf number Leaf number counted 20 days after emergence
40. Pigmentation between Veins
    1 - Absent
    2 - Present
41. Hairiness of leaf surfaces
    1 - Upper and lower surface
    2 - None
    3 - Lower surface only
    4 - Upper surface only
42. Leaf arrangement
    1 - Opposite
    2 - Alternate
    3 - Both
43. Onset of leaf
    1 - Early
    2 - Late
44. Leaf density
    1 - Dense
    2 - Intermediate
    3 - Sparse
45. Internode no to 1st assimilating leaf
46. Leaf type
    1 - Simple, entire, shalowly lobed
    2 - Serated
    3 - Compound
    4 - Deeply lobed
47. Leatheriness
    1 – Present
    2 – Absent
48. Undulation of leaf margin
    1 - Few
    2 - Many
49. Veins per leaf
50. Leaf colour
    1 - Green
    2 - Very dark green
    3 - Very light green
51. Hairiness of upper surface
    1 - Dense
    2 - Sparse
52. Hairiness of lower surface

1 - Dense

2 - Sparse

53. Waxiness of upper/lower surface

1 - Both

2 - Waxy upper surface

3 - Waxy lower surface

54. Leaf shape

1 - Cordate broad

2 - Sagitate broad

3 - Sagitate long

4 - Cordate long

5 - Cordate

6 - Ovate

7 - Hastate

55. Lobe shape

1 - Rounded

2 - Pointed

56. Distance between lobes

1 - No measurable distance

2 - Intermediate

3 - Very distant

57. Leaf base shape

1 - Emarginate

2 - Obtuse

3 - Acute

58. Upward folding of leaf along main vein

1 - Weak

2 - Strong

59. Downward arhing of leaf along main vein

1 - Present

2 - Absent

60. Upward folding of leaf lobes

1 - Present

2 - Absent

61. Downward arching of leaf lobes

1 - Absent

2 - Present

62. Stipules

1 - Absent

2 - Present

63. Leaf length Unit: cm.

64. Leaf width Unit: cm.

65. Position of the broadest leaves

1 - Medium part

2 - Upper part

3 - Lower part

66. Leaf tip

1 - Short

2 - Medium

3 - Long

67. Leaf tip colour

1 - Dark green

2 - Colours other than dark green and red

3 - Red

68. Petiole length Unit: cm.

69. Petiole length in correlation to leaf blade length

1 - Short

2 - Long

3 - Medium

70. Hairiness of petiole

1 - Dense

2 - Sparse

71. Colour of spots on petiole

1 - Purple

2 - Red

72. Coloured spots position on petiole

1 - End

2 - Medium

73. Spininess of petiole

1 - Absent

2 - Present

74. Amount of leafing in October

1 - Intermediate

2 - Dense

3 - Sparse

75. Amount of leafing in January

1 - Sparse

2 - Dense

3 - Intermediate

76. Flowering

1 - Absent

2 - Present

77. Days to flowering Unit: days.

5 - 150

78. Inflorescence smell

1 - Absent

2 - Present

79. Sex

1 - Male

2 - Female

3 - Female and Male [mostly female]

4 - Male and Female [mostly Male]

80. Inflorescence position

1 - Apical

2 - Basal

81. Number of inflorescence per plant

1 - Many

2 - Few

3 - Average

82. Inflorescence type

1 - Spike-like raceme

2 - Spikes

83. Number of inflorescence per internode

84. Average length of inflorescence Unit: cm.

85. Number of flowers per inflorescence

86. Flower colour at maturity

1 - Yellow

2 - Other colours outside white yellow and purple

3 - White

4 - Purple

87. Female flower length Unit: cm.

88. Male flower diameter Unit: cm.

89. Fruit formation

1 - Absent

2 - Present

90. Fruit position

1 - Apical

2 - Basal

91. Fruit quality

1 - Well-developed

2 - Poorly-developed

92. Fruit shape

1 - Elongated

2 - Trilobated capsule

3 - Equal in length and width

93. Fruit size

1 - Small

2 - Large

94. Fruit hairiness

1 - Dense

2 - Sparse

95. Fruit waxiness

1 - Absent

2 - Present

96. Dark spot inside fruits

1 - Absent

2 - Present

97. Maturity (tubers) after emergence

1 - Intermediate

2 - Early

3 - Late

98. Tuber growth

1 - Annual

2 - Perenial

99. Number of tubers per Hill

1 - One

2 - Few

3 - Several

100. Relationship of tubers

1 - Fused at neck

2 - Completely saparated and distant

3 - Completely separate and close together

101. Corm

1 - Present

2 - Absent

102. Corm size with tubersize

1 - Small

2 - Intermediate

3 - Large

103. Corm ability to be separate from tuber

1 - Absent

2 - Present

104. Spininess of root
    1 - Absent
    2 - Present
105. Sprouting at harvest
    1 - Absent
    2 - Present
106. Aerial tuber formation
    1 - Absent
    2 - Present
07. Skin color
    1 - Dark brown
    2 - Light brown
    3 - Greyish
    4 - Colours other than brown and grey
108. Surface texture
    1 - Wrinkle
    2 - Smooth
    3 - Rough
109. Bumps
    1 - Absent
    2 - Present
110. Skin thickness
    1 - Thin
    2 - Thick
111. Tuber shape
    1 - Cylindrical
    2 - Oval
    3 - Round
    4 - Oval-oblong
    5 - Irregular
112. Uniformity of tuber shape
    1 - Very uniform
    2 - Medium
    3 - Not uniform
113. Tendency of tuber branch
    1 - Highly branched
    2 - Slightly branched
    3 - Branched
114. Place where tuber branch
    1 - Lower third
    2 - Middle
    3 - Upper third
115. Tuber length Unit: cm.
116. Tuber width Unit: cm.
117. Spiny roots at tuber surface
    1 - Few
    2 - Many
118. Roots on the tuber surface
    1 - Few
    2 - Many
119. Rugosity of tuber surface
    1 - Medium
    2 - Smooth
    3 - Rugose
120. Cracks on tuber surface
    1 - Present
    2 - Absent

ANNEX 4. SELECTED METRICS FOR YAMS (GENUS DIOSCOREA) AND POTATO (AS COMPARISON)

This annex was written by Dr. Felix Frey, International Consultant, Global Crop Diversity Trust

Khoury et al. (2021) compiled a comprehensive dataset as part of a project funded by the International Treaty on Plant Genetic Resources for Food and Agriculture and the Crop Trust, led by the International Center for Tropical Agriculture (CIAT). The aim was to introduce normalized five reproducible indicators that provide an evidence base to prioritize actions with respect to conservation and use of crop genetic resources for food and agriculture. The indicators enclose metrics associated with the USE of a crop (Global importance), the INTERDEPENDENCE between countries with respect to genetic resources, the DEMAND of researchers for genetic resources, the SUPPLY of germplasm by gene banks and the SECURITY of germplasm conservation. The indicator results are visualized publicly available on an interactive online website. To generate the five indicators, Khoury et al. 2021 collected a comprehensive dataset from multiple sources. In the following, we don't present the indicators created by Khoury et al. (2021), but discuss the underlying raw data to shed light on the different aspects represented by the indicators.

To put some numbers into context, we compare the minor crop of yams with potato, a major crop of the world. Both crops are comparable with respect to type of propagation, cultivation and genetic of genepool. In contrast to a wider range of cultivation and use of potato, cultivation and consumption of yams is mainly restricted to certain regions of the world, foremost West Africa (Table included in this annex). Khoury et al. (2021) used *Dioscorea* and Solanum to represent the genera of yams and potato, respectively. To represent the most important species of yams, they used *D. rotundata*, *D. cayenensis* and *D. alata*, potato was represented with the species *S. tuberosum*, *S. ajanhuiri*, *S. juzepczukii* and *S. curtilobum*.

The metrics for "Global production", "Food supply" and "Quantity exported globally" from the indicator domain "Crop use" are annual average values drawn from FAOSTAT data (FAOSTAT, 2019) between the years 2010-2014. The percentage of countries producing and consuming (being supplied with) the crop is calculated as the number of countries, where the respective crop is within the top 95 % of most important crops divided by the total number of countries which report respective numbers (production 216, food supply 175). The global production of yams is at about 55 Million tons annually, which is about 15 % of the global potato production (363 M t). However, as most of yam production is done by small-scale farmers and most of yam production is consumed locally a high percentage of production is not reported to FAOSTAT, we can presume thus a much higher value. The quantity of food supply, i.e. the average global consumption is at 12 g per capita per day, which is 13 % of the value of potato (94 g). 28 and 35 % of countries in the world do produce and consume (are supplied with) yams, respectively. Potatoes are produced in 74 % and consumed in 100 % of countries. This reflects the wide range of importance of potato compared to a more local importance of yams. Consumption of yams is important in more countries than production, implying some level of export from producing countries. However, do to missing data there are no export numbers reported for yams, where about 5 % of potato production is exported.

The crop use metrics with respect to research are assessed by manual search on google scholar,

searching for the respective *genus* or most important species in the titles of publications, including patents and citations, between the years 2009 and 2019. Google scholar search hits represent importance with respect to scientific interest in a crop. With respect to the yam *genus Dioscorea*, publication records are relatively high indicated by 3,880 hits on google scholar. This represents 24 % of hits for the potato *genus Solanum* (16,500), stating that yam research is overrepresented compared to its share of production compared to potato (15 %). This is especially notable, as the *Solanum* hits are highly inflated by hits for other plant species besides potato (e.g. eggplant and tomato). 10 % of the *Dioscorea* hits referred directly to the three most important yam species (*D. rotundata*, *D. cayenensis* and *D. alata*) in the title of the publications (401 hits), whereas 37 % (6160 hits) of *Solanum* publication titles referred to different potato species (*S. tuberosum*, *S. ajanhuiri*, *S. juzepczukii* and *S. curtilobum*). The high research interest (and minor representation of the three major yam crops species in research) putatively (after a short manual revision of search results) is due to a high diversity of actually utilized yams (including wild species) in medicinal research.

Khoury et al. (2021 defined interdependence as a measure for the degree of dependence of the global cultivation and use of a certain crop from germplasm present at the primary centers of diversity of the respective crop. Primary centers of diversity are not represented by countries, but by 23 agroecological zones (Khoury et al. 2016), as crop diversity does not follow national boarders but rather climatic and agroecological boundaries. Interdependence is high in crops which originate from a small area and are cultivated and used globally. For production, interdependence is calculated by dividing a crops' production outside of the primary center of diversity by the global production. If all production would be outside the primary center of diversity, interdependence would be 100 %. For food supply, interdependence is calculated by dividing the food supply by the world average. Food supply outside can be higher than inside of primary regions of diversity and thus also higher than the global mean. Therefore, interdependence with respect to food supply can be above 100 %. Interdependence of cultivation and use of potato, whose primary origin of diversity is Andean South America, is very high. With values of 98 % and 100 % for production and food supply, respectively, global potato production and food supply are highly dependent on germplasm originating from a small region of the world. In contrast, yams have, with 7 % and 12 %, very low interdependence with respect to production and food supply. This is due to the fact, that primary centers of diversity of yams are in West Africa, Tropical South America, South Asia and Southeast Asia. These are also the regions where yams are mainly cultivated and used and there is virtually no interdependence of germplasm.

Demand for germplasm is defined by two metrics. First, by the number of distributions of accessions by gene banks, as an annual average between 2014 and 2017 drawn from the Plant Treaty Information System. Second, by the number of varieties released during the five years between 2014 and 2018, obtained from the International Union for the Protection of New Varieties of Plants (UPOV, https://www.upov.int). Although research interest in yams is relatively high, the demand for germplasm was very low with 57 distributions annually between 2014-2018 and no variety was released during the past 5 years. These numbers are even more extreme when compared to potato with 13,483 annual germplasm distributions and 21,434 varieties released in the past 5 years. One of the main reasons are phytosanitary problems restricting distribution of genetic material.

Khoury et al. (2021) illustrated the supply of germplasm with the number of accessions available in *ex situ* collections around the world, with respect to the crop *genus* and the most important species of the respective crop. Furthermore, Khoury et al. (2021) assessed the number of accessions (again with respect to *genus* and species) which were available under the multilateral system (MLS) of the Plant Treaty. This was done first, directly, as notation (in MLS / not in MLS) in the public online databases Genesys, FAO WIEWS and GBIF. Secondly, availability of accessions was assessed via the status of the country where the institution was located which held the respective germplasm collection. If the country was contracting partner of the Plant Treaty, the respective accession was regarded as available via the MLS. Global *ex situ* collections count a total of 10,275 *Dioscorea* accessions, where the three most important species (*D. rotundata*, *D. cayenensis* and *D. alata*) make up the largest part of it (7,257). The global yams collections account for 8 % of the size of the international potato collections (122,252 accessions). Only 1 % of *Dioscorea* accessions (0 % of the three major species) are directly available through the multilateral system (MLS) in comparison with 32 % of *Solanum* accessions (45 % of above-mentioned potato species). However, accessions which are held by countries who are contracting parties of the plant treaty are also available through the MLS. 69 % of *Dioscorea* accessions and 84 % of *Solanum* accessions (82 % and 88 % with respect to the major yam and potato species) are thus available indirectly through MLS.

Security of germplasm conservation is represented here with two metrics, the safety duplication status at the Svalbard Global Seed Vault (SGSV) and the equality of global distribution with respect to several crop use metrics. The numbers of accessions safety duplicated with respect to *genus* and species were drawn from the website of the SGSV and divided by the total number of accessions stored in global *ex situ* collections (see above), resulting in the percentage of safety duplicated germplasm. To represent the equality of distribution across different agroecological regions of the world (Khoury et al., 2016), Khoury et al. (2021) used the reciprocal 1-Gini index with respect to the different crop use metrics. The Gini index is the most commonly used inequality index (Gini index, 2008), foremostly known for the quantification of global income inequality. The 1-Gini index, presented here, ranges from 0 to 1, where 0 reflects very unequal distribution across world regions, 1 would represent a completely equal global distribution of the respective metric across the worlds' regions. It reflects the security of crop cultivation and use, where e.g. small indices of production and thus geographical restriction go hand in hand with a higher vulnerability of supply, e.g. in cases of natural disasters. None of the yam *ex situ* accessions is safety duplicated at the SGSV, in comparison with 14 (*Solanum*) and 43 % (major species) potato accessions. There is thus a strong need to store yam germplasm at SGSV (e.g. as seeds). Equality of production of yams is, with 0.01, lower than the value of 0.05 for potato and thus more unequally distributed across the worlds' regions. This is obviously due to the more restricted area of production, mainly in West Africa. Yam supply is thus more vulnerable to regional shortfalls of production. Equality of food supply across the different regions of the world of yams and potato are, with 0.05 and 0.20 relatively higher than equality of production. The much lower equality of distribution of food supply of yams in contrast to potato reflects that the different regions of the world differ hugely in their supply of yams, which is obviously related with the fact that yams are only consumed in some regions of the world, foremost West Africa, whereas potatoes are more globally utilized.

Literature (of this annex):

FAOSTAT (2019) Statistics for 2010-2014. www.fao.org. Accessed 2019.

Gini Index. In: The Concise Encyclopedia of Statistics (2008) Springer, New York, NY. https://doi.org/10.1007/978-0-387-32833-1_169

Khoury CK, Sotelo S, Amariles D, Guarino L, and Toledo A (2021) A global indicator of the importance of cultivated plants, and interdependence with regard to their genetic resources worldwide. Forthcoming

Khoury, C., Sotelo, S. Amariles, D. (2019) The plants that feed the world: baseline information to underpin strategies for their conservation and use. International Treaty on Plant Genetic Resources for Food and Agriculture (Rome) Project 2018 – 2019

Khoury, C. K., Achicanoy, H. A., Bjorkman, A. D., Navarro-Racines, C., Guarino, L., Flores-Palacios, X., Engels, J. M.M., Wiersema, J. H., Dempewolf, H., Sotelo S., Ramírez-Villegas, J, Castañeda-Álvarez, N. P., Fowler, C., Jarvis, A., Rieseberg, L. H., Struik, P. C. (2016). Origins of food crops connect countries worldwide. Proceedings of the royal society B: biological sciences, 283(1832), 20160792.

Khoury, C. K., Achicanoy, H. A., Bjorkman, A. D., Navarro Racines, C., Guarino, L., Flores Palacios, X., Engels, J. M.M., Wiersema, J. H., Dempewolf, H., Ramírez-Villegas, J., Castañeda-Álvarez, N. P., Fowler, C., Jarvis, A., Rieseberg, L. H., Struik, P. C. (2015). Estimation of countries' interdependence in plant genetic resources provisioning national food supplies and production systems. The International Treaty, Research Study 8

Indicator domain | subdomain	Metric	Yams	Potatoes	Yams / Potato	Source
Crop use | Production	Global production [tons]	55439104	362697957	15%	FAOSTAT, annual average (2010-2014)
Crop use | Food supply	Food supply (Amount consumed) [g/capita/day]	12	94	13%	FAOSTAT, annual average (2010-2014),
Crop use | Count countries (Production)	Percentage of countries producing crop *	28%	74%	38%	FAOSTAT, annual average (2010-2014),
Crop use | Count countries (Food supply)	Percentage of countries consuming (being supplied with) crop *	35%	100%	35%	FAOSTAT, annual average (2010-2014),
Crop use | Trade	Quantity exported globally [t]	NA	18287593		FAOSTAT, annual average (2010-2014),
Crop use | Research	Number of publications between 2009-2019, including patents and citations, searching title of publication (Google scholar search hits) for genus **	3880	16500	24%	Google scholar, manual search
Crop use | Research	Number of publications between 2009-2019, including patents and citations, searching title of publication (Google scholar search hits) for species ***	401	6160	7%	Google scholar, manual search
Interdependence | Production	Interdependence of global production from germplasm from primary centers of diversity [0-1] ****	7%	98%	8%	
Interdependence | Food supply	Interdependence of global food supply from germplasm from primary centers of diversity [0-1] ****	13%	100%	13%	
Demand | Distribution	Accessions distributed from gene banks (Annual average 2014-2017)	57	13483	0%	Plant Treaty Information System (2014-2017)
Demand | Variety release	Variety releases in 5 years (2014-2018)	0	21434	0%	UPOV (International

Indicator domain | subdomain	Metric	Yams	Potatoes	Yams / Potato	Source
					Union for the Protection of New Varieties of Plants) https://www.upov.int
Supply | Genebank collections	Number of accessions in *ex situ* collections of genus **	10275	122252	8%	Databases: Genesys, FAO WIEWS, and GBIF (living specimens only)
Supply | Genebank collections	Number of accessions in *ex situ* collections of species ***	7257	27750	26%	Databases: Genesys, FAO WIEWS, and GBIF (living specimens only)
Supply | Multilateral system	Accessions of the genus ** available through Multilateral System (MLS) directly noted in databases [%]	1%	32%	2%	Databases: Genesys, FAO WIEWS, and GBIF (living specimens only)
Supply | Multilateral system	Accessions of the species *** available through Multilateral System (MLS) directly noted in databases [%]	0%	45%	0%	Databases: Genesys, FAO WIEWS, and GBIF (living specimens only)
Supply | Multilateral system	Accessions of the genus ** available through Multilateral System (MLS) indirectly by matching institute countries with party status [%]	69%	84%	82%	Plant Treaty website 2019/3/12
Supply | Multilateral system	Accessions of the species *** available through Multilateral System (MLS) indirectly by matching institute countries with party status [%]	82%	88%	93%	Plant Treaty website 2019/3/12
Security | Safety duplication	Accessions of genus ** safety duplicated in Svalbard Global Seed Vault [%]	0%	14%	0%	https://seedvault.nordgen.org; Databases: Genesys, FAO WIEWS, and GBIF (living specimens only)

Indicator domain | subdomain	Metric	Yams	Potatoes	Yams / Potato	Source
Security | Safety duplication	Accessions of species *** safety duplicated in Svalbard Global Seed Vault [%]	0%	43%	0%	https://seedvault.nordgen.org; Databases: Genesys, FAO WIEWS, and GBIF (living specimens only)
Security | Equality of distribution	1-GINI index for equality of production across the world [0-1] *****	0.01	0.05	27%	1- GINI index (equality between countries) using summed average to derive regional values; FAOSTAT, annual average (2010-2014),
Security | Equality of distribution	1-GINI index for equality of food supply across the world [0-1] *****	0.04	0.20	20%	1- GINI index (equality between countries) using weighted average to derive regional values; FAOSTAT, annual average (2010-2014)

ANNEX 5. LIST OF PRIORITY CWR OF DIOSCOREA

Genus	Species	Species Authority	Concept Level	Relative of	IUCN Red List status	Number of valid, non-duplicated GBIF occurrences (%)
Dioscorea	*abyssinica*	Hochst. ex Kunth	T / P / P	*Dioscorea alata / Dioscorea cayenensis / Dioscorea rotundata*	NA	7 (1.1%)
Dioscorea	*antaly*	Jum. & H.Perrier	S / S	*Dioscorea bulbifera / Dioscorea dumetorum*	LC	1 (0.2%)
Dioscorea	*arachidna*	Prain & Burkill	S / S	*Dioscorea bulbifera / Dioscorea dumetorum*	NA	0 (0.0%)
Dioscorea	*birmanica*	Prain & Burkill	T	*Dioscorea esculenta*	NA	0 (0.0%)
Dioscorea	*brevipetiolata*	Prain & Burkill	S	*Dioscorea alata*	VU	5 (0.8%)
Dioscorea	*bulbifera*	L.	P / S	*Dioscorea bulbifera / Dioscorea dumetorum*	NA	125 (19.5%)
Dioscorea	*burkilliana*	J. Miège	P	*Dioscorea cayenensis*	LC	11 (1.7%)
Dioscorea	*calcicola*	Prain & Burkill	S	*Dioscorea alata*	NA	0 (0.0%)
Dioscorea	*cayenensis*	Lam.	T / P / P	*Dioscorea alata / Dioscorea cayenensis / Dioscorea rotundata*	NA	160 (24.9%)
Dioscorea	*cayenensis* subsp. *rotundata*	Lam.	S / P / P	*Dioscorea alata / Dioscorea cayenensis / Dioscorea rotundata*	NA	0 (0.0%)
Dioscorea	*cirrhosa*	Lour.	S	*Dioscorea alata*	NA	22 (3.4%)

Genus	Species	Species Authority	Concept Level	Relative of	IUCN Red List status	Number of valid, non-duplicated GBIF occurrences (%)
Dioscorea	*daunea*	Prain & Burkill	T	*Dioscorea esculenta*	NA	1 (0.2%)
Dioscorea	*decipiens*	Hook.f.	S	*Dioscorea alata*	NA	1 (0.2%)
Dioscorea	*dumetorum*	(Kunth) Pax	S/ P	*Dioscorea bulbifera / Dioscorea dumetorum*	NA	34 (5.3%)
Dioscorea	*esculenta*	(Lour.) Burkill	P	*Dioscorea esculenta*	NA	7 (1.1%)
Dioscorea	*glabra*	Roxb.	S	*Dioscorea alata*	NA	13 (2.0%)
Dioscorea	*hamiltonii*	Hook. f.	S	*Dioscorea alata*	NT	4 (0.6%)
Dioscorea	*hispida*	Dennst.	S/ P	*Dioscorea bulbifera / Dioscorea dumetorum*	NA	9 (1.4%)
Dioscorea	*inopinata*	Prain & Burkill	S	*Dioscorea alata*	NA	0 (0.0%)
Dioscorea	*lanata*	Bail	S	*Dioscorea alata*	LC	0 (0.0%)
Dioscorea	*minutiflora*	Engl.	P	*Dioscorea cayenensis*	LC	27 (4.2%)
Dioscorea	*nummularia*	Lam.	P	*Dioscorea alata*	NT	7 (1.1%)
Dioscorea	*oryzetorum*	Prain & Burkill	S	*Dioscorea alata*	NA	1 (0.2%)
Dioscorea	*pentaphylla*	L.	S/ S	*Dioscorea bulbifera / Dioscorea dumetorum*	NA	10 (1.6%)
Dioscorea	*petelotii*	Prain & Burkill	T	*Dioscorea esculenta*	NA	0 (0.0%)
Dioscorea	*praehensilis*	Benth.	P/ P	*Dioscorea cayenensis / Dioscorea rotundata*	NA	30 (4.7%)
Dioscorea	*preussii*	Pax	T	*Dioscorea esculenta*	NA	19 (3.0%)
Dioscorea	*pseudonitens*	Prain & Burkill	T	*Dioscorea esculenta*	NA	0 (0.0%)

Genus	Species	Species Authority	Concept Level	Relative of	IUCN Red List status	Number of valid, non-duplicated GBIF occurrences (%)
Dioscorea	*rotundata*	Poir.	T/ P / P	*Dioscorea alata* / *Dioscorea cayenensis* / *Dioscorea rotundata*	NA	0 (0.0%)
Dioscorea	*schimperiana*	Hochst. ex Kunth	S	*Dioscorea alata*	LC	13 (2.0%)
Dioscorea	*smilacifolia*	De Wild. & T.Durand	P	*Dioscorea cayenensis*	LC	21 (3.3%)
Dioscorea	*transversa*	R. Br.	P	*Dioscorea alata*	LC	66 (10.3%)
Dioscorea	*wallichii*	Hook.f.	S	*Dioscorea alata*	LC	0 (0.0%)

Based on the prioritization process carried out by Vincent et al. (2013), 33 species of *Dioscorea* have been selected as priority crops for germplasm collections and *in situ* conservation. Out of the 33 spp., only 11 (33.3%) have been assessed by the IUCN Red List. The occurrence data available on the 33 species on GBIF portal totals to 2,439 entries, of which only 970 (41.7%) have valid coordinates and only 641 unique values (non-duplicated data). The highest number of valid, unique coordinates have been recorded for *D. cayensis* (160), followed by *D. bulbifera* (125) and *D. transversa* (66). No valid data is recorded for five species, namely, *D. birmanica*, *D. calcicola*, *D. pseudonitens*, *D. rotundata* and *D. wallichii*. Of the 33 species, only one of the priority species has potential use trait recorded which is *D. abyssinica* for Yam Mosaic Virus resistance (Kikuno et al, 2011). Concept level: P = Primary, S = Secondary, T = Tertiary.

References (of this annex):

Vincent, Holly, John Wiersema, Shelagh Kell, Hannah Fielder, Samantha Dobbie, Nora P. Castañeda-Álvarez, Luigi Guarino, Ruth Eastwood, Blanca León, and Nigel Maxted. "A prioritized crop wild relative inventory to help underpin global food security." Biological Conservation 167 (2013): 265-275.

Dioscorea abyssinica Hochst. ex Kunth: Kikuno, H., Kumar, P. L., and Asiedu, R. Ranjana Bhattacharjee,

Melaku Gedil, Alieu Sartie, Emmanuel Otoo, Dominique Dumet. (2011). *Dioscorea*, In Wild Crop Relatives: Genomic and Breeding Resources Industrial Crops (pp. 71-96). Springer Berlin Heidelberg.

CROP TRUST

GENERAL CONTACT
+49 (0) 228 85427 122
info@croptrust.org

THE CROP TRUST
Platz Der Vereinten Nationen 7
53113 Bonn, Germany

MEDIA CONTACT
+49 (0) 228 85427 141
media@croptrust.org