E

联合国粮食及农业组织 Food and Agriculture Organization of the United Nations Organisation des Nations Unies pour l'alimentation et l'agriculture Продовольственная и сельскохозяйственная организация Объединенных Наций Organización de las Naciones Unidas para la Alimentación y la Agricultura منظمة الأغذية والزراعة للأمم المتحدة

COMMISSION ON GENETIC RESOURCES FOR FOOD AND AGRICULTURE

Item 8.2 of the Provisional Agenda

Twentieth Regular Session

Rome, 24–28 March 2025

DRAFT STUDY ON THE SUSTAINABLE USE AND CONSERVATION OF EDIBLE FUNGI AND INVERTEBRATES USED AS DIETARY COMPONENTS OF FOOD/FEED

NOTE BY THE SECRETARIAT

1. The Commission on Genetic Resources for Food and Agriculture (Commission), at its Seventeenth Regular Session, adopted its Work Plan for the Sustainable Use and Conservation of Micro-organism and Invertebrate Genetic Resources for Food and Agriculture (Work Plan).[1] The Work Plan addresses microorganisms and invertebrates as functional groups[2] and foresees that the two functional groups considered by the Commission at its Twentieth Regular Session will be (i) edible fungi and invertebrates used as dietary components of food/feed and (ii) microorganisms used in food processing and agro-industrial processes.[3]

2. In response to the Work Plan, FAO commissioned the preparation of a study on edible fungi and invertebrates used as dietary components of food/feed. In line with the Work Plan, the study does not cover aquatic invertebrates, as they are covered under the Commission's work on aquatic genetic resources for food and agriculture (AqGR). The study does, however, touch on aquatic insects, a group that shares characteristics with its terrestrial counterparts and that has rarely been addressed in AqGR-related work.

3 A draft version of the study was made available to the First Session of the Intergovernmental Working Group on Micoorgansism and Invertebrate Genetic Resources for Food and Agriculture, which took note of it and provided comments on it in writing.[4] A revised draft is contained in this document.

[1] CGRFA-17/19/Report, *Appendix E*.
[2] CGRFA-17/19/Report, *Appendix E*, paragraphs 8–14.
[3] CGRFA-17/19/Report, *Appendix E*, paragraph 14.
[4] CGRFA-20/25/8.1, paragraphs 15–16.

DRAFT STUDY ON THE SUSTAINABLE USE AND CONSERVATION OF EDIBLE FUNGI AND INVERTEBRATES USED AS DIETARY COMPONENTS OF FOOD/FEED

Eric Boa[1] and Jeffery Bentley[2]

[1] University of Aberdeen, Aberdeen, United Kingdom

[2] Agro-Insight, www.agroinsight.com

This document has been prepared at the request of the Secretariat of the FAO Commission on Genetic Resources for Food and Agriculture with a view to facilitating consideration by the Commission of the sustainable use and conservation of edible fungi and invertebrates used as dietary components of food/feed, at its Twentieth Regular Session. The content of this document is entirely the responsibility of the authors, and does not necessarily represent the views of the FAO or its Members.

.

TABLE OF CONTENTS

Acknowledgements 4
Executive summary 5

1 General introduction 8
2 Edible fungi 11
2.1 Introduction 11
2.2 An overview of edible fungi 13
2.3 Genetic resources and conservation status 17
2.4 Production and trade 27
2.5 Institutional frameworks 32
2.6 Regulatory frameworks 35
3 Edible invertebrates 38
3.1 Introduction 38
3.2 An overview of edible terrestrial invertebrates 38
3.3 Genetic resources and conservation 47
3.4 Production and trade 53
3.5 Institutional frameworks: research and research institutes 55
3.6 Regulatory frameworks 57
3.7 Policy frameworks 62
4 Gaps, needs and opportunities 64
References 68

Acknowledgements

Thanks to the following people for sharing information on cultivated and wild-gathered species. BRAZIL: Nelson Menoli. CHINA: Li Huili. GREECE: Eleni Topalidou. ITALY: Enrico Vidale, Alessandra Zambonelli. NETHERLANDS (KINGDOM OF THE): Arend Van Peer, Jan Van Nuffel. SOUTH AFRICA: Robi Caseletti, Peter Mortimer, Tony Cunningham. SPAIN: José Antonio Bonet. MEXICO: Daniel Martínez Carrera. UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND: Paul Kirk, David Minter. UNITED STATES OF AMERICA: Bryn Dentinger, Daniel Winkler.

Leo Beukeboom, José Antonio Bonet, Giulia Muir, David Novotny, Jana Obšteter, Dafydd Pilling, Christoph Sandrock, Masami Takeuchi and anonymous reviewers from the Kingdom of the Netherlands made valuable comments on previous drafts of this study.

Executive summary

1 A huge range of edible fungi and invertebrates are consumed worldwide amid mounting concerns about sustainable use and conservation of biodiversity.

Knowledge and public awareness of edible fungi and invertebrates have expanded greatly in the last few decades, but there are still major gaps in understanding of the range of species consumed, where they come from, how they are produced, their importance to nutrition and income generation, and the scale and importance of their trade at all scales from local to international. Wild harvesting and cultivation of these groups of organisms are expanding and have contributed to increasing concerns about their sustainable use. Further threats to their biodiversity stem from habitat loss, environmental degradation and climate change.

"Edible fungi" refers in this study to a small group of larger species of macrofungi – typically having a stem and a cap with gills or pores but also including other forms, such as truffles. There are over 2 300 recorded species of edible mushrooms, as they are more commonly referred to, of which a small group of 100 to 200 species are regularly consumed worldwide. "Edible invertebrates" refers here to edible terrestrial invertebrates. Aquatic invertebrates (such as shrimp) are not covered, although some information on aquatic insects is included. The main focus is on insects (which are the biggest and most important group of edible terrestrial invertebrates, with over 2 100 species) and snails.

A small number of cultivated mushrooms dominate a well-established commercial market that sustains a vigorous international trade. The most popular and valuable cultivated species worldwide include *Agaricus bisporus* (button mushroom), *Lentinula edodes* (shiitake) and *Pleurotus* spp. (oyster mushrooms). However, increased interest in more varied diets and – in some countries – a search for alternatives to meat and other animal products have led to the commercial cultivation of additional species. Mushrooms have long been harvested from the wild throughout the world. An overwhelming majority of these species cannot be cultivated because of their complex growth requirements.

Edible invertebrates are also wild harvested around the world, especially in the tropics. Insect farming has expanded rapidly since 2000, especially in tropical countries where terrestrial invertebrates are a part of local cuisines. Improved rearing technologies have allowed insect farming also to become established in temperate countries. Insects are now reared by households and in large facilities worldwide for food, fertilizer and, especially, for animal feed. Snails are increasingly reared as food, especially in Africa and Europe. About two dozen species of terrestrial invertebrates are now being farmed.

A small number of saprobic edible mushrooms have been successfully domesticated. The extent to which genetic improvement techniques are being applied in the mushroom industry is difficult to assess because of producers' commercial confidentiality. Research on improved production and the use of new substrates is being carried out by public universities and research institutes in a few countries, notably in China, Denmark, France, the Kingdom of the Netherlands and the United Kingdom of Great Britain and Northen Ireland.

Ex situ conservation of saprobic mushrooms in culture collections works well. Some species with complex growth requirements are also held in culture collections, where they require special attention. Conservation, however, depends on the success of *in situ* approaches. The use of modern DNA technologies to map the genetic diversity of edible species in the wild is still evolving and practical application is still at an early stage.

2 Patterns of use and increased consumption are influenced by cultural preferences, perceived risk of eating poisonous species, and opportunities to develop new sources of feed.

Introducing edible insects into the diets of urban consumers in the Global North is constrained by cultural aversions to eating them. Overcoming this reluctance would create opportunities to add

nutritious and environmentally friendly foods to diets in Europe and North America. Converting insects into powders or "flour" has potential as a means of expanding their use, for example in baked goods. There are also major opportunities to develop edible insects as an environmentally friendly feed for livestock, pets and farmed fish, thereby reducing carbon emissions and providing an alternative to fishmeal and to soy grown on land cleared from rainforests. The use of edible mushrooms as animal feed is limited, but there is some potential for health gains from feeding those with (largely untested) medicinal properties to poultry.

National governments and regional authorities, such as the European Union, have approved legislation allowing certain insects to be used as human food. Guaranteeing the safety of foods derived from terrestrial invertebrates and mushrooms is vital to the future development of these sectors. Codex Alimentarius has only general guidance on food safety relating to product quality and the detection of contaminants in edible insects and mushrooms. National food-safety legislation in Europe and North America provides more detail on the production and sale of edible insects and mushrooms but contains little on how to protect consumers from poisonous mushroom species, many of which can be difficult to distinguish from their edible relatives. Eating poisonous insects is less common, although commercialization has led to some cases of toxic species being mislabelled and sold as edible ones.

The fear of eating poisonous mushrooms is a significant issue in countries where urban populations have little or no tradition of eating wild species. Some countries have drawn up preferred lists of edible mushrooms and food-safety protocols and procedures. Opinions differ, however, on which mushrooms can be consumed. Approaches used to confirm species as edible or inedible also differ. A classification and assessment scheme for edible mushrooms[5] has been proposed. It offers a possible pathway for resolving differences in reported properties and sustaining the use of a wider range of species.

3 Overexploitation is often seen as a threat to wild-harvested species, but climate change and habitat loss are also important.

Overharvesting – the extraction of unsustainable volumes of individuals from a given species in the wild – is the threat most often reported by countries, scientists and conservationists, as well as by local harvesters facing influxes of poorly informed commercial collectors. The scientific evidence does not always support fears of excessive extraction, particularly in the case of wild harvesting of edible mushrooms.

The term "overexploitation" more explicitly includes the impact of collectors who use inappropriate and harmful harvesting practices. These include the raking of leaf litter and soil for edible mushrooms or cutting down trees to gather caterpillars. Such practices can degrade wild habitats and harm the ability of some species to reproduce. Training harvesters in good practices and incorporating this learning into the process of issuing permits can have positive impacts. However, as with many conservation measures, concrete evidence with which to assess the effectiveness of these approaches is difficult to find or simply unavailable.

Besides overharvesting, other threats to the sustainable use of edible mushrooms and invertebrates include climate change, habitat loss and degradation (urbanization, deforestation, pollution, etc.), and the loss of traditional knowledge of how to manage and harvest these groups of organisms. Traditional knowledge on which species to collect and good harvesting practices, for example, can support efforts to conserve and sustainably use edible mushroom and invertebrate species. More could be done to document local practices and preferred species and to share knowledge among countries.

[5] Li, H., Tian, Y., Menolli, N. Jr, Ye, L., Karunarathna, S.C., Perez-Moreno, J. & Rahman, M.M. 2021. Reviewing the world's edible mushrooms: a new evidence-based classification scheme. *Comprehensive Reviews in Food Science and Food Safety*, 20(2): 1982–2014. https://doi.org/10.1111/1541-4337.12708

Conservation measures that target a given area, whether they target individual plant or animal species or biodiversity hotspots, will tend to benefit the mushrooms and invertebrates that live in the area. However, it is unclear whether conservation priority-setting for biodiversity in general currently ensures that all important habitats for edible mushrooms and invertebrates are adequately targeted. The impact of climate change on populations of edible mushrooms has been modelled for European forests. Similar approaches have been used, also in Europe, to identify forest management practices that support sustainable production. Research results are promising but need to lead to practical implementation and to application on a wider geographical scale.

4 Steady progress has been made on identifying edible species that are at risk and the actions needed to conserve the biodiversity of edible fungi and invertebrates.

Interest in – and research on – the conservation of macrofungi in general has expanded hugely in the last three decades or so. Red lists of endangered mushroom species have been published. Momentum is building for more detailed assessments of the listed species and for the addition of new ones. Edible mushrooms are included in the monitoring of endangered macrofungi, although there are as yet no specific efforts to prioritize the species that are of the highest value to people or for which there are concerns about overexploitation.

Many invertebrate species, especially insects, have become extinct or threatened in recent years. An unknown number of edible species face some kind of threat from overharvesting or environmental change. A few species of agricultural pests (e.g. grasshoppers and locusts) are extremely abundant and could be sustainably harvested in the wild. The environmental impact of eating some locusts would surely be less than the damage caused by spraying the swarms with insecticides. Wild species that are gathered for sale and cannot be farmed are probably at the greatest risk. There is a need for well-informed regulation of commercial wild harvesting as well as for better conservation of forests and other wildlands where edible invertebrates are found.

5 There are still major gaps in knowledge of the importance of edible species and of the effectiveness of conservation measures for them.

Local, national and international trade flows illustrate the economic importance of edible species and highlight why governments need to pay attention to their sustainable use and conservation. New data on national and international trade in wild edible mushrooms are available and can be used to help guide the development and implementation of evidence-based sustainable use and conservation policies. Information on local trade and the use of edible mushrooms and invertebrates is patchy or unavailable, an issue exacerbated in some countries by assumptions about their low economic value. There is good evidence from countries with strong traditions of using edible mushrooms and insects to counter this assumption and justify wider studies.

Ethnobiological studies are also a useful way to gather information on the effectiveness of conservation measures, particularly the use of permits and other regulations aimed at countering the threat of overexploitation, and also on measures aimed at improving production. Such measures could include selection of tree species for reforestation that have known edible-mushroom associations (mycorrhizae). Local people have often developed techniques for sustainable harvesting of edible insects and snails, and this knowledge should be incorporated into regulations and recommended best practices for collecting such species from the wild.

6 There are opportunities to share knowledge and experiences on sustainable use and conservation more widely among countries and stakeholders.

There has been a steady growth of research interest and government involvement in matters related to edible mushrooms and invertebrates. Opportunities for interdisciplinary collaborations have expanded, but only in some regions and countries. Wider and stronger networks of stakeholders have

been created, although these also tend to be geographically limited, for example focused on Europe or the Pacific Northwest of the United States of America. There are clear opportunities for greater sharing of knowledge and experiences on the effectiveness of sustainable use and conservation measures. Progress has been made through the creation of endangered species lists (for edible mushrooms) that can be commented on, used and added to worldwide. Wider collaborations and partnerships could be facilitated by heightening awareness of edible mushrooms and terrestrial invertebrates in the context of environmental protection schemes or food-safety regulations.

1. GENERAL INTRODUCTION

Edible fungi and terrestrial invertebrates are a source of nutrition and income for many people around the world, especially in developing countries. Many kinds of terrestrial invertebrates are also fed to animals. Both groups of organisms are both harvested from the wild and cultivated or raised by humans. Increased demand has provided strong incentives to expand cultivation. However, the shift from wild gathering towards cultivation only applies to a few dozen species of fungi and invertebrates, as many key species cannot be cultivated. Wild gathering will remain a vital activity in many countries.

Various estimates of the worldwide monetary value of edible mushroom production have been published. Niego *et al.* (2023) give figures of USD 3.6 billion for wild species and and USD 24.5 billion for cultivated species in 2020. Other authors have reported higher values, with Royse *et al*. (2017) for example giving figures of USD 5 billion for wild edible mushroom production and USD 34 billion for cultivated species production. These and other estimates exclude the value of wild edible mushrooms to ecosystem services (other than provisioning services) and healthy ecosystem functioning.

The value of global trade in edible insects (the group of terrestrial invertebrates that is the most important source of human food) was predicted to reach USD 1.2 billion in 2023 (Liceaga, 2021, cited in Tanga and Kababu 2023).

Interest in both groups of organisms is increasing because of their potential as relatively environmentally friendly sources of nutritious food and feed, particularly as alternatives to livestock products in human diets, and soybean and fishmeal in animal diets. There are also growing concerns, on the part of both scientists (e.g. Antonelli *et al.*, 2023; Collen *et al.*, 2012) and the general public, about the threats faced by both groups in the wild, the latter prompted by in part by recently published popular books (e.g. Sheldrake, 2020; McGavin, 2024).

The world hosts an estimated 2.2 to 3.8 million species of fungi (Hyde, 2022) and about 7.1 million species of terrestrial invertebrates: 7 million terrestrial arthropods (Stork, 2018) and 29 400 described species of terrestrial and freshwater snails and other molluscs (Rosenberg, 2014), besides many more species, many of which are still undescribed. Few fungi and invertebrate species are edible to humans. Of 155 000 described species of fungi, only about 2 000 are edible (Li *et al.*, 2021). Among terrestrial invertebrates, most edible species are insects, and out of 1.5 million described insect species (Antonelli *et al.*, 2023), just over 2 100 are edible (Jongema, 2017). Even fewer species are eaten in substantial amounts (around 100 to 200, for fungi and terrestrial invertebrates combined).

This study is intended to support the work of the Commission on Genetic Resources for Food and Agriculture (Commission) on the sustainable use and conservation of the genetic resources of edible fungi and invertebrates used for food or feed. This is taken to include all the elements of the policy, legal and institutional frameworks (including research, collaboration, information sharing and awareness raising) needed to support sustainable use and conservation. The two groups of organisms constitute a “functional group” under the Commission’s Work Plan for Micro-organism and Invertebrate Genetic Resources (FAO, 2019a), and it was considered that there are sufficient commonalities in their management to make it appropriate to address them both in one study.

The scope of the study is global, and it covers both farmed and wild-gathered species. Some regions and countries feature more prominently than others, reflecting differences in levels of use, cultural attitudes, culinary preferences and institutional capacities, as well as the availability of literature. In line with the Commission's Work Plan, aquatic invertebrates are excluded, as they are covered under the Commission's work on aquatic genetic resources for food and agriculture (AqGR). Aquatic insects are, however, touched upon, as they share characteristics with their terrestrial counterparts and have received little attention in the Commission's AqGR work. In the case of fungi, the scope is limited to macrofungi. Yeasts and other fungi used in food processing are covered under the Commission's work on food-processing microorganisms. The term "mushrooms" (see Section 2.2) is used in the study to refer to edible macrofungi. "Edible" is taken to mean edible to humans – or, in the context of use for animal feed, to the respective species of animals.

Information has been drawn from a wide range of sources and the authors' long experiences working on agriculture and natural-resources management projects around the world. Sources include peer-reviewed articles and books, reports by organizations involved in work on edible fungi and invertebrates, official trade data and interviews with knowledgeable colleagues (see acknowledgements section for details). Reliable data on production and trade have been difficult to come across, although the incorporation of named edible mushrooms in UN statistics[6] is a welcome development.

Key terms used in this study to describe how edible species are obtained (Table 1) follow suggestions by Muir *et al.* (2020). The collection of wild food is also described as "gathering" or "harvesting".

Table 1: Terminology related to the production of edible fungi and invertebrates

Term	Definition	Notes
Wild (food)	Obtained by collecting or gathering, not by cultivation, for human use	Often associated with forests, but other habitats also feature. Valuable edible species such as *Termitomyces* and *Pleurotus*, occur in open, grassy areas. Edible wild locusts and grasshoppers are gathered on agricultural fields, where these insects can be pests.
Semi-cultivation	Techniques used by humans to promote the reproduction of edible species in their natural habitats	Human intervention is intermittent. Examples include the tending of trees artificially inoculated with truffles (*Tuber* spp.) in defined areas, closing ant nests after collecting some larvae and pupae, and leaving palm trunks on the forest floor as natural food for edible grubs.
Cultivation	Production of edible species under controlled conditions	Requires regular human intervention to ensure reliable production. Cultivation depends on the use of a wide variety of substrates.
Farmed	Production of edible species that involves human intervention	Typically, only used for edible invertebrates. It is similar to "cultivation" and "rearing" but does not imply domestication.
Domestication	Process by which wild species are selected and	A term more usually applied to plants and animals (e.g. crops, garden plants, livestock and pets). According to this definition, the important

[6] www.cometradeplus.un.org

	genetically modified for cultivation.	commercial edible mushrooms *Agaricus* and *Pleurotus* spp. have been domesticated.
Breeding	The genetic manipulation of a species to select for traits desired by humans.	Usually follows domestication. Includes conventional methods, such as artificial selection.

Source: Adapted from Muir, G.F., Sorrenti, S., Vantomme, P., Vidale, E. & Masiero, M. 2020. Into the wild: Disentangling non-wood terms and definitions for improved forest statistics. *International Forestry Review*, 22(1): 101–119. https://doi.org/10.1505/146554820828671553

Three main groups of collectors are considered in the study:

1) Individual or recreational collectors who gather edible species for occasional personal use. Edible mushrooms and invertebrates can be an important part of family diets. Although some communities may avidly collect choice species when they are in season, less is known about volumes obtained or their contribution to nutrition. Many species are also collected as delicacies, rather than as staple foods.

2) Small-scale collectors and part-time traders selling their produce in local markets and sometimes also eating some of what they gather.

3) Commercial traders, who may buy from the small-scale collectors and seek consistent supplies within the limitations of the seasonal production of wild foods.

The body of the study consists of a section on fungi, a section on invertebrates, and a concluding section on gaps, needs and opportunities that covers both groups of organisms and is intended to provide guidance to the Commission and its Members concerning potential actions that might be taken to improve the management of the genetic resources of edible fungi and edible terrestrial invertebrates.

The sections on fungi and invertebrates have similar structures. They start with an overview of the main species in the respective group, their characteristics and significant features, including where they occur and how they are collected and produced. They then cover sustainable use, risks to wild populations, the general status of genetic resources, the viability of wild collection and how commercial production might alleviate pressure on natural resources, conservation efforts (and in the case of invertebrates the use of insects to replace some conventional livestock feeds) and the state of production and trade. The next subsections provide overviews of organizations working on research on the respective groups of organisms and on other aspects of their management (including national and international networks), and regulatory frameworks for wild-gathering and for food and feed safety at national and international levels.

2. EDIBLE FUNGI

2.1 Introduction

Humans now eat more edible fungi worldwide than ever before, both cultivated and wild-gathered,[7] and interest in edible species and knowledge of their biology, ecology and social and economic importance has expanded over recent decades. The study of wild edible fungi has grown as a result of increased interest in non-wood forest products (NWFPs), concerns about the loss of fungi biodiversity (Niskanen *et al.*, 2023) and recognition of the need to assess and monitor the status and trends of fungi species (Floccia *et al.*, 2024). The first major global survey of the use and importance of wild edible fungi was published 20 years ago (Boa, 2004).

The geographical spread of research and other activities related to wild edible fungi is still heavily weighted towards Europe and North America. Research in China has surged in recent decades, although reviewing of Chinese publications for this study has been restricted by language barriers. Mexico is also active in the study of wild edible mushrooms, but beyond the Americas there is limited wider awareness of relevant findings from Mexico on sustainable use and conservation.

The list of wild edible species eaten continues to expand. Overall, there has been little change in the last two decades in terms of what species of wild and cultivated edible fungi are the most popular worldwide. However, there have been significant changes in consumer preferences, especially in countries that traditionally only ate *Agaricus bisporus*, the most common cultivated species. Trade in other cultivated species has increased as a result.

The acceptability of a wider range of edible fungi species reflects a greater recognition of their qualities as food, particularly among those who do not eat meat. Growing interest in foraging for wild food, usually for individual consumption, has also stimulated greater interest in the diversity of edible fungi (Cook, 2013). The fear of eating poisonous species still exists, and it continues to influence the willingness of consumers to eat a wider range of edible species. The risks are, however, often overstated and stoked by exceptional poisonous events that receive wide publicity (e.g. FSN, 2024).

Edible fungi are rarely used in animal feed. One review (Bederska-Lojewska, Swiatkiewicz and Muszynska, 2017) noted “a noticeable growth in interest in the potential of edible mushrooms” as animal feed, but this appears to be restricted to experimental approaches focusing on poultry (Amara and El-Baky, 2023; Vargas-Sánchez *et al.*, 2018).

Medicinal mushrooms are not a specific focus of this study.[8] However, a high proportion of medicinal species are also edible and thus matters concerning their sustainable use and conservation are implicitly addressed. Of the 470 species reported to have medicinal or therapeutic properties, 71 percent were also eaten (Boa, 2004). The volume of production and trade of mushrooms gathered from the wild solely for medicinal purposes is tiny in comparision to that of cultivated species. The major exception is *Ophiocordyceps sinensis*, harvested from high altitudes across the Himalayas (Winkler, 2008) and into Yunnan province in China. The vast bulk of medicinal mushrooms are cultivated, and there are around 30 to 40 key species, including *Ganoderma lucidum* and *Inonotus obliquus*. There is intense commercial interest in developing medicinal mushrooms because of the potential benefits to human health.

The increase in consumption of edible mushrooms has had notable positive outcomes. Increased production of cultivated species, along with the increasing demand for (non-cultivable) wild species, has boosted local and national economies (Niego *et al.*, 2023). Greater trade flows have helped rural

[7] UN Comtrade data (https://comtradeplus.un.org) are discussed later in this section.

[8] The functional group referred to under the Commission’s Work Plan is specifically edible fungi (and invertebrates) used for food/feed.

folk earn more money but have also heightened concerns about sustainable use and environmental impacts, prompting calls for more effective regulation of collecting.

Selling *Schizophyllum commune* and wood ear mushrooms in Beni, the Democratic Republic of the Congo. © Eric Boa.

Termitomyces seller, Kigali, Rwanda. © Eric Boa.

2.2 An overview of edible fungi

Edible species of fungi are usually referred to collectively as edible mushrooms (fungi with round flat caps and short stems), even though their form varies considerably, from those with gills and pores under the cap to truffles, which grow underground and could be mistaken for lumps of soil. A comprehensive review of the world's edible mushrooms found over 2 300 edible species (Li *et al.*, 2021) and the main groups gathered from the wild are shown in Table 2.1 Disputes continue regarding the toxicity of some edible species, and this remains an issue when considering which species can be recommended and officially sold in markets. For example, the trade of *Tricholoma equestre* is banned in Spain but permitted in Portugal (Klimaszyk and Rzymski, 2018). This issue of diverging opinions on edibiliy is dealt with below as part of the discussion on food safety.

Wild edible species are typically collected from forests, and the majority that are mycorrhizal (form fungus-roots) cannot be cultivated because of complex growth requirements and dependency on a suitable plant host. The mycorrhizal association benefits the fungus and enables the establishment and survival of the host species, most of which are trees. The extent of forests and health of trees is inextricably linked to the production and survival of many edible mushroom species (Egli, 2011).

Host species are, unsurprisingly, best identified and known for the more valuable edible mushrooms, such as the true truffles (Zambonelli, Ioti and Murat, 2015). Desert truffles (e.g. species of *Terfezia* and *Tirmania*) are closely associated with *Helianthum*, a shrub found in arid zones of countries from Morocco to southern Iraq (Morte *et al.*, 2021). Host-plant species provide important ecological clues to collectors on the likely sites of edible mushrooms, although production is dependent on other factors, such as soil type, temperature and periods of rain (Degreef *et al.*, 2020). In communities with long experience of harvesting wild species, traditional knowledge is an invaluable source of information on productive sites (Pérez-Moreno *et al.*, 2020).

There are three main production categories of edible mushrooms: those that are gathered from the wild (Table 2.1), those that are semi-cultivated (Table 2.2) and those that are cultivated (Table 2.3). Selected examples are given for each category. The list of edible species for countries around the world (Boa, 2004) continues to expand, with recent updates for Africa (Sileshi, Tibuhwa and Mlambo, 2023), for example.

Leucoagaricus mushrooms on sale in Cochabamba, Plurinational State of Bolivia. © Eric Boa.

Semi-cultivation techniques for true truffles (*Tuber* spp.), which involve inoculating host trees and managing them in protected areas, are well established in Europe, China, New Zealand and the United States of America (Zambonelli, Ioti and Murat., 2015). Attempts continue to semi-cultivate *Cantharellus* and *Boletus* species (Pérez-Moreno *et al.*, 2020), for example, but without evidence of success on any significant or commercially viable scale. The semi-cultivation of desert truffles (*Terfezia* spp.) is also under investigation. Although successful methods have been developed, yields are variable (Morte *et al.*, 2021).

Commercial production of morels, which also have exacting growth requirements, began in 2011 in China (CEFA, 2022) and technologies have been licensed for use in India and Pakistan. Yields of up to 15 tonnes per hectare have been achieved but cannot be guaranteed (Xu *et al.*, 2022). A 2022 breakthrough in morel cultivation in Denmark promised reliable commercial-scale production (Kirk and Kirk, 2021). With the exception of truffles and morels – two groups of gourmet edible mushrooms – commercial production of cultivated edible mushrooms will for the foreseeable future rely on tried and tested species (Table 2.3).

Table 2.1: Edible mushrooms commonly gathered from the wild

Group (genus)	Notable species	Notes on genus
Amanita	*A. caesaria*	Includes highly toxic species.
Boletus	*B. edulis* (porcini)	There are many other edible species.
Cantharellus and allies	*C. cibarius*	Allies include species of *Craterellus.*
Lactarius	*L. deliciosus* (saffron cap)	Milk-caps. Around 90 edible species.
Morchella	*M. esculenta* (morel)	Morels are wild-harvested and semi-cultivated.
Russula	*R. delica*	Over 120 edible species.
Terfezia and allies	*Terfezia arenaria*	Desert truffle(s). Allies includes species of *Tirmania*.
Termitomyces	*T. clypeatus*	Widely distributed from Africa to Asia.
Tricholoma	*T. matsutake*	Demand from Japan has attracted imports from other countries (e.g. China and the United States of America).
Tuber	*T. melanosporum*, *T. aestivum* (truffles)	Truffles – also semi-cultivated. Over 20 species.

Source: Authors' own elaboration.

Table 2.2: Examples of edible mushrooms that are semi-cultivated

Genus	Examples	Notes
Morchella	*M. importuna*	China is the main producer; others are rising in importance (e.g. Denmark and Pakistan).
Tuber	*T. melanosporum*, T. aestivum, *T. oregonense**	Produced in Europe, New Zealand and North America*

Source: * Used for medicinal purposes. Authors' own elaboration.

Table 2.3: Examples of notable edible mushrooms that are cultivated

Group	Notable species	Notes
Agaricus	*A. bisporus**	The genus includes species with medicinal properties.
Auricularia	*A. auriculae-judae**	Wood-ear; this and other species have medicinal properties.
Hericium	*H. erinaceum**	Lion's mane.
Hypsizygus	*H. tessulatus**	
Lentinus	*L. edodes**	Shiitake.
Pleurotus	*P. ostreatus**	Around 40 species in total. Not all are cultivated. At least three species have medicinal properties.
Volvariella	*V. volvacea**	Paddy straw mushroom.

* Used for medicinal purposes. *Source:* Authors' own elaboration.

A relatively small number of wild edible mushroom species are consumed or traded in significant amounts. Local consumption and trading of a wide range of species is still of vital importance to many rural communities for income and nutrition (e.g. Degreef *et al.*, 2020), even though the quantities sold are usually small (e.g. Mayett *et al.*, 2006). Studies such as these continue to add to a body of knowledge of local collecting and trading practices that is still sparse, particularly in the Global South. Gathering good data and estimating the value of harvests to rural communities remains challenging (Alexander *et al.*, 2011).

Harvesters bring matsutake mushrooms to traders in Oaxaca, Mexico. © Eric Boa.

Termitomyces sellers in Kigali, Rwanda. © Eric Boa.

2.3 Genetic resources and conservation status

Status and trends

Macrofungi (including edible mushrooms) were ignored or given limited attention in early efforts to assess risks to biodiversity and identify endangered species (Niskanen *et al.*, 2023). Concerns about the status of macrofungi began to emerge in the late 1980s and were linked to habitat loss in Europe. Coordinated efforts through the International Union for Conservation of Nature (IUCN) have steadily improved information on which macrofungi, including important edible mushroom species, are most at risk. The Global Fungal Red List is introduced in a paper by Mueller *et al.* (2022), which also includes a discussion of the general threat status of fungi.

None of the limited number of edible species that appear in The Global Fungal Red List are under major threat (Table 2.4), although some assessments have yet to be completed. Only nine edible species have been fully assessed, three have received a preliminary judgement and ten assessments have not been completed. There are many valuable edible mushrooms that have yet to be included in The Global Fungal Red List. Some of these species have had partial assessments carried out, for example on threats facing *Tricholoma matsutake* from harvesting techniques (Luoma *et al.*, 2006).

The Global Fungal Red List did not gather momentum until 2013. Individual countries, mostly in Europe, began compiling their own lists of endangered fungi species much earlier, in the 1980s, and there are now approximately 40 countries with national red lists (Mueller *et al.*, 2022). Assessments of threat status are most common in Europe, North America and South America.

Field guides on mushrooms are a good source of information on the diversity and distribution of macrofungi, including edible species, and many also discuss wider threats to fungi biodiversity. Strong traditions in natural history as well as in observing (and eating) wild mushrooms in many parts of Europe are reflected in the depth of information available on species diversity (e.g. Laessoe and Petersen, 2019). A number of excellent national field guides have explored the diversity, ecology and use of wild edible species in Africa, including Benin (de Kesel, Codjia and Yorou, 2002), Burundi (Buyck, 1994), the United Republic of Tanzania (Härkönen, Niemallä and Mwasumbi, 2003) and Zambia (Härkönen *et al.*, 2015). These are also useful sources of information on species diversity, sustainable use and general threats.

Much less is known about the genetic diversity within wild mushroom species. Recent advances in molecular detection techniques show considerable promise in filling major gaps in knowledge. Environmental DNA barcoding allows for detailed analysis of fungi in soil samples and is being used to assess the diversity of macrofungi species (Niskanen *et al.*, 2023). A majority of wild edible mushrooms are mycorrhizal, i.e. they form fungus-root associations with plant hosts and cannot be cultured in the laboratory. Barcoding offers a new method for analysing genetic diversity and thus monitoring changes in fungal populations *in situ*.

Table 2.4: Conservation status of edible mushroom species and IUCN risk categories

Scientific name	Assessed	Conservation status
Amanita caesarea	Yes	Included in red lists of many European countries but does not meet criteria for inclusion in a threatened category at global scale.
Boletus edulis	Yes	No evidence of decline.
Cantharellus cibarius	Ongoing	Decreasing population trend but proposed for inclusion in the Least Concern category.
Grifola frondosa	Preliminary	Threatened in places but evaluated as of Least Concern globally.
Hericium erinaceus	Yes	Of least concern but vulnerable in places because of habitat loss and decline
Kalaharituber pfeillii	Ongoing	Concerns that harvesting may be unsustainable.
Macrocybe gigantea	Yes	No immediate threats because of its non-specific habitat.
Pleurotus albidus	Yes	Considered Near Threatened because of loss of habitat and habitat "quality".
Pleurotus magnificus	Yes	Considered Endangered.
Pleurotus rickii	Yes	Near Threatened – habitat loss in Brazil and Argentina.
Suillus luteus	Yes	No evidence of decline.
Terfezia arenaria	Ongoing	No clear conclusion as yet.
Terfezia boudieri	Ongoing	No clear conclusion as yet.
Terfezia claveryi	Ongoing	No clear conclusion as yet.
Thelephora ganbajun	Preliminary	Considered Near Threatened. "Harvesting and over-exploitation are a concern."
Tirmania nivea	Ongoing	No clear conclusion as yet.
Tricholoma matsutake	Yes	Red listed globally as Vulnerable.
Tricholoma mesoamericanum	Yes	Classed as Endangered, based on concerns about overexploitation.
Tricholoma portentosum	Ongoing	No clear conclusion as yet.
Tuber indicum	Preliminary	Near Threatened.

Source: IUCN. 2024. *Global Fungal Red List*. [Last accessed 6 February 2025]. https://redlist.info/en/iucn/welcome

Drivers of change

The main threats to edible mushrooms are those shared by all macrofungi. According to an overview by Niskanen *et al.* (2023), the main threats in descending order of frequency are: land-use change; climate change; invasive species; pollution; and direct exploitation. A white paper on policy priorities on non-wood products in Europe (Martinez de Arano *et al.*, 2021) highlights the major threats posed by climate change, uncontrolled or untrained harvesting and land-use changes, and how these apply to edible mushrooms. These are the three main drivers of change reviewed below.

LAND-USE CHANGE AND HABITAT DEGRADATION: Conversion of forests to agricultural land and clearfelling will reduce production of wild edible mushrooms, as will general habitat loss, caused by urbanization for example. No quantitative data are available to estimate the extent to which production has been affected by land-use change, though there is a general consensus that significant reductions have occurred (Sileshi *et al.*, 2023). Specific concerns have been expressed about the impact of clearfelling (Härkonen *et al.*, 2015) and intensive coppicing of miombo trees (Degreef *et al.*, 2020) for charcoal production in eastern and southern Africa, practices that reduce the productive potential of valuable edible mushrooms.

The loss of habitats because of major changes in land use, for example deforestation, is difficult to reverse. Habitat degradation can be moderated by the introduction of improved forest management practices. Evidence for the theoretical benefits of improved practices has been obtained using empirical models to predict the production of wild mushrooms in northern Spain (Bonet *et al.*, 2008; de Miguel *et al.*, 2014). However, putting improved practices into everyday use requires further attention.

Wild animals, for example deer, boar, squirrels and monkeys also eat mushrooms, though their preferences may not match those of humans. When animal populations put increased pressure on the availability of natural food sources, disturbances to habitats may affect the viability of mushroom populations. Wild boars are a known threat because they root and scrape the soil when looking for food (Carpio *et al*., 2022),

Land-use change can enhance edible mushroom production. Planting of *Pinus nigra* forests on land used for agricultural production in Castilla y León, Spain, led to an upsurge in the production of *Lactarius deliciosus*, a prized edible species. The unplanned consequence of choosing *Pinus nigra* created a new business and source of income for local communities (de Roman and Boa, 2006).

Eucalypts are widely planted in Africa for fuelwood (charcoal) and timber. Their introduction from Australia has often been seen in a negative light, despite their acceptance by farmers (FAO, 2009). In Madagascar, eucalypt plantations are a productive source of edible mushrooms (*Russula* and *Cantharellus* spp.), another positive and unplanned consequence of land-use change (Buyck, 2008).

CLIMATE CHANGE: The effects of climate change on mushroom production and diversity are difficult to separate from the influence of other production variables (Tahvanainen, Milna and Kurttila, 2019). A study of Mediterranean forest ecosystems used a modelling approach to estimate the effects of climate change on the distribution and productivity of five important edible species, including *Boletus edulis* and *Lactarius deliciosus* (Morera *et al.*, 2024). The model showed different impacts on the different species and that "optimal productivity areas may be shifted to higher elevations".

A study in Czechia covering the period from 1994 to 2021 compared variation in temperature and rainfall with the quantities of wild mushrooms (mixed species) collected and found that major increases in production were correlated with increased precipitation, much less so with temperature (Procházka *et al.*, 2023). Other studies point towards complex interactions between climate change and wild mushroom production (Tahvanainen *et al.*, 2016).

Another long-term study showed that the timing of mushroom fruiting changed significantly (happened later in the year) over a 66-year period in Norway (Kauserud *et al.*, 2008). The researchers used dated herbarium records to demonstrate that increased temperatures in autumn and winter were

the principal cause. The implications for production are unclear, as there was considerable variation in how species responded, and the study did not attempt to report separate results for edible mushrooms. Growing seasons for early-fruiting mushrooms were truncated.

The broad impacts of climate change are likely to reduce mushroom production, but positive impacts, for example more production because of increased rainfall, may also occur (Procházka *et al.*, 2023).

HARVESTING AND SUSTAINABILITY: There is a vigorous debate on the impact of harvesting intensity and harvesting techniques on the sustainability of production. Arora (2008) puts it succinctly: "The focus on 'overharvest' (of wild edible mushrooms) appears to be an instinctive, almost moral stance rather than one emerging from objective scientific inquiry."

A review by Schunko *et al.* (2022) found that the main drivers of reduced abundance of wild edible plants and mushrooms according to local communities were land-use changes, closely followed by "direct exploitation". There is strong evidence to suggest that overharvesting does not depress future production of edible mushrooms, as shown by a study of miombo woodlands in Burundi and the Democratic Republic of the Congo (Degreef *et al.*, 2020). Luoma *et al* (2006) also showed that the amounts of *Tricholoma matsutake* harvested each year had no effect on future production.

Wild edible mushrooms that belong to the Ascomycota are a possible exception to the conclusions reached by Schunko *et al.* (2022) and other studies cited above. This is because their reproduction depends on two different mating types within the species (heterothallism). Field observations on the production of true truffles (*Tuber* spp.) support possible threats to natural populations (A. Zambonelli, personal observations). Commercial truffle harvesting in Hungary was not permitted during the communist era. When this ended in 1989, commercial harvesting was quick to start, and large-scale extraction of truffles took off. Production significantly declined over the years and has not recovered in areas of intensive harvesting. The suspected reason is a reduction in genetic diversity and permanent loss of different mating types needed to produce new truffles.

Some harvesting techniques do affect future production, particularly those that involve physical disturbance, such as raking of litter layers and soil to uncover the most valuable, unopened specimens of *Tricholoma matsutake* (Luoma *et al.*, 2006). Simply picking mushrooms by hand may do less damage. A landmark long-term study by Swiss researchers (Egli *et al.*, 2006) stated clearly that "mushroom picking does not impair future harvests". The study found no evidence that trampling has a damaging effect of on production.

There has been research on the impact of forest management practices on fungal diversity and production. A broad conclusion is that more intensive practices aimed at maximizing timber production reduce the diversity of mushrooms, including valuable edible species (Tomao *et al*, 2019). Balancing the priorities of competing users of forests, for example by reducing the timber harvest in favour of production of edible mushrooms, is possible but may be challenging to achieve.

Pleurotus tuoliensis on sale in Tajikistan. © Eric Boa.

Conservation measures

Codes of practice aimed at promoting responsible harvesting are widely used by many organizations. The Association of Foragers,[9] which represents individuals mainly from the United Kingdom of Great Britain and Northern Ireland and mainland Europe, has a common code of practice intended to "promote and support responsible foraging". The code covers diverse topics relevant to wild edible mushrooms, from best foraging practices to food safety and the need for accurate identification. Truffle collectors in Italy need to sit an exam to show that they have adequate knowledge of truffles, harvesting practices, rules and regulations, and even truffle-dog management[10] before they can obtain a permit. Some organizations take a sterner approach to conservation measures. The National Trust,[11] a membership-based organization that manages 260 000 ha of land in England, Wales and Northern

[9] https://foragers-association.org
[10] See, for example, https://agricoltura.regione.emilia-romagna.it/tartufi/raccolta, which provides information (in Italian) on truffle permits for Emilia-Romagna, which issued 26 000 permits in 2016, the highest number in Italy for that year.
[11] https://www.nationaltrust.org.uk

Ireland, including wooded areas, has a ban on commercial collecting of mushrooms. Collecting for personal use is permitted.

Encouraging responsible harvesting is only one small element of mushroom conservation. More ambitious efforts in Europe are being led by the Joint Network for Wild Fungi (JoNeF),[12] funded under the European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) programme. JoNeF's main goal is to integrate fungi conservation into European Union legislation on nature conservation. Its first step has been to identify partners that can coordinate efforts and collect essential data to support conservation strategies (Floccia *et al.*, 2024).

General recommendations on how to conserve edible mushrooms are well meant but often offer little guidance on practical implementation. Senn-Irlet *et al.* (2007) published a detailed guide to conservation of macrofungi in Europe that includes chapters on their status, their management and threats affecting them. It contains much useful information but has few details of operational conservation schemes.

The Castilla y León Mycology Programme (Micocyl)[13] is a good example of a pragmatic approach to the collection of wild edible mushrooms. Created by researchers working with local government in Castilla y León, Spain, the programme's website provides information on forests that are regulated (for collecting wild edible fungi) and how to buy permits for recreational and commercial purposes. There are links to mushroom markets and other information about training, mycotourism and the agrifood industry. The challenge for all conservation initiatives that address threats to edible mushrooms is to balance the implementation of conservation measures with sustainable use. Micocyl combines use with conservation and suggests an approach that could have wider applications in other countries.

Mushroom conservation activities outside Europe include the work of the Mushroom Initiative,[14] which operates "ectomycorrhizal reforestation" projects in Thailand, Indonesia and Viet Nam (Mushroom Initiative, 2025). The aim is to plant native trees using seedlings that have been inoculated with specific species of ectomycorrhizal fungi so that farmers can harvest edible mushrooms while caring for the forest. Tree planting in Thailand was completed in 2021, with a reported average survival of saplings of 80 percent. The Indonesia projects planned to establish 100 ha. Few details are available for Viet Nam, and the current status of all the afforestation schemes is unclear.

[12] https://www.impel.eu/en/projects/joint-network-for-wild-fungi-jonef
[13] www.micocyl.es
[14] https://www.ecomushrooms.org/en/history-2/#:~:text=Established%20in%202008%2C%20the%20Mushroom,storage%20and%20restoring%20soil%20biodiversity

Chanterelles on sale on a roadside in Angola. © Hilario Tshitshi Gomes.

Wild-harvested mushrooms on sale in Tallin, Estonia. © Eric Boa.

***Ex situ* conservation**

The majority of wild edible mushrooms are mycorrhizal and have complex growth requirements. In nature they require the presence of a host plant to survive and fruit, and mimicking these conditions artificially is challenging. *In situ* conservation is the ideal approach (Mueller *et al.*, 2022) but is equally challenging. Cultivated edible mushrooms are easier to maintain in culture because they are saprobic, and such species are well represented in culture collections.

The Global Catalogue of Microorganisms,[15] part of the World Data Centre for Microbiology (WDCM), provides information on strains of edible mushrooms held by 154 culture collections in 51 countries. The list (Table 2.5) is dominated by saprobic species, although it also reveals progress in the *ex situ* conservation of mycorrhizal species. *Agaricus bisporus*, one of the most widely consumed edible mushrooms, has fewer strains in culture collections than *Lentinula edodes* (shiitake), a species that is equally widely consumed and is especially popular in China.

The representation of wild edible mushrooms in culture collections worldwide is generally weak – there are only four strains of *Boletus edulis*, a prized species. However, there has been success with some. Culture collections in Japan hold 93 strains of *Tricholoma matsutake*.

As of December 2024, the World Federation of Culture Collections[16] included 141 culture collections registered from 49 countries. It fosters international collaborations and information exchange, and is a useful point of contact for those interested in *ex situ* conservation.

Table 2.5: Strains of edible mushrooms held in culture collections worldwide, including those with notable medicinal properties

Edible species (* indicates those with medicinal properties)	Strains	Saprobic	Global/regional distribution and countries and territories with notable collections (number of strains shown in brackets)
*Agaricus bisporus**	285	Yes	Global – China (75); Taiwan Province of China (39)
Amanita caesaria	3	No	Netherlands (Kingdom of the) (1), Republic of Korea (1), Spain (1)
*Auricularia auricula-judae**	93	Yes	Asia and Europe – China (40)
Boletus aereus	2	No	France (1), Netherlands (Kingdom of the) (1)
Boletus edulis	4	No	Asia and Europe
Calocybe gambosa	5	No	Europe
Cantharellus cibarius	2	No	United States of America (1), China (1)
*Flammulina velutipes**	276	Yes	Global – Netherlands (Kingdom of the) (58), China (72)
Ganoderma lucidum **	221	Yes	Global – Belgium (18), China (81), Taiwan Province of China (30)
*Grifola frondosa**	85	Yes	Global, most in China
*Hericium erinaceum**	117	Yes	Global – China (42)

[15] www.gcm.wdcm.org
[16] https://wfcc.info

Edible species (* indicates those with medicinal properties)	Strains	Saprobic	Global/regional distribution and countries and territories with notable collections (number of strains shown in brackets)
Hypsizygus tessulatus	5	Yes	Europe
Lactarius deliciosa	17	No	Mostly Europe but also Canada
*Lentinula edodes**	614	Yes	Global – China (approximately 270)
Morchella elata	33	?No	Canada (15)
Morchella esculenta	47	?No	Asia and Europe – Taiwan Province of China (11)
Pholiota nameko	43	Yes	Global – China (23)
*Pleurotus eryngii**	186	Yes	Global
*Pleurotus ostreatus**	642	Yes	Global
*Pleurotus pulmonarius**	190	Yes	Global
Sparassis crispa	36	Yes	Mainly Europe
Termitomyces albuminosus	11	Yes	Taiwan Province of China (5)
Tricholoma matsutake	104	No	Japan has almost all (93)
Tuber borchii	2	No	Under-represented; personal collections are maintained by research groups (e.g. University of Bologna, Italy)
*Volvariella volvacea**	55	Yes	Global – China (14)

** *Ganoderma* is not used as a food.
Source: Global Catalogue for Microorganisms. 2024. In: *World Data Centre for Microorganisms*. [Cited 1 August 2024]. https://gcm.wdcm.org

Macrofungi are well-represented in herbaria (or fungaria, the preferred term for fungi collections) and other collections found under the Mycology Collections Portal.[17] These collections predominantly consist of dried specimens used for taxonomic research and studies of fungi diversity, although they have also been used in a study of mushroom fruiting and climate change (Kauserud *et al.*, 2008).

Domestication and breeding

Table 2.5 gives a snapshot of the saprobic edible mushroom species that have been domesticated. Genetic manipulation, which can be done under controlled conditions, either on artificial media or on a suitable substrate, such as straw, is restricted to cultivable species. Information on genetic improvement is often commercially sensitive and not widely available, but there are researchers working in the public domain (e.g. Jyothi and Thara, 2021).

A small number of cultivable strains of edible mushrooms have registered property rights. Registration is a lengthy and expensive process and requires extensive proof that strains are distinct and different. The International Union for the Protection of New Varieties of Plants (UPOV)[18] has

[17] https://www.mycoportal.org/portal/index.php
[18] https://www.upov.int/portal/index.html.en

guidelines for reviewing applications to register strains of the edible fungi *Agaricus bisporus* and *Pleurotus ostreatus.* It appears that none have yet been registered.

Commercial companies continue to prospect for new strains of edible mushrooms. The head of mushroom research at Wageningen University and Research (WUR), a leading centre for cultivated species, said that the Nagoya Protocol and access and benefit-sharing (ABS) principles are followed for all strains held in their collection (Arend Van Peer, personal communication).

There is widespread sharing of strains of known characteristics among commercial growers. Prominent sellers of strains and spawn include Mycelia[19] in Belgium and Sylvan[20] (now owned by a Chinese company) in the Kingdom of the Netherlands. Shandong Qihe Biotechnology Company[21] is one of many companies in China that produce spawn. This company also grows common and exotic species of mushrooms in the United States of America.

Agaricus bisporus production in northern Italy. © Eric Boa.

2.4 Production and trade

FAOSTAT[22] publishes annual data on the global trade in edible mushrooms. It does not distinguish between wild-gathered, semi-cultivated and cultivated production under the broad category of "mushrooms and truffles". UN Comtrade[23] has in recent years started to report trade-flow data for selected groups of the most valuable edible fungi, including the state in which they are exported and imported (fresh or chilled, dried and prepared or preserved). The following categories are covered: *Agaricus; Boletus; Cantharellus*; Shiitake (*Lentinus edodes*); Tricholoma (five species are grouped); Truffles (*Tuber* spp.); and Truffles and mushrooms nec (not elsewhere classified).

The volume and value of trade in cultivated species is considerably higher than that for wild edible species, as illustrated by the selected UN Comtrade data presented in Table 2.6 and Table 2.7. China

[19] https://mycelia.be
[20] https://www.sylvaninc.com
[21] https://www.qihebiotech.com
[22] https://www.fao.org/faostat/en/#home
[23] www.comtrade.un.org

is the world's biggest producer of *Agaricus*, most of which is consumed locally. Poland was the biggest exporter and earner from *Agaricus* exports in 2021–2022, followed by Canada and the Kingdom of the Netherlands.

Table 2.6: Agaricus fresh/chilled export quantity and value, selected countries 2021–2022

Country	Exports (1 000 tonnes) 2021	Exports (1 000 tonnes) 2022	Exports (USD million) 2021	Exports (USD million) 2022
Poland	234	244	470	493
Netherlands (Kingdom of the)	63	52	200	162
Canada	62	65	290	323
China	18	18	27	35
Mexico	11	9	25	29

Source: UN Comtrade 2024. UN Comtrade Database. [Accessed 1 August 2024.] https://comtradeplus.un.org.

Table 2.7: Boletus fresh/chilled exports and value, selected countries 2022–2023

Country	Exports (1 000 tonnes) 2022	Exports (1 000 tonnes) 2023	Exports (USD million)2022	Exports (USD million) 2023
Croatia	585	359	4.7	4.2
Bulgaria	193	56	1.7	1.2
Romania	2660	3059	21.3	24.2

Source: UN Comtrade 2024. UN Comtrade Database. [Accessed 1 August 2024]. https://comtradeplus.un.org.

The economic benefits from wild edible mushroom species are more widely spread than those from cultivated species, and are of crucial importance to rural communities in poorer countries. Supply chains involve large numbers of harvesters and traders active in rural areas, where employment opportunities are few and incomes are low. EDULIS,[24] part of Africa's Best Foods, a private company, is the largest exporter of wild-gathered mushrooms from southern Africa (Eswatini, South Africa, Zambia and Zimbabwe). In 2023, 20 tonnes of chanterelles were harvested. The average harvest of Boletus is 200–250 tonnes each season, and the total value of all wild mushrooms harvested is around USD 5 million. EDULIS hires 1 000 skilled collectors each year (Robi Caseletti, personal communication).

UN Comtrade data on wild edible mushrooms are incomplete. China exported much more than the reported 4 tonnes of fresh/chilled *Boletus* during the 2022–2024 period (CEFA, 2024). Yunnan Province produced 316 000 tonnes of wild edible fungi in 2022, of which *Boletus* was one of the major species (CEFA, 2024). According to UN Comtrade, South Africa exported only 6 tonnes for the same period, much lower than figures reported to the authors (R. Casaletti, personal communication).

A small number of countries monitor the trade in wild edible mushrooms, but there are big gaps (Turtiainen and Nuutinen, 2012) and information can be hard to find. For example, the Korea Forest Promotion Institution,[25] established in 2016 in the Republic of Korea, has extensive data on wild-gathered species, which is not widely known outside the country. A similar situation exists for China, where regular trade data for wild edible fungi are published regularly by the China Edible Fungus Association (e.g. CEFA, 2022).

Lack of awareness of the extent of wild edible mushroom gathering, the numbers of people involved and the sizes and values of harvests hinders attempts to gain the attention and support of national governments. Production data are also of value to researchers analysing, for example, trends in relation to climate change (Procházka *et al.*, 2023) or the contributions made by wild mushrooms to human nutrition (de Roman, Boa and Woodward, 2006).

Truffle buyers are always looking for new sources of supply. *Tuber* spp. are the most valuable edible mushrooms in terms of price paid per unit weight, and Italy is the leading trader. Increasing attention has, however, been paid to truffle exports from elsewhere in the world, including from the Islamic Republic of Iran (Puliga *et al.*, 2021). In 2021 the latter country's customs seized a "record" USD 105 million haul of truffles (16 tonnes) bound for Slovenia, according to a news website (Presstv, 2021). The same news report states that the Islamic Republic of Iran has "banned harvesting and prohibited exports of truffle", though it is unclear if this has been fully implemented. Two years later there were news reports of 240 Syrian (desert) truffle hunters being murdered (e.g. Middle East Eye, 2023).

[24] https://www.edulis.com/about-us
[25] https://www.kofpi.or.kr/eng/main.do

UN Comtrade has made a welcome step forward in documenting the trade in wild edible fungi. The undocumented movement of valuable species still represents a significant volume and value, as suggested by the above-mentioned report of smuggling. In many other countries, a less dramatic reason for under-recording wild-harvested edible mushrooms is that there are poor mechanisms for monitoring sales in local markets and sharing export data.

Wild-harvested mushrooms on sale on a roadside in Romania. © Eric Boa.

Pleurotus growing on straw in Nepal. © Eric Boa.

Wild mushrooms and shiitake on sale in a market in Porto, Portugal. © Eric Boa.

2.5 Institutional frameworks

Research on edible mushrooms is driven by a number of different imperatives. The commercial value of the species attracts research funding, particularly for high-value truffle species. Numerous groups in Italy and the United States of America are investigating the biology and ecology of *Tuber* spp. and how to improve semi-cultivation. The development of the truffle industry in New Zealand was the result of initiatives taken by individual scientists and subsequently supported by an emerging commercial sector (Hall, Brown and Zambonelli, 2007). The truffle industry in Australia is also on the rise, and the country is now the fourth largest producer worldwide (ATIA, 2021).

There are separate research groups that focus on major cultivated species, such as *Agaricus* and *Pleurotus*. The mushroom research group at WUR[26] is a notable example and has close ties with commercial producers in the Kingdom of the Netherlands and around the world. Foreign students who study in Europe are often important focal points for the emergence of new research groups on edible species in their home countries. Mexico has recently established the Centre of Biotechnology of Medicinal, Functional and Edible Mushrooms at the College of Postgraduates in Puebla,[27] an initiative of Dr Daniel Martínez-Carrera (who did his PhD in the United Kingdom).

[26] https://www.wur.nl/en/education-programmes/wageningen-university.htm
[27] https://hongosmedicinalesytusalud-cb-hcfm.com

China is the only country to have a separate Institute of Edible Fungi.[28] There are also several other research groups studying edible species, for example at the Kunming Institute of Botany.[29] China has also supported academic exchanges to promote collaboration on edible mushrooms. Multinational companies such as Sylvan[30] have their own research staff, often with connections to academia (e.g. in the Kingdom of the Netherlands and in China). The increasing focus on medicinal mushrooms is also driving research interest on how to grow new species and do so profitably. Efforts to grow wild species, including *Cantharellus* and *Boletus*, continue to attract the interest of academic researchers but without achieving major breakthroughs.

There are important groups of scientists and other parties interested in growing edible species who meet regularly for international conferences or coalesce through networks supported by projects. The European Union has sponsored a number of such networks through its research programmes, for example one established by the Intact Project,[31] members of which share an interest in the "cultivation, preservation and processing of wild truffles". The European Mycological Institute[32] is a "territorial cooperation" with a small office in Soria, Spain. Activities are funded by partners and their projects or places of work. It has five full institutional members and 12 partners from across Europe, with benefactor partners from Australia Canada, China, Japan and Switzerland

An International Workshop on Edible Ectomycorrhizal Mushrooms began in the 1990s and continues to attract scientists from around the world. The most recent workshop (IWEMM 11)[33] was held in Argentina. The workshop programmes are an important window into current research and stimulate collaborations between researchers as well as allowing students to showcase their work.

Mycological societies facilitate collaborations between field mycologists who collect, eat and document edible species and full-time scientists. Prominent societies, such as the Gruppo Micologico G. Bresadola in Italy,[34] the Puget Sound Mycological Society in the United States of America[35] and the British Mycological Society,[36] play an important role in documenting and monitoring macrofungi and running training courses on different aspects of field mycology. Their members make useful contributions to mapping distributions and promoting conservation efforts.

While the above examples illustrate that coordination of research efforts and collaborations between different interest groups is improving, particularly in Europe, there is considerable scope for similar progress to be made in other countries rich in edible species (Mueller *et al.*, 2022). Collaborations on wild edible mushrooms between Spain and Ethiopia (Dejene, Oria-de-Rueda and Martín-Pinto, 2017), Belgium, Burundi (Buyck 1994) and the Democratic Republic of the Congo (Degreef *et al*., 2020), and Finland, the United Republic of Tanzania and Zambia (Härkönon, Niemelä and Mwasumbi, 2003; Härkönon *et al*., 2015) point to successful templates for future wider collaborations and sharing of knowledge.

Unlike edible insects, there are no international research organizations with particular interests in wild-gathered fungi. The World Agroforestry Centre and the Centre for International Forestry (now combined)[37] have had some involvement in projects looking at the management and conservation of Miombo woodlands. FAO has played an important role in promoting the study of wild-gathered

[28] https://en.saas.sh.cn/researchinstitutes/content_23616#:~:text=It%20was%20the%20first%20institute,senior%20sci%2Dtech%20professional%20qualification.
[29] http://english.kib.cas.cn/
[30] https://www.sylvaninc.com
[31] https://intactproject.eu (see Table 2.8).
[32] https://eumi.eu
[33] https://www.ciefap.gob.ar/index.php/en
[34] https://www2.muse.it/bresadola
[35] https://www.psms.org
[36] https://www.britmycolsoc.org.uk
[37] https://www.cifor-icraf.org

edible mushrooms under the banner of NWFPs (e.g. Muir *et al.*, 2020; FAO, 2019b). FAO is the international focal point for research on key social and economic aspects of wild-gathered species.

The European Union is a strong supporter of projects and networks concerned with edible mushrooms. These projects and networks are often part of work on a bigger topic, such as NWFPs, and are funded through various channels (Table 2.8). Their publications and other outputs are a rich source of information, some of which is cited in this study.

Table 2.8: Examples of European Union projects and networks relevant to edible mushrooms

Title	Funding and website	Period and aim
INCREDIBLE Innovation Networks for Cork, Resins and Edibles	EU Horizon programme https://www.incredibleforest.net/content/project-0	2017 – 2021 Foster innovation in science and exchange. Has a large repository of open-access publications on "mushrooms and truffles".
INTACT Innovation in truffle cultivation, preservation, processing and wild truffle resources management	EU Horizon program (Marie Curie) https://intactproject.eu	2022 – 2025 Create a multilateral network of research and innovation staff active in the sustainable use of both wild and farmed truffles.
STARTREE Multipurpose trees and non-wood forest products	EU Specific Programme "Cooperation": Food, agriculture and biotechnology https://star-tree.eu/	2012 – 2016 Support forest owners, resource managers, enterprises, decision-makers, other public and private entities in optimizing the management of multipurpose trees and developing innovative approaches for increasing the marketability and profitability of NWFPs
JONEF Joint Network for Wild Fungi	EU Network for the Implementation and Enforcement of Environmental Law https://www.star-tree.eu/index.html	First phase ran from 2023 to 2024
European non-wood forest products (NWFPs) network	EU Cost Action FP1203 https://nwfps.eu	2013 – 2017 Included 29 COST countries (EU) and 10 non-COST institutions. One of the four working groups addressed mushrooms and truffles.

Sources: Websites of the respective projects.

Truffle hunting in northern Italy. © Eric Boa.

2.6 Regulatory frameworks

Food safety

The major food-safety concern for edible mushrooms is possible confusion with lookalike, toxic species. Some countries operate informal services for mushroom identification. Pharmacists in France receive formal training (Bourdon, Ekeland and Brion, 2008), for example. In Norway, the Norwegian Association for Mycology and Foraging has an app, "Sopp kontroll"[38] (mushroom control), that helps with the identification of species and provides information on places (run by knowledgeable volunteers) where people can go in person for advice. Regulations on what can be sold to the public in Europe were reviewed by Peintner *et al.* (2013). The review lists countries in Europe that publish guidelines on the commercialization of species and on which can be eaten. How the guidelines are enforced is unclear.

The Nordic Council, representing Denmark, Finland, Iceland, Norway, Sweden, the Faroe Islands, Greenland and Åaland, has published a comprehensive list of wild edible mushrooms "suitable for commercialisation" (Nordic Council of Ministers, 2012). Codex Alimentarius[39] has little to say on the matter of poisonous mushrooms and focuses on issues of product quality and contamination that are common to other foodstuffs.

Opinions differ on which species can be eaten (Rubel and Arora, 2008), creating uncertainty about what is safe. Li *et al.* (2021) have proposed a classification scheme for determining the edibility of mushroom species based on published (case) reports and resolving conflicting accounts.

Food-safety authorities carry out regular testing of edible mushroom species that are sold, and there are standards set for acceptable amounts of heavy metals and other chemicals that can taint produce. The European Food Safety Agency[40] publishes the results of tests, with one recent example

[38] www.soppkontroll.no

[39] https://www.fao.org/fao-who-codexalimentarius/en/ (search for mushrooms and truffles – updated 2022)

[40] https://www.efsa.europa.eu/en

concerning pesticide residues from straw used as a substrate for cultivating oyster mushrooms (EFSA, 2024).

Food-safety regulations and national bodies that are responsible for regulating them are more active in richer countries. The Food and Drug Administration (FDA)[41] in the United States of America, for example, publishes regular reports of contamination of cultivated edible mushrooms and occasional reports of reactions to toxic wild-gathered species. The Chinese Centre for Disease Control and Prevention [42] also publishes annual reports of mushroom poisoning.

Collecting wild mushrooms

There is considerable variation in how different authorities run permit schemes and regulate the activities of collectors. The depth of information available from different continents varies, and much of the focus is on Europe. Sitta and Davoli (2012) provide a helpful of review of international markets and regulations. More recent reviews (in Europe) have been undertaken as part of work on NWFPs (Bonet *et al.*, 2020; Martinez de Arano *et al.*, 2021). The approach to regulation of wild collections and licensing of commercial collectors in countries such as Canada, Mexico and the United States of America varies hugely. The issuing of permits in the Pacific Northwest of the United States of America has been described as "a jungle" (Winkler, 2022). Regulations applying to the collection of matsutake, a valuable commercial edible mushroom, differ from those for other species, and regulations vary by national forest. Williamette National Forest in Oregon requires that "at least one-third of the mushroom caps of any species on the collection area should be left intact" (USDA, 2024).

Harvesting regulations in the edible mushroom-rich provinces of southwest China appear to be largely under the control of local communities. Some regulate access to collecting areas and hold auctions for permits (Peter Mortimer, personal communication). It is unclear how these schemes work or how effective they are in balancing use and conservation. The viability of introducing payments for harvesting wild edible mushrooms in Spain was reviewed by Prokofieva *et al*. (2016). A survey of mushroom pickers indicated that they supported the idea, though the success of such a scheme also needs forest owners to accept reduced income from harvesting timber.

The effectiveness of regulating collections is difficult to assess, and the current study has been unable to find reliable evidence of their effectiveness. Even so, the general observation, based on available information, is that local control of harvesting is more successful (and flexible) than legislation introduced and monitored by local or national governments. Forests that are privately owned have a vested interest in regulating harvests, balancing forest management needs with additional income from issuing permits. EDULIS (see above) negotiates contracts with private owners for the collection of *Boletus* from pine plantations in southern Africa. Commercial collection of *Cantharellus* and other valuable edible species from Miombo woodlands, an area that extends from Angola to Mozambique, is not, to the best of the authors' knowledge, regulated.

FAO and the European Forest Institute have published policy priorities for NWFPs and a summary of the challenges that face national and local authorities in regulating wild collections (Martinez de Arano *et al.*, 2021). The report gives examples of how truffle pickers have worked with landowners to develop a system of contracts and permits that rewards both parties. It is less clear how the wider challenges and risks to sustainable use might be mitigated and managed through the introduction of regulations for other wild mushrooms and in countries with weak local and national authorities.

The INCREDIBLE project (see Table 2.8) published details of approaches to harvesting in different places, for example in Castilla y León, Spain (Incredible Project, 2020). There is a long history of formulating and implementing regulations on truffle harvesting in Italy (Diritto Vitivinicolo, 2022). A new, comprehensive law on the truffle supply chain was first proposed in 2019, and is under

[41] https://www.fda.gov
[42] https://en.chinacdc.cn

discussion by the Italian parliament at the time of writing. Truffle harvesting attracts particular attention because of its income-earning potential and extensive, often dominant, commercial interests.

Italy has also attempted to improve the effectiveness of the regulation of wild-harvested mushrooms in general. Collectors are exempt from value added tax up to EUR 7 000 in a year and pay a flat annual tax of EUR 100. There is a reduced tax rate on profits in an attempt to support and control wild collections in a more transparent manner.

Regulatory guidelines for wild-harvested mushrooms published by the Association of Food and Drug Officials in the United States of America (AFDO, 2021) emphasise food safety, and advise wild harvesters on how to obtain licences (Martinez de Arano *et al.*, 2021).

Regulatory frameworks for wild mushrooms are varied and often confusing to interpret for harvesters and traders. Further review is needed of how well existing regulations work and of the degree to which local communities, as opposed to national authorities, set rules and manage wild harvests. The Italian method of legislating nationally and allowing regions to adapt rules locally appears to be a good way forward.

3. EDIBLE INVERTEBRATES

3.1 Introduction

Edible terrestrial invertebrates[43] are a diverse group of animals eaten by people and livestock around the world. Well over 2 000 species are edible to humans, although many are only eaten on a small scale (Omuse *et al.*, 2024). Eating terrestrial invertebrates is especially widespread in the tropics, but there is growing interest in Europe and North America.

Edible invertebrate species tend to be the larger insects and snails; they are often gregarious and live or move in groups rather than being solitary (Dufour and Sander, 2000). Since 2000, a few species of insects and snails have been farmed by smallholders, from Cameroon (giant African snails) to the United States of America (mostly crickets) to Thailand (crickets, silkworm pupae and others). Industrial-scale production of insects as feed is now developing rapidly, with a handful of promising species being raised – black soldier flies (*Hermetia illucens*), house crickets (*Acheta domesticus*), yellow mealworms (*Tenebrio molitor*), lesser mealworms (*Alphitobius diaperinus*) and house flies (*Musca domestica*) (van Huis, 2022a) –in North America, Asia and Europe, and on a smaller scale in East Africa and South America (Table 3.3).

About 2012, emphasis shifted from harvesting invertebrates as food in the tropics to rearing insects (and snails) as food and feed around the world. Crickets are used as human food, while the black soldier fly is the main species devoted to animal feed. Mealworms are used for both human food and animal feed. The species farmed are chosen according to the ease of automating their production, their acceptance of cheap substrates (insect feed), the ease with which they can be protected from diseases and their market potential (van Huis, 2022a).

3.2 An overview of edible terrestrial invertebrates

This section covers invertebrates that are 1) wild-harvested as food for humans, 2) farmed as food for humans, 3) wild-harvested as animal feed, and 4) farmed as animal feed.

Gathering wild invertebrates as food for humans

Harvesting of wild invertebrates is usually seasonal and local. Some species are staple foods, but many are delicacies or used to make spices (Franklin *et al.*, 2022; Gadzama and Ndudim, 2022; FAO, 2021). Jongema (2017) documented 2 111 edible insect and spider species (Table 3.1). A later study listed 2 205 insect species, eaten in 128 countries (Omuse *et al.*, 2024).

[43] As noted in the general introduction, the focus of this study is on edible terrestrial rather than aquatic invertebrates, although edible aquatic insects are mentioned.

Table 3.1: Edible insects and spiders

Order	Common names	Recorded edible species
Araneae	Spiders	15
Blattodea	Termites	59
Blattodea	Cockroaches	37
Coleoptera	Beetles, grubs	659
Dermaptera	Earwigs	1
Diptera	Flies	37
Ephemeroptera	Mayflies	10
Hemiptera	True bugs, cicadas	237
Hymenoptera	Ants, bees, wasps, sawflies*	321
Lepidoptera	Caterpillars, moths, butterflies	362
Megaloptera	Dobsonflies	4
Odonata	Dragonflies, damselflies**	61
Orthoptera	Grasshoppers, locusts, crickets	278
Phasmatodea	Stick insects	7
Phthiraptera	Lice	3
Plecoptera	Stoneflies, salmonflies	9
Psocoptera	Barklice	1
Trichoptera	Caddisflies	10
Total		2 111

Source: Adapted from Jongema Y. 2017. *List of edible insects of the world*. Wageningen, Netherlands, Wageningen University and Research. https://www.wur.nl/en/research-results/chair-groups/plant-sciences/laboratory-of-entomology/edible-insects/worldwide-species-list.htm
*Jongema (2017) does not mention sawflies, but one species is reported to be eaten (as larvae in willow galls), in some Inuit communities (Ferreira *et al*., 2018). **Jongema (2017) does not mention damselflies, but eight species are reported to be eaten (Siddiqui *et al.*, 2024).

Some of the world's most popular insect foods are caterpillars (including mopane worms: *Gonimbrasia belina*), locusts (Egonyu *et al.*, 2021), palm grubs (also called palm weevils, *Rhynchophorus* spp.) and stink bugs (Pentitomidae) (Dufour and Sander 2000; van Huis *et al.*, 2013). All are relatively large and can be gathered in large amounts. Insects are often eaten in immature stages, as larvae, but occasionally as pupae. Immature insects tend to be soft and rich in protein and fat (Dufour and Sander, 2000). The fat content increases as larvae grow older (Downer and Matthews, 1976). Adult wings, legs and exoskeletons are made of chitin, which humans cannot digest (Tang *et al.*, 2019; Egonyu *et al.*, 2021). Insects are more commonly eaten in the tropics, in part because of the greater biodiversity of the tropics (Lesnik, 2019).

Some groups of invertebrates are currently reported to be eaten in volumes that may be significant to human nutrition, food security, livelihoods or trade on a large scale (Table 3.2). An FAO study on

terrestrial animal source foods (TASF) (FAO, 2023) treats invertebrates as one of the five TASF groups (along with eggs, dairy, meat and "food from hunting and wildlife farming"). It notes that insects are high in iron, zinc, vitamin E, protein and healthy fats but that research is needed on the nutrient bioavailability and composition of insects and insect products.

Table 3.2*:* Major groups of invertebrates eaten by contemporary humans

Edible invertebrate	Region	Notes on use
Palm grub (*Rhynchophorus* spp.)	Amazon Basin, Central Africa, Southeast Asia	Collected wild, also semi-cultivated by leaving palm trunks in the forest (Franklin *et al.*, 2022; Krongdang *et al.*, 2023; Roos, 2018).
Locusts: ten species (migratory, desert, red, brown, Sahelian, Bombay, Australian plague, Italian, Siberian and South American) of *Schistocerca*, *Locusta* and related genera	Mainly East Africa through Southwest Asia, but have been used as feed or food in 65 countries	Governments often respond to outbreaks with mass insecticide applications (Egonyu *et al.*, 2021; FAO, 2021, 2024).
Chapulín or Mexican grasshopper (*Sphenarium purpurascens*)	Central and southern Mexico	Sold commercially in Mexico and as a nostalgia food in parts of the United States of America. Many more could be harvested (Hernández-Rodríguez *et al.*, 2022; Piña-Domínguez *et al.*, 2022; van Huis and Oonincx, 2017).
Escamoles (immature stages of ants – *Liometopum apiculatum*)	Central Mexico	Once sustainably harvested by native people, now threatened by commercial harvesting by outsiders (Ramos-Elorduy, 2006).
House cricket (*Acheta domesticus*), field cricket or two-spotted cricket (*Gryllus bimaculatus*), oriental ground cricket (*Teleogryllus testaceus*)	Especially in Southeast Asia, but increasing elsewhere	Reared in Thailand and other countries, including (more recently) in large facilities (e.g. in Europe and North America) and by smallholders in Africa (Hanboonsong and Durst, 2020; van Huis and Oonincx, 2017; Nalunga, 2023).
Pupae of the silkworm, (*Bombyx mori*)	East Asia, especially China	They are often eaten immediately after unravelling the silk (Dufour and Sander, 2000).
Mopane caterpillar (*Gonimbrasia belina*)	Southern Africa	Threatened by unsustainable harvesting, such as cutting down trees to collect the worms (van Huis and Oonincx, 2017).
Miombo woodland caterpillars (about 30 species, especially Saturniidae)	Southern Africa	Widely harvested, starting to be sold commercially. Threatened by habitat loss (Kenis *et al.*, 2006).

Edible invertebrate	Region	Notes on use
African caterpillars (*Cirina forda*, *Aframomum alboviolaceum*, among many other species)	West, East and Southern Africa	Threatened by overharvesting and habitat loss. Some efforts to improve management with education (Latham, 2015; Latham *et al.*, 2024).
Edible stink bug (*Encosternum delegorguei*)	Southern Africa	Some conservation efforts in South Africa, especially via community outreach (Dzerefos, 2018).
Grasshoppers (*Ruspolia differens*, *Melanoplus bivittatus*, and at least 60 other species)	Sub-Saharan Africa (and rice grasshoppers in Asia)	Collected and sold locally. These crop pests could be harvested in larger numbers (van Huis and Oonincx, 2017; Leonard, 2021; Gadzama and Ndudim, 2022)
Witchetty or witjuti grubs (larvae of several moth species, e.g. *Endoxyla leucomochla*)	Australia	Threatened by overharvesting for tourist restaurants (Yen, 2009; Dufour and Sander, 2000).
Bardi grubs, larvae of woodboring beetles (Cerambycidae)	Australia	Same as above.
Honey-pot ants (*Camponotus inflatus*)	Australia	Threatened by overharvesting for tourist restaurants (Yen, 2009).
Yellow mealworm (*Tenebrio molitor*). Lesser mealworm (*Alphitobius diaperinus*)	Widespread	Now produced on a large scale for food and feed (van Huis, 2022a).
Brown garden snail (*Cornu aspersum*)	Europe	Threatened in western Europe by overharvesting. Subject to regulations to limit collection. Now farmed (Rygało-Galewska, Zglińska and Niemiec, 2022; Gheoca, 2013).
Roman snail (*Helix pomatia*)	Europe	Same as above, but reproduces more slowly than the brown garden snail, so there is less interest in farming it (Rygało-Galewska, Zglińska and Niemiec, 2022)
Giant African snail (*Achatina* [*Lissachatina*] *fulica*, *A. achatina*, *A. marginata*)	Sub-Saharan Africa	Is now a cosmopolitan pest, but wild populations in Africa are declining because of overharvesting. Starting to be farmed on a small scale in parts of Africa (Silva *et al.*, 2022; Cobbinah, Vink and Onwuka, 2008).

Sources: See references within the table.

BEETLES AND GRUBS (ORDER: COLEOPTERA). Palm grubs or palm weevils (e.g. genus *Rhynchophorus*, family Dryophthoridae) are eaten by native peoples in the Amazon rainforest. *Rhynchophorus*, and other genera are widely eaten in Angola, Cameroon and other parts of Africa, where they are sometimes semi-cultivated by leaving palm trunks in the forest, where the beetles can oviposit. The grubs can be eaten stewed, fried or grilled. Sago palm grubs (*R. bilineatus*) are eaten in feasts of hundreds of pounds of larvae, including some larvae and adults of other beetle species

(Dufour and Sander, 2000). At least 24 species in six families of adult beetles and grubs are eaten in Southeast Asia, including the palm grub *Rhynchophorus*, and dung beetles (family Scarabaeidae) (Dufour and Sander, 2000).

Cockchafer grubs were eaten in mountains of Europe until the 1800s, and during the Irish famine of 1688 (Dufour and Sander, 2000). Grubs of the European stag beetle (*Lucanus cervus*) were eaten in ancient Greece and Rome (Dufour and Sander, 2000). The bardi grub (larva of a Cerambycid woodboring beetle) is eaten by Australian aboriginals, and is on the menu in some Australian restaurants (Dufour and Sander, 2000).

Jongema (2017) lists 659 species of edible grub and beetle species, making them the insect order with the largest number of edible species.

Caterpillars, moths and butterflies (Order: Lepidoptera). Pandora moth larvae were collected by Native Americans in the western United States of America (Dufour and Sander, 2000). Five species of caterpillar are eaten by native peoples in the Amazon rainforest (Dufour, 1987, cited in Dufour and Sander, 2000).

Mopane worms are one of various caterpillars eaten in many African countries. Favourite species are those that occur in large aggregations, making them easy to collect (Dufour and Sander 2000). Maize porridge can be fortified with mopane worm powder, known for its high protein content. A study that gave 20 kg children a 50 g portion of fortified porridge found that protein uptake was 130 percent higher than from a non-fortified control porridge and that iron and zinc uptakes were also higher (Ledbetter *et al.*, 2024). The main host for the mopane caterpillar is the mopane tree (*Colophospermum mopane*). In Africa, edible caterpillars are often named for their host tree (Latham *et al.*, 2024). Caterpillars are collected from the trees mostly by women and children, who gut them, boil them in salt water and dry them to eat or to sell (van Huis *et al.*, 2013). Of 133 edible caterpillars and chrysalises in Africa, about 60 are commonly eaten in at least one location (Latham *et al.*, 2024).

Pupae of the silkworm, *Bombyx mori*, are eaten in China, the Democratic People's Republic of Korea, and the Republic of Korea, and are exported from the latter country to the United States of America. They are often eaten immediately after unravelling the silk (Dufour and Sander, 2000). Bundles of caterpillars infected with the fungus *Cordyceps* (and tied together with the fungus) were sold as a delicacy in East Asia (Dufour and Sander, 2000). The pupae of various wild silkworms are also eaten in Africa, usually after the silk is harvested, including *Anaphe reticulata* in Nigeria, *A. venata* in West Africa, *Borocera cajani* in Madagascar, and *Gonometa postica* in Namibia, Botswana, Kenya and South Africa (Latham *et al*., 2024).

Many Australian Aboriginal groups have eaten witchetty grubs: the larvae of several species, including *Xyleutes leuchomochla*, a Cossid moth, and caterpillars of the giant ghost moth (family Hepialidae). The witchetty grub is now offered in Australian restaurants (Dufour and Sander, 2000). Adults of the moths *Agrotis infusa* were collected in vast numbers in the Bugong Mountains of New South Wales, Australia, until the 1890s (Dufour and Sander, 2000). Caterpillars and moths are the second largest group of edible insects, with 362 edible species (Jongema, 2017).

ANTS, BEES AND WASPS (ORDER: HYMENOPTERA). Leafcutter ants, virgin queens of the genus *Atta*, are collected as they swarm out of their nests on their nuptial flights early in the rainy season. They are eaten in northeastern Colombia and by native peoples throughout the Amazon Basin (Dufour and Sander, 2000).

Bakuti is a dish made in Nepal of the larvae and pupae of giant honey bees cooked like scrambled eggs (Dufour and Sander, 2000). Thailand exports frozen, steamed ant larvae and pupae to the United States of America as a speciality food (Brickey and Gorham, 1989, cited in Dufour and Sander, 2000). Bee larvae are steamed, still in the honeycombs, in North Thailand (Dufour and Sander, 2000). Some Honduran campesinos who collect honey in the wild also eat bee brood raw, in the comb (J. Bentley,

personal observation). Weaver ants (*Oecophylla smaragdina*) were used to make a condiment and a drink in South and Southeast Asia (Dufour and Sander, 2000).

Some workers of the black honey ant (*Camponotus inflatus*) have enlarged bodies the size of grapes and are a favourite of Australian Aboriginals. The 321 species of edible ants, bees and wasps make Hymenoptera the third largest group of edible insects (Jongema, 2017).

MAGGOTS AND FLIES (ORDER: DIPTERA). *Ephydra hians*, the alkali fly or shore fly, was eaten by Native Americans in the Great Basin, especially at Mono Lake (Dufour and Sander, 2000). Jongema (2017) ranks flies as the eighth largest group of edible insects, with 37 edible species, tied with cockroaches.

GRASSHOPPERS, LOCUSTS, CRICKETS, MANTIDS AND STICK INSECTS (ORDER: ORTHOPTERA). The Mormon cricket (*Anabrus simplex*, Orthoptera: Tettigoniidae), which is actually a katydid not a true cricket, was collected by Native Americans in Utah (Dufour and Sander, 2000). Native Americans around the Great Salt Lake, in Utah, have eaten grasshoppers (*Melanoplus sanguinipes*) for at least 5 000 years. During the summer, salted and sun-dried grasshoppers washed up on beaches and formed windrows up to 20 cm deep, 1.5 metres wide and 15 kilometres long. This was a dense nutrition source, providing 3 010 kcal/kg. Experiments by archaeologists suggest that ancient harvesters may have achieved harvest rates of 272 649 kcal/hour (Madsen and Kirkman, 1988; Madsen, 1989). Contemporary Native American chefs are now introducing grasshoppers into fashionable restaurants in Salt Lake City (Weist, 2023).

Grasshoppers on sale in Cambodia. © Eric Boa.

The gregarious *nsenene* katydid (*Ruspolia differens*) is eaten in southern Africa. In the United Republic of Tanzania, *nsenene* are collected early in the morning, wherever they light, often in banana groves, and are eaten or sold locally (van Huis *et al.*, 2013).

The desert locust (*Schistocerca gregaria*) belongs to the family Acrididae of short-horned grasshoppers. It is widely eaten across Africa. It was eaten in the Middle East into the twentieth century, where it was cooked in salt water and then sun dried. Three tribes in Assam, India eat a "surprising number of locusts" on a mass scale (Dufour and Sander, 2000). Locusts are also eaten in New Guinea and in East Asia, especially those belonging to the genera *Oxya* and *Locusta* (Dufour and Sander, 2000). The desert locust is a serious international transboundary pest in much of Africa, the Near East and Southwest Asia. Populations are monitored by several countries in collaboration with FAO's Desert Locust Information Service (DLIS) (FAO, 2024). Locusts were, however, once considered a dish fit for a king. King Ashurnasirpal II (who ruled the Neo-Assyrian Empire from 883 to 859 BCE) provided his guests with meat and 10 000 locusts washed down with beer and wine (Frankopan, 2023). Grasshoppers were eaten in ancient Greece and in China, where they were fried in sesame oil (Dufour and Sander, 2000). Stick insects and mantids are widely eaten in New Guinea (Dufour and Sander, 2000).

This group of insects has 278 species documented as edible, making them the fourth largest group recorded by Jongema (2017).

TRUE BUGS AND CICADAS (ORDER: HEMIPTERA). Adults and eggs of four species of true bug (*Krizousacoriza* spp. and *Corisella* spp.) were eaten in central Mexico into the twentieth century (Dufour and Sander, 2000). Cicadas (superfamily Cicadoidea) were eaten in ancient Greece (Dufour and Sander, 2000). The giant water bug (*Lethocerus indicus*) is eaten in Southeast Asia and China (Dufour and Sander, 2000). Jongema (2017) ranks true bugs as the fifth largest group of edible insects, with 237 edible species.

DRAGONFLIES (ORDER ODONATA). Dragonflies (and termites) are collected in Thailand by setting lighted candles in dishes of water (Dufour and Sander, 2000). Jongema (2017) ranks dragonflies as the sixth largest group of edible insects, with 61 edible species.

TERMITES AND COCKROACHES (ORDER: BLATTODEA). Termites are widely eaten in Africa, especially during the early rainy season, when the young, winged, reproductive adults swarm out of their nests and can be easily collected and eaten raw or fried. Termites are also widely eaten in New Guinea (Dufour and Sander, 2000). Termites are the seventh largest group of edible insects (59 edible species) according to Jongema (2017).

OTHER EDIBLE, WILD-HARVESTED TERRESTRIAL INVERTEBRATES. These include arachnids, myriapods, molluscs, woodlice and earthworms. Snails (molluscs) are the most commonly eaten invertebrates besides insects. Edible land snails in the circum-Mediterranean include *Theba pisana, Eobania vermiculata, Otala lactea, Otala punctata, Helix pomatia, H. aspersa, H. lucorum* (Gheoca, 2013). The giant African snail (*Achatina, Lissachatina fulica,* and *Archachatina marginata*) is popular in West Africa (Cobbinah, Vink and Onwuka, 2008). Edible earthworms include *Dendrobaena veneta, Eisenia andrei, Eisenia fetida* (all temperate) and *Eudrilus eugeniae* and *Perionyx excavatus* (both tropical) (see Sonntag *et al.*, 2023).

In Europe and the Mediterranean, the land snail has been eaten at least since Ancient Roman times – and was eaten throughout the Middle Ages (Cattaneo-Vietti, Doneddu and Trainito, 2016). Snail eating then fell out of fashion in Europe and was not popular again until the early twentieth century, when escargot became haute cuisine in France, Spain and Greece (Rygało-Galewska, Zglińska and Niemiec, 2022). In West and Central Africa, land snails are collected from the wild during the rainy season, providing a source of livelihood for some people (Pissia, Matsakidou and Kiosseoglou, 2021).

The reluctance to eat terrestrial invertebrates is cultural and learned. Aversion to edible invertebrates, especially insects, is more common in Europe and North America (Lesnik, 2019). Recently, food manufacturers have sought to overcome this aversion by incorporating powdered crickets into tortilla chips, cookies and other baked goods.

A grasshopper collection site in Uganda. © Eric Boa.

Farmed invertebrates as food for humans

Cultivating insects for human food is becoming more common. Smallholders in Southeast Asia and sub-Saharan Africa rear some insects commercially, especially crickets (Nalunga, 2023). The two-spotted, native (or field) cricket (*Gryllus bimaculatus*) and the house cricket (*Acheta domesticus*) are cultivated in Southeast Asia (van Huis *et al.*, 2013) and (beginning more recently) in the United States of America. The FAO report *Edible insects* (van Huis *et al.*, 2013) sparked much interest among the general public. For example, Chirps, a company in the United States of America, now sells products online, including cookies and tortilla chips, made with cricket powder (Chirps, 2024). This and similar efforts are helping to overcome Western aversions to eating insects (Perreault, Haddad and Doyen, 2022). There are also companies in Europe that produce insects for human food, including Eurocrickets[44] (Lithuania), Crickets Online[45] (Finland) and Portugal Bugs.

In just two decades, Thailand has emerged as a major producer, and now holds 12 percent of the global market share for edible insects (Krongdang *et al.*, 2023). More than 20 000 insect farms are registered in Thailand. Most are small, household operations, 80 percent operated by women (Krongdang *et al.*, 2023). The most commonly farmed insects are the two-spotted cricket, house cricket, ground cricket (*Teleogryllus mitratus*), red palm weevil (*Rhynchophorus ferrugineus*) and silkworm pupae (*Bombyx mori*) (Krongdang *et al*., 2023). In Europe and North America, mealworms and crickets are now being reared for food (and for animal feed). The technology is developing

[44] https://eurocrickets.com/home
[45] https://www.cricketsonline.fi

quickly to improve automation, lower the cost and improve the quality of substrates (van Huis, 2022a; 2022b).

Snails are being reared for sale in Europe and in Africa, often in small facilities. The brown garden snail (*Cornu aspersum*) and the Roman snail (*Helix pomatia*) are both collected from the wild in Europe, and snail rearing (particularly of the former species) is expanding in the region. Brown garden snails awake from hibernation in February or March, and are sold at the end of September, with a small part of the herd being kept for reproduction. Roman snails reach maturity after 12 to 14 months, or up to four years in the wild. Their slow growth contributes to lower profitability, and so they tend to be wild collected rather than farm reared (Rygało-Galewska, Zglińska and Niemiec, 2022).

Because of the scarcity of snails in West Africa, various non-governmental organizations (NGOs) now encourage smallholders to keep penned snails to eat and sell (Amedd, Mobiom, Nawaya and Songhaï Centre, 2017; Cobbinah, Vink and Onwuka, 2008). In Nigeria, Cameroon and Ghana, giant African snails are starting to be reared by young, literate suburban women (Mvodo Meyo *et al.*, 2021). A 2018 survey of 60 urban and peri-urban snail farmers in Cameroon found that none had farmed snails for more than seven years but that they were rapidly increasing their production. Over half of the farmers produced between 600 kg and 1 000 kg of meat per month to eat or to sell on local and international markets (Mvodo Meyo *et al.*, 2021). Production costs were only USD 0.40 per kg, which produced a fivefold return on investment and a profit of USD 2 per kg of snail sold (Mvodo Meyo *et al.*, 2021).

Gathering invertebrates from the wild as animal feed

Various invertebrates, including grasshoppers, crickets, cockroaches, termites, lice, stink bugs, cicadas, aphids, scale insects, psyllids, beetles, caterpillars, flies, fleas, bees, wasps and ants, have traditionally been used to feed poultry in several countries (van Huis *et al.*, 2013). In Honduras, farmers collect the nests of arboreal termites (*Nasutitermes* spp.), which are easily broken off from trees and brought back to the farmstead, where chickens eat the escaping termites (Bentley, personal observation). Termites are also fed to poultry in Ghana (Boafo *et al.*, 2019). In Uganda, some farmers feed termites and earthworms to fish. In Southeast Asia farmers hang electric lights over ponds to attract flying insects, which fall into the water and are eaten by fish (van Huis *et al.*, 2013). Pigs (*Sus scrofa*) are highly omnivorous and (if they are not penned) will root invertebrates, including insects, earthworms, myriapods, crustaceans, gastropods, nematodes and spiders (Ditchkoff and Mayer, 2009). In general, however, there is only modest traditional use of wild-harvested invertebrates as livestock feed.

Farmed invertebrates as animal feed

A few species of insects are now being mass produced around the world in large facilities (van Huis, 2022a, 2022b). The invertebrate feed industry is new but is growing quickly. It is highly mechanized, and the insects are usually reared indoors, especially in temperate countries. The feed industry benefits from experience gained from raising live insects as pet food and fishing bait (Wade and Hoelle, 2020; FAO, 2021). Entrepreneurs often express an interest in producing insects because of their lower environmental impact than conventional meat animals (Ashour, 2022). Table 3.3 shows the main species mass reared for feed.

The rising price of fishmeal (and concerns about soybean imports at the cost of deforestation in South America) are stimulating insect production as an alternative source of feed for many kinds of farmed animals, including poultry (Dörper *et al.*, 2022), fish (Pechal *et al.*, 2022), shrimp (Guidou *et al.*, 2022) and Chinese soft-shelled turtles (Lusheng *et al.*, 2022). The black soldier fly is the main species cultivated, mainly because production is easy to automate using cheap substrates (van Huis, 2022b). Other species used for animal feed include termites, house flies and mealworms. Black soldier fly larvae can convert a wide range of organic waste into animal feed, but this refuse may be contaminated with pathogens, including some that are resistant to antibiotics, which is a safety

concern. However, black soldier flies have antimicrobial properties (Moyet *et al.*, 2022). Li, Zhang and Cai, 2022) found that the intestinal microbes in black soldier fly larvae were able to degrade 90 percent of the antibiotic penicillin G present in the manure on which the insects were reared.

Table 3.3: Major insect species cultivated for livestock feed

Names	Genetic strains
Black soldier fly, *Hermetia illucens*	At least 16 wild and captive clusters. Wild strains are native to the Americas, including indigenous genetic hot spots in central South America. Unique population structures have been established on all non-native continents, but most captive strains are derived from a single laboratory population from North America (Kaya *et al.*, 2021). Remarkable trait variation has been documented among different strains (Sandrock *et al.*, 2022). Titan® is a new strain recently bred in Israel (Alyagor, 2023). Other strains include Texas, Guangzhou (China) and Wuhan (China) (Zhou *et al*., 2013).
Yellow mealworm, larva of the beetle *Tenebrio molitor*	At least six captive strains from Greece, Italy, Spain, Türkiye and the United States of America (Adamaki-Sotiraki, Rumbos and Athanassion, 2022). However, genetic analyses suggest that most captive populations are closely related worldwide and are strongly diverged from wild populations (Eleftheriou *et al*., 2022).
House fly, *Musca domestica*	Genetic structure of house fly populations in the Old World is largely characterized by geographic distance (Bahrndorff *et al*., 2020). New World populations reflect massive translocations (Kafsur *et al*., 2005). Distinct geographic strains of house flies, including wild Spanish, Dutch and Italian populations, have been found to show important differences in lipid content (Boatta *et al.*, 2023).
House cricket, *Acheta domesticus*	The natural population structure of the house cricket remains unknown. Captive strains are being developed (Dossey *et al.*, 2023).
Lesser mealworm, larva of the beetle *Alphitobius diaperinus*	

Source: Adapted from van Huis, A. 2022. Progress and prospects. *Journal of Insects as Food and Feed,* 8: S5.

3.3 Genetic resources and conservation

Risks to natural populations

Many invertebrate species are threatened by habitat loss, pollution and climate change (Sekonya and Wynberg, 2022). About 40 percent of the world's insects could be extinct in the next few decades (Sánchez-Bayo and Wyckhuys, 2019). Lepidoptera, Hymenoptera and dung beetles (Coleoptera) are the most affected, whereas four major taxa (Odonata, Plecoptera, Trichoptera and Ephemeroptera – which are aquatic in their larval stages) have already lost many species (Sánchez-Bayo and Wyckhuys, 2019). For insects in general, i.e., not focusing particularly on the ones that people eat, the main drivers of species loss, in order of importance, are:

i) habitat loss and conversion to intensive agriculture and urbanization;

ii) pollution, mainly caused by synthetic pesticides and fertilizers;

iii) biological factors, including pathogens and introduced species; and

iv) climate change (especially in the tropics) (Sánchez-Bayo and Wyckhuys, 2019).

Edible invertebrates face all of the above threats, plus additional pressure from overexploitation (Adla *et al.*, 2022; Cardoso *et al.*, 2020; Lange and Nakamura, 2021; Piña-Domínguez *et al.*, 2022).

Overexploitation

Gathering invertebrates relies on some ethnobiological knowledge. Commercialization can lead to overharvesting of wild populations, as has happened with the mopane caterpillar in Africa since the 1990s (Table 3.2). For example, over-eager collectors may chop down mopane trees for quick access to the caterpillar (Illgner and Nel, 2000; van Huis *et al.*, 2013).

Rural people in the Democratic Republic of the Congo understood that two generations of edible *ngala* caterpillars (*Cirina forda*) were produced in a season. The first generation was left to pupate before harvesting the (larger) second generation. Caterpillars spotted on high tree branches would also be spared. With greater population pressure, local people no longer respect these norms (Latham, 2015).

Edible insects that have small populations and are harvested in their juvenile stages can suffer population loss and even risk extinction (Cerritos, 2009). In the miombo woodlands of Angola, Malawi, Mozambique, the United Republic of Tanzania and Zimbabwe, about 30 species of caterpillar (mostly Saturniidae) are harvested and eaten. Many species have become locally extinct because of forest clearing, burning and overgrazing (Kenis *et al.*, 2006).

Overharvesting in nature has led to declining populations of witchetty and bardi grubs and honey ants in Australia. Anthropologist Alan Yen noted that “better access” (probably cars and roads) allowed overharvesting by Indigenous Peoples, in part for the ecotourism and restaurant markets (Yen, 2009). In Tulancalco, a community near Mexico City, the Indigenous Peoples once harvested 30 species of insects from five orders. For example, escamoles, ant larvae and pupae (*Liometopum apiculatum*), were once harvested by expert “*escamoleros*”, local men who knew how to dig into the nests and remove some of the escamoles and then close the nest. In the absence of regulations, clumsy outsiders, seeking to supply the lucrative restaurant trade, simply dug up the nests, destroying them and driving this ant species close to local extinction (Ramos-Elorduy, 2006).

Wild harvesting may also transfer diseases between insect populations if pathogens are carried on the boots and equipment of collectors (Berggren and Low, 2024).

Habitat degradation (including deforestation, pollution and the effects of pesticides)

Even abundant insects can become extinct. Besides the grasshoppers mentioned in Section 3.2, Native Americans ate other orthopterans, including the Rocky Mountain locust, *Melanoplus spretus*. This species once swarmed in vast numbers around the Great Salt Lake, but it is thought to have become extinct by 1900 because of the conversion of montane river valleys to agriculture by Anglo-American settlers after 1847 (Lockwood, 2010). In the Democratic Republic of the Congo, many edible caterpillars pupate in the soil, and they are killed when secondary forest is cleared and burned for planting crops. As fallows shorten, this becomes more of a problem (Ombeni *et al.*, 2022). The caterpillar of the moth *Anaphe venata* was widely eaten across West Africa, but it is becoming rare because of the loss of its main host tree, *Triplochiton scleroxylon* (Latham *et al.*, 2024).

Besides palm grubs, many other insects are semi-cultivated. For example, the Aztecs would place bundles of leaves in lake waters to encourage several genera of aquatic Hemiptera to lay their eggs (*ahuautle*). The Spaniards called this delicacy “Mexican caviar.” *Ahuautle* were harvested until the twentieth century, when pollution destroyed the lake habitat (van Huis *et al.*, 2013). The insects are now induced to lay their eggs on artificial lakebed nurseries consisting of clumps of grass inserted into the shallow lake bottom (van Huis and Oonincx, 2017).

In West Africa, wild snail populations have declined not just because of harvesting but also because of deforestation, pesticide use and slash-and-burn agriculture (Cobbinah, Vink and Onwuka, 2008). In northeast India, Loktak Lake was home to 31 edible insect species, including the giant water bug (*Lethocerus indicus*), which was abundant during the summer in rice fields, on the lake shore and in local markets. It is now disappearing because of pollution from chemical fertilizers and pesticides (van Huis and Oonincx, 2017).

Invasive species

Wild invertebrates in general may be threatened by alien species introduced as pets, human food or animal feed (Kumschick *et al.*, 2016). If invasive insect species become ecologically dominant, they may out-compete native ones. The recent introduction of the fall armyworm (*Spodoptera frugiperda*) in Africa is displacing a native noctuid, *Busseola fusca* (Fortuna *et al.*, 2022). While some invasive plants may benefit certain invertebrate species, most have a negative impact on native taxa (Landsman Schmit and Matthews, 2021).

There is clear genetic evidence that humans have fuelled historical insect colonizations and that managed strains do escape and interbreed with local wild populations or establish new populations (Kaya *et al.*, 2021). The black soldier fly is not a pest, but it is expanding its range. There is a concern that some traits selected for in mass-rearing may find their way into wild populations (Christoph Sandrock, personal communication). Insect pathogens tend to adapt to rearing facilities and to be amplified there. Entomopathogens could escape from commercial facilities, not just with the insects themselves but also in feed or faecal waste (Berggren and Low, 2024). Black soldier flies are now established in the wild on all continents (except for Antarctica); their dispersal was almost certainly aided by humans, unintentionally (Kaya *et al.*, 2021). Except for honey bees, there are no diagnostic procedures or certified laboratories for diagnosing the diseases of insects (Jensen and Lecocq, 2022).

Climate change

The exact effect of climate change on tropical insect populations is unclear (Lange and Nakamura, 2021). However, monitoring programmes across the world show that the declines of insect populations "have been staggering" as a result of climate change, habitat loss and pesticides (Halsch *et al.*, 2021). Climate change is the most serious of these threats; for example, highland butterflies in Northern California have suffered severe population decline, even without habitat destruction (Halsch *et al.*, 2021). In general, climate change will have pervasive, often disruptive, effects on insects at the individual, population and community levels, including impacts on their geographical ranges, their life cycles and the availability of their food (Harvey *et al.*, 2023).

There are few studies on the impact of climate change and invasive species specifically on edible invertebrates. However, the above-cited risks to wild invertebrates in general may have similar effects on edible species.

Conservation efforts

Conservation efforts can include community outreach. For example, efforts have been made to educate villagers in the Democratic Republic of the Congo about carefully timing agricultural burns in early June to avoid killing the caterpillars of *Cirina forda*, which pupate in the soil, or leaving some mopane worms in the trees (Latham, 2015). As part of community outreach, villagers could also be encouraged to establish reserves for caterpillars, in woodlands where there are many beehives or in traditional burial ground forests (Latham, 2015). In southern Africa, sacred places, such as inselbergs and groves of special trees, once inadvertently served as havens for biodiversity (Dzerefos, 2018). In many African communities, "if a colony of young caterpillars is found on a branch at some distance from the village, the branch with the caterpillars is often cut and taken back to the village and either placed on the same species of tree or one that the caterpillars are known to feed on. They are then kept until large enough to eat" (Latham *et al.*, 2024). In South Africa, where the edible stink bug *Encosternum delegorguei* is harvested for sale, some communities harvest the species unsustainably

by felling trees or using light traps to harvest too many individuals. However, other communities are implementing adaptive management, such as monitoring insect populations, preventing fires or closing the harvest season when copulation commences (Dzerefos, 2018). Also in South Africa, resources have been developed for schoolteachers to plan lessons on insects and sustainable use, including information booklets on conserving edible caterpillars and termites (Dzerefos, 2018).

Formal protected areas are another option. In South Africa, there are a few protected areas for threatened butterflies. If the edible insects such as beetles, stinkbugs, caterpillars, locusts and termites that are found in these refuges benefit, this is by accident rather than by design. However, since 1994 the Kruger National Park has issued permits that allow harvesters to collect mopane caterpillars, thus enabling local people to benefit from the park (Dzerefos, 2018).

In the Serra do Pingano, a proposed protected area in the province of Uíge, Angola, edible insects include the African palm weevil (*Rhynchophorus phoenicis*), which is eaten and sold year-round. The edible cricket, *Brachytrupes membranaceus*, is found in agricultural fields in the area (Lautenschläger, 2022). The mopane worm and some 15 other species of edible caterpillars are harvested in January and February, mostly by children who climb trees to collect them (Lautenschläger, 2022). In Africa, edible caterpillars are often collected by children, who sometimes eat most of their catch (Latham *et al.*, 2024).

A strategic approach has been proposed in Australia to improve the conservation of insects, arachnids and crustaceans, including 204 species classified as threatened (Taylor *et al.*, 2018). The strategy involves engaging the public, documenting traditional foods and using “flagship species” to raise awareness. Flagship species are defined as those of special scientific or social interest. The flagship species themselves are not necessarily threatened, but it is hoped that paying greater attention to them will allow closer engagement between scientists and local communities to protect threatened invertebrates in general. Some of the proposed flagship species are edible, including the weaver ant (*Oecophylla smaragdina*) and honey-pot ants (e.g. *Camponotus inflatus*).

The Government of Thailand is making efforts to protect its insect populations through the conservation of forests and natural areas (Halloran *et al.*, 2015). For example, national regulations prohibit harvesting of wild beehives in the forest.

In spite of the threats from overexploitation, wild harvesting may bring certain benefits for conservation. It may induce the public to see the value of insects, appreciate traditional knowledge related to them and become advocates for the conservation of invertebrate habitats and populations (Berggren and Low, 2024).

The authors of this study could find no references to *ex situ* conservation of edible invertebrates. However, there has been some planning in Australia and New Zealand for the *ex situ* conservation and assisted migration of terrestrial invertebrates. This includes the insects hosted by two species of banksia shrubs (*Banksia* spp.), insects living on Stirling Range beard heath (*Leucopogon gnaphalioides*), the parasites of wild cats, the mites and ticks on Duvaucel’s gecko (*Hoplodactylus duvaucelii*) and ectoparasites of the tuatara (*Sphenodon punctatus*) (a reptile) (Moir *et al.*, 2012). There have been *ex situ* conservation programmes since 1991 to save 15 endangered (although not edible) species of Hawaiian tree snails, *Achatinella* spp. and related genera (Price *et al.*, 2015).

Conservation approaches should be informed by knowledge of the population genetic structure of potentially threatened species. This knowledge can be used to identify high-priority regions for preserving the genetic integrity of wild resources and to trace the genetic introgression from mass-rearing facilities (Kaya *et al.*, 2021).

Edible agricultural pest insects

Some wild-harvested insects, especially orthopterans, are agricultural pests. Many could be more widely eaten and sold, in part to reduce their impact on crop production. For example, the Mexican

grasshopper, or chapulín (*Sphenarium purpurascens*) is a pest of maize, beans, pumpkins and alfalfa. Every year, 200 tonnes of chapulines are harvested annually, a fraction of the 350 000 tonne potential (van Huis and Oonincx, 2017). Besides grasshoppers, other insect pests eaten in Mexico include *chicatanas* (virgin queens of the leafcutter ant *Atta mexicana*) and two caterpillars: *chinicuil* (agave red worm, *Comadia redtenbacheri*) and *meocuil* (agave whiteworm, *Aegiale hesperiaris*) (Piña-Domínguez *et al*., 2022).

More than 60 grasshopper and locust species are eaten in Africa, and most are crop pests. Farmers in the Sahel can make more money by selling grasshopper pests of millet than from the grain itself (van Huis and Oonincx, 2017; Piña-Domínguez *et al*., 2022). Also in Africa, the corn earworm (*Helicoverpa armigera*) caterpillar, a serious pest of various crops, including cotton, maize, tomato, sunflower, pigeon pea and common beans, is eaten in Cameroon, the Democratic Republic of the Congo and Zambia (Latham *et al.*, 2024). Likewise, armyworm (*Spodoptera exempta*, and *S. littoralis*) caterpillars, serious pests of maize, sorghum and other crops, are eaten in Zambia, the Congo, Nigeria and Zambia (Latham *et al.*, 2024).

Abundant insect pest species can only be used as food or feed if they are not contaminated with pesticides. Populations of edible rice grasshoppers (*Oxya* spp.) declined in Japan, the Republic of Korea and Thailand after insecticides killed many of the insects (van Huis and Oonincx, 2017). In Kuwait, locusts were a popular food during outbreaks. However, during the winter of 1988–1989, the insects contained such high concentrations of insecticides that they were not fit for human consumption (van Huis and Oonincx, 2017). Of 21 known locust species, ten have been eaten or fed to animals, in 65 countries. Researchers from the International Centre of Insect Physiology and Ecology (ICIPE) report that alternatives to massive insecticide applications are being rapidly developed, including biopesticides (Egonyu *et al.*, 2021). Aerial spraying is still widely used; the insecticides accumulate in the locusts' bodies and are a great health risk for human consumers and animals (wild and domestic). Some investment in developing better harvest techniques for the locusts (instead of just sweeping them into trenches) might make it possible to use them as food and feed (Egonyu *et al.*, 2021; van Huis and Oonincx, 2017).

Contributions of insect farming to wider conservation efforts

The mass rearing of insects will not necessarily reduce pressure on wild-harvested ones. The main impact on conservation may be the use of farmed insects to reduce the pressure to convert land for food production (Berggren and Low, 2024) and to manage food waste problems (Fowles and Nansen, 2020). Two major global threats to biodiversity are the clearing of the Amazon rainforest to plant soybean (Du Bois, 2018) and overfishing driven by demand for fishmeal to feed poultry. Mass rearing of insects as feed may help to solve these problems by replacing some of the fishmeal and soybeans (van Huis, 2022a; Mhemdi and Mezdour, 2022; FAO, 2021; Amulen *et al.*, 2022; Guidou *et al.*, 2022; Heuel *et al.*, 2021).

The World Wide Fund for Nature (WWF) sees insects in animal feed as key to global conservation efforts. For example, it reports that demand for insect meal to feed salmon, pigs and poultry in the United Kingdom is forecast to reach 540 000 tonnes by 2050; a projected 237 000 tonnes of this meal could be produced domestically, and the rest imported. Insect farming would convert 3.4 million tonnes of manure and refuse into feed, keeping it from becoming waste and sparing 150 000 hectares of farmland (WWF, 2021). Private companies such as Protix and Nutrition Technologies are now producing insect meal commercially, with a self-conscious environmental focus (van den Eshof, 2022; Piggot, 2022). However, in the near future, insect meal may be too expensive to replace soy and fishmeal. Challenges include problems related to the use of large amounts of food waste (Biteau *et al.*, 2024). There is limited hard evidence to show that cultivating insects for feed is helping to conserve wildlife. The mass production of insects to replace fish and soybean is just getting started, and more data on biodiversity impacts may emerge once the industry has matured.

Several West African countries where massive fishmeal factories have spurred overexploitation and threaten fisheries for human consumption are developing a black soldier fly industry to replace fishmeal in animal feed (Ndiaye *et al.*, 2022). Rearing the African palm weevil (*Rhynchophorus phoenicis*), a popular seasonal food in the Democratic Republic of the Congo, can provide twice the income obtained from hunting, and insect cultivation is being encouraged to reduce the pressure on animals hunted for bushmeat in the Okapi Wildlife Reserve (Franklin *et al.*, 2022). A new initiative in Madagascar is encouraging local people to rear a large planthopper (*Zanna tenebrosa*). Making this protein-rich delicacy more available should help to relieve pressure on lemurs, which are hunted for food (Côté-Andreetti, 2024).

Domestication

There is a spectrum from wild-gathered invertebrates to those semi-cultivated and farmed to these that have undergone domestication (Muir *et al.*, 2020). Honey bees (*Apis mellifera*) were domesticated for their honey, although the brood is edible and is high in protein, fats, minerals and other nutrients (Guiné *et al.*, 2022). This species is clearly domesticated, having gone genetic and behavioural changes (e.g. producing ample honey and being easier to handle) (Carpenter and Harpur, 2021; Oldroyd, 2012; Abou-Shaara, 2020). The silkworm (*Bombyx mori*) has been domesticated and is farmed for its fibre. The pupae of the silkworm are eaten in China, the Democratic People's Republic of Korea, the Republic of Korea and Thailand after unravelling the silk (Dufour and Sander, 2000). Although insects have traditionally and extensively been gathered from the wild for many years, none have been specifically domesticated for food (van Huis *et al.*, 2013).

However, new domestications of insects are likely underway. While the domestication status of the yellow mealworm is still debated (Eleftheriou *et al.*, 2022), there is a clear genetic distinction between wild black soldier fly populations and captive ones, some of which can be considered domesticated (Athanassiou *et al.*, 2024). Wild populations have much greater genetic diversity. Certain captive populations are much less diverse as a result of the demographic bottlenecks they have been through (Kaya *et al.*, 2021; Generalovic *et al.*, 2022). Worldwide, all captive black soldier flies, including several recently split subpopulations, share the same farmed origin. These captive flies have been undergoing genetic change for about 20 years and now show many genetic "signatures of domestication": genes associated with development, behaviour, reproduction, metabolism and immunity on chromosomes two, four and five (Generalovic *et al.*, 2023; Hull *et al.*, 2024). Artificial selection in captivity is rapidly changing the genetic structure of their populatons (Generalovic *et al.*, 2023; Broeckx *et al.*, 2022; Cai *et al.*, 2024) and depleting their genetic diversity (Kaya *et al.*, 2021). If the black soldier fly has not been domesticated yet, it soon will be. However, genetic response is highly population-specific, and not all domestication attempts are successful (Rhode *et al.*, 2020).

Breeding

Insect breeding is a new and rapidly advancing field (Hansen *et al.*, 2024). Breeders are learning the lessons from genetic manipulation used in the domestication of crops and livestock (Picard *et al.*, 2022). Compared with vertebrate breeding, insect breeding has some advantages, such as the animals' short generation intervals and the possibility of rearing them in huge numbers. Constraints include insects' small size and short lives, and in some cases the fact that they go through metamorphosis, all of which increase the difficulty of phenotyping them. There is a lack of information on genetic diversity and lack of proper methods for controling mating. Estimating breeding values in insects is challenging (Slagboom *et al*., 2024; Gowda, Jerry and Zender, 2025).

Farmed insects are evolving to adapt to captivity, and entrepreneurs have recently started to breed for traits such as low chitin, large body mass and high lipid content (Gruber, Melton and Nature Magazine, 2023). In 2019, two private companies in the Netherlands (Hendrix Genetics Research, Technology & Services BV and Protix Biosystems BV) started breeding black soldier flies, and great improvements in larval weight, dry matter, protein and fat levels are reported (Facchini *et al.*, 2022). Dedicated breeding programmes, however, are still scarce (Slagboom *et al.*, 2024), Captive insects should generally be kept in large populations, which has been shown to help avoid inbreeding and random genetic drift, and to allow natural selection to operate, maintaining high fitness and facilitating adaptation to the farm environment (Jensen *et al.*, 2017).

In 2023, the Paris-based company Ÿnsect,[46] released a high-density digital chip to help breeders identify genes linked to desirable traits in mealworms, such as growth performance, reproduction and disease resistance. This chip contains 679 205 single-nucleotide polymorphisms covering more than 99 percent of the mealworm's coding regions (Gruber, Melton and Nature Magazine, 2023).

In Israel, a consortium of insect-based animal feed companies is using machine learning and fly genomics to edit genes to improve protein quality and speed up hatching and growth. The startup FreezeM,[47] which is part of the consortium, has used CRISPR–Cas9 to develop a new strain of black soldier fly, Titan® (Alyagor, 2023). The company has deployed 400 CRISPR–Cas9 guide RNAs to target about 150 genes that control metabolism, which has yielded strains with bigger larvae, a longer larval period and increased resilience under stress. One of the genes regulates moulting from larva to pupa, editing the gene yields larvae that are 50 percent larger. BugEra, also an Israeli company, has used CRISPR–Cas9 gene-editing to develop a black soldier fly strain (BSFx2) with double the lipid content in order to increase the fat content of feed produced from it (Gruber, Melton and Nature Magazine, 2023; Melkov, 2024). Concerns have been raised about the insect welfare implications of some forms of genetic modification such as the production of insects that are wingless or have delayed maturation (Barret *et al.*, 2023).

Researchers in the Republic of Korea have recently identified black larval morphs of the yellow mealworm (*Tenebrio molitor*) and have bred a separate population. The researchers are exploring unspecified industrial applications (Song *et al.*, 2022). The first high-quality annotated genome assembly of the house cricket has recently been published to provide information needed for genetic manipulation. CRISPR technology is now being used to breed more nutritious and disease-resistant crickets (Dossey *et al.*, 2023).

3.4 Production and trade

The global trade in edible insects was USD 1.2 billion in 2023; figures for farmed and wild-harvested products are not disaggregated, but most of the value is from captive insects (Precedence Research, 2024). There are now about 2 300 insect farms in Africa alone, including about 50 large facilities (Tanga and Kababu, 2023).

[46] https://www.ynsect.com
[47] https://www.freezem.com

International trade may start as a means of meeting demand for niche or nostalgia foods, for example when vendors from Oaxaca travel to California to sell seasonal insects to Mexicans living in the United States of America. Oaxacan insect dealers have a network on Facebook Marketplace. They drive to Southern California and sell insects such as chapulines and escamoles to farm workers (Wade, 2023). Chapulines (grasshoppers) from Mexico are now sold in some high-end Mexican restaurants in the United States of America (Broadbent, 2024).

Insect farming in Thailand now generates 7 000 million baht (about USD 200 million) per year, mostly from local, fresh markets (Krongdang *et al.*, 2023). There is also a growing national demand for processed insect-based foods (including frozen, canned and powdered insects) (Wade, 2023). Thailand exported USD 200 000 worth of insects (mostly crickets) to the United States of America, Japan and the United Kingdom in 2022 (Krongdang *et al.*, 2023).

Snails are imported into France, Morocco, Portugal, Spain and elsewhere. Major producers include Morocco, Lithuania and Romania (Rygało-Galewska, Zglińska and Niemiec, 2022). Global trade in edible snails is worth EUR 1 billion annually, with a total of 300 000 tonnes traded, including 100 000 tonnes in Europe.

In Kinshasa, 80 percent of residents report eating insects on at least five days per year, and 9 600 tonnes are sold in the city annually, often by women (Ombeni *et al.*, 2022). Most consumers surveyed report that they would eat more insects if more were available. There is significant trade of insects between the Democratic Republic of the Congo and many other African countries, including Chad, Nigeria and South Africa. Some edible insects are shipped from airports in the Democratic Republic of the Congo to France and Belgium (Ombeni *et al.*, 2022).

Edible grasshoppers collected in Uganda. © Eric Boa.

3.5 Institutional frameworks: research and research institutes

There are few if any dedicated structures that promote research, information exchange and policy discussion on edible terrestrial invertebrates, and they are also not yet fully mainstreamed into the work of more general food policy and advisory bodies.

International

ICIPE has been conducting research on edible insects since at least 2015 (Kelemu 2015; Niassy *et al.*, 2022; Tanga *et al.*, 2022; Egonyu *et al.*, 2022; Omuse *et al.*, 2024). FAO has played a large role in raising awareness of the potential for edible insects (van Huis *et al.* 2013; FAO 2021; Hanboonsong and Durst, 2020). ICIPE now houses a major programme on Insects for Food, Feed and Other Uses. It is carrying out research on methods for preparing insects such as desert locusts as food and black soldier fly larvae meal as animal feed, low-cost diets, traps for large-scale collection of locusts, and insect commercialization (in collaboration with the Institute of Ethiopian Standards) (ICIPE, 2024).

The International Platform of Insects for Food and Feed (IPIFF),[48] an European Union non-profit organization that represents producers of insects for food and feed, helps its members implement European Union food- and feed-safety regulations and develop shared standards and good hygiene practices, and educates the wider public on the benefits of eating insects and using them as animal feed. It anticipated the European Union's plans to expand edible insect production by releasing the *IPIFF guide on good hygiene practices for European Union (EU) producers* (IPIFF, 2024). The Asian Food and Feed Insect Association (AFFIA) plays an important role in supporting the development of the insect industry in Indonesia, Malaysia and Thailand (Preteseille *et al.*, 2018).

The European Federation for Animal Science (EAAP) includes a Study Commission on Insects,[49] which addresses biomass as substrate for insect rearing, nutritional requirements of insects, insect production, ethics, processing methods of insect products, feeding value of insect products, market applications, regulations, consumer acceptance, environmental and socioeconomic sustainability.

National

In Australia, the Commonwealth Scientific and Industrial Research Organisation (CSIRO)[50] has a research programme on insects for food and feed, which looks into the development of new technologies for rearing insects, the use of insects to reduce food waste and the environmental impact of insect production. The Indian Council of Agricultural Research (ICAR)[51] has a research programme on insects for food and feed, which addresses the development of new varieties of insects for food production, improving the nutritional value of insect-based foods, and the safety of insects for human consumption.

Several institutions in China focus on insect research, including the Research Institute of Resource Insects under the Chinese Academy of Forestry and the Key Laboratory of Cultivating and Utilisation of Resource Insects administered by the National Forestry and Grassland Administration. The Jiangsu Academy of Agricultural Sciences is conducting research on the nutritional value of insects as food (Tang *et al.*, 2019). In the United States of America, the Center for Environmental Sustainability through Insect Farming (CEIF)[52] brings together industry and academic experts to develop new methods for the use insects as a sustainable alternative feed for livestock, poultry and aquaculture.

[48] https://ipiff.org/about-ipiff
[49] https://eaap.org/study-commissions/insects/
[50] https://www.csiro.au/en
[51] https://icar.org.in
[52] https://iucrc.nsf.gov/centers/center-for-environmental-sustainability-through-insect-farming/

Universities

Many universities study edible invertebrates, including WUR[53] in the Kingdom of the Netherlands, whose work has included the publication of a manual on snail farming in West Africa (Cobbinah, Vink and Onwuka, 2008), reviews of the sustainability of insects as food and feed (van Huis and Oonincx, 2017; van Huis 2022a), influential research on insect nutrition (Oonincx and Finke, 2021) and work on the genetics of edible insects. In 2014 WUR organized the first Insects to Feed the World conference in Wageningen, Kingdom of the Netherlands. Further conferences in the series were held in Wuhan, China (2018), Quebec City, Canada (2022) and Singapore (2024). Other universities conducting research on the genetics of edible insects include Aarhus University[54] and Aalborg University[55] in Denmark, Cambridge University[56] in the United Kingdom, the University of Groningen[57] and Thomas More University[58] in Belgium, Texas A&M[59] in the United States of America and the Research Institute of Organic Agriculture, Switzerland.[60]

The late Gene DeFoliart, at Montana State University,[61] United States of America, helped to start much of the current interest in research on edible insects. Research by Khon Kaen University[62] was instrumental in developing the insect sector in Thailand (Hanboonsong and Durst, 2020). Makerere University,[63] Uganda, has sponsored research on the influence of relationships between plants and the environment on the survival of the edible grasshopper (*Ruspolia differens*) in the country (Leonard, 2021). The Warsaw University of Life Sciences,[64] Poland, is conducting research on snail rearing in Europe (Rygało-Galewska, Zglińska and Niemiec, 2022).

The European Cooperation in Science and Technology (COST) supported SUStainable INsect CHAIN (SUSINCHAIN),[65] a project coordinated by WUR that ran from 2019 to 2023 and brought together a comprehensive, multiactor consortium of 18 industry partners and 17 academic institutes. SUSINCHAIN aimed to help provide novel protein for feed and food in Europe by overcoming barriers to open markets and increasing the economic viability of the insect value chain(Veldkamp *et al*., 2022). It contributed many publications,[66] tools, best practice sheets[67] and a roadmap for future of insect protein production in the European Union (SUSINCHAIN, 2023). COST is currently supporting three related projects: CA22129, Using Image-based AI for Insect Monitoring & Conservation (InsectAI);[68] CA22140, Improved Knowledge Transfer for Sustainable Insect Breeding (Insect-IMP);[69] and CA23127, Group on Insect Nutrition: To Open Nutritional Innovative Challenges (GIN-TONIC).[70]

Other European Union programmes that have fostered collaborations include INSECTINOV-Sud[71] a research network supported by the Institut de Recherche pour le Développement (IRD) that targets the

[53] https://www.wur.nl/en.htm
[54] https://qgg.au.dk/en/research/animal-genetics/insect-team
[55] https://www.bio.aau.dk/edible-insects-for-a-sustainable-future-e28489
[56] https://www.zoo.cam.ac.uk/research/evolutionary-genetics-and-genomics/insect-evolution-genomics-group
[57] https://research.rug.nl/en/organisations/beukeboom-lab-evolutionary-genetics
[58] https://thomasmore.be/en/sustainable-biomass-and-chemistry/expertise/insect-rearing
[59] https://www.tamu.edu
[60] https://www.fibl.org/en/locations/switzerland/departments/animal-sciences/animal-nutrition
[61] https://www.montana.edu
[62] https://kku.ac.th
[63] https://www.mak.ac.ug
[64] https://www.sggw.edu.pl/en
[65] https://susinchain.eu/
[66] https://susinchain.eu/project-outcomes/scientific-publications
[67] https://susinchain.eu/project-outcomes/best-practice-sheets
[68] https://www.cost.eu/actions/CA22129/
[69] https://www.cost.eu/actions/CA22140/
[70] https://www.cost.eu/actions/CA23127/
[71] https://www.ird.fr/irn-insectinov-sud-innover-pour-produire-et-valoriser-les-insectes-et-leurs-productions

development of value chains for edible insects in the Global South, especially in Cameroon, Côte d'Ivoire, Gabon, Kenya and Peru (INSECTINOV-Sud, 2024).

3.6 Regulatory frameworks

Food and feed regulations

A global review of regulations on the use of insects for food and feed (Lähteenmäki-Uutela, Marimuthu and Meijer, 2021) found that national regulations do not allow all species to be used. While governments focus mainly on food and feed safety, the differences in rules between countries complicate international marketing strategies for insect products. Some insects are allowed to be used as feed but not as food. Some countries (and the European Union) have specific rules for novel foods, while others do not (Lähteenmäki-Uutela Marimuthu and Meijer, 2021). Where insects are part of local food culture, eating them tends to be lightly regulated, but this is changing as food insects become commercialized.

As the edible-insect industry grows, there is a need for international standardization of regulations to facilitate trade and ensure safety. Regulations should cover the entire production chain, starting from farming or wild harvesting, and include monitoring for food and feed safety. Insect health and welfare standards, processing, transport and food handling, as well as the impact of insect farming on the economy, environment and communities, also need to be regulated (Żuk-Gołaszewska *et al.*, 2022). Regulations will also have to cover how products are packaged and labelled, for example making it clear when products contain insects. Codex Alimentarius[72] has little to say about edible insects (FAO, 2021). The inclusion of recommended edible insect species in the Codex Alimentarius international food standards would be a useful step in terms of international standards for the industry (Halloran, 2014).

Globally, regulations for reared insects tend to give too little attention to insect diseases (entomopathogens), stocking, breeding and rearing (Berggren and Low, 2024). The World Organisation for Animal Health's Terrestrial Animal Health Code does not provide guidance on health regulations for any insects other than bees (Torres *et al*., 2022). The transfer of individuals between facilities is under-regulated. The black soldier fly is highly adaptable, and although it is native to the tropics of South America, it is cold-tolerant, and escaped populations could become established in the wild, even in temperate regions, with unknown consequences (Berggren and Low, 2024).

In Africa, insect farming promises to provide low-cost protein and youth employment. However, as trade increases, it will be important to respect the (often sophisticated) local knowledge of insects as food. Regulations should guard against overexploitation and ensure that insects are correctly labelled by species so that poisonous ones are not erroneously sold as food (Niassy *et al.*, 2022). A few insect species are toxic, including some of the caterpillars eaten in Africa. Local people often know how to remove the toxins during preparation, for example by gutting the insects (Latham *et al.*, 2024). In Nigeria, reliance on the caterpillar *Anaphe venata* as a protein source has led to seasonal deficiency of thiamine (vitamin B1), because these larvae are high in thiaminases, which break down vitamin B1 (Adamolekun, 1992). No African country has so far explicitly included edible insects in their food legislation, although some, for example Morocco, prohibit the extraction of insects from the wild without a permit (Grabowski *et al.* 2020). In Kenya, regulations once limited the growth of insect farming (Halloran *et al.*, 2015). However, in recent years the Government of Kenya and ICIPE are encouraging insect production in the country. The Kenya Bureau of Standards (KEBS) has approved standards to support the development of insect-derived protein-rich food products for human consumption (Kinyuru and Ndung'u, 2022).

[72] https://www.fao.org/fao-who-codexalimentarius/en

Many high-income countries are rapidly developing regulations for insects as food or feed as industrial-scale insect farming gets underway. For example, since January 2018, insect foods in the European Union fall under the novel food regulation EU 2015/2283. The seller of an insect-based product must apply to the European Commission and have a follow-up scientific evaluation by the European Food Safety Authority (FAO, 2021).

European Union food regulations are conservative and stringent. The first official authorization to market insects (under the 2015 novel food regulation) was not granted until 2021, to a French company, Agronutris,[73] which was authorized to produce yellow mealworm larvae as a human food (Auriol, 2022). Products may be authorized as "safe foods" if the edible insects are traditional foods from third countries with at least 25 years of safe use, but only Canada, the Republic of Korea, Switzerland, Thailand, Viet Nam and the United Kingdom can legally export insect food products to the European Union (FAO, 2021). In 2023, the European Commission approved an application from the company Ÿnsect[74] for lesser mealworm (*Alphitobius diaperinus*) and one from Cricket One Co. Ltd[75] to produce a powder obtained from the house cricket (*Acheta domesticus*). As of 2023, four insect-based foods had been approved in the European Union, and eight additional applications were pending (European Commission, 2023).

Van Huis (2022a) notes that (at least in Europe) legislation is becoming more conducive to the use of insects in food and feed. The European Union granted permission to use insects as aquafeed in 2017. In 2021, it authorized the use of insect-processed animal proteins (from eight species: black soldier fly, housefly, yellow mealworm, lesser mealworm, house cricket, banded cricket, field cricket and domesticated silkworm) in poultry and pig feed. That same year, the European Union authorized the use of insect-derived proteins in pet food (e.g., for dogs, cats, birds and reptiles) and for fur animals (e.g. mink). As of 2024, the European Union had policies regarding the use of six categories of insect-based feeds for six groups of animals (Table 3.4). Three insect products were authorized as human food in 2021 and 2022: 1) dried, frozen and powder forms of yellow mealworm; 2) dried and frozen migratory locust; 3) dried, ground and frozen house cricket. The European Union prohibits feeding manure, slaughterhouse waste or catering waste to farmed animals (including invertebrates), but supermarket waste can be used as long as it does not contain fish or meat (van Huis 2022a; IPIFF, 2024). These regulations may hamper the development of insects for feed and food.

Table 3.4: Categories of insect-based feeds and the animals they can be fed to in the European Union

[73] https://www.agronutris.com/en
[74] https://www.ynsect.com
[75] https://www.cricketone.asia

	Ruminants	Aqua-culture	Poultry	Pigs	Pets	Fur and other animals (e.g. zoo)
Insect proteins	☒	☑**†	☑**†	☑**†	☑	☑
Insect fats	☑	☑	☑	☑	☑	☑
Whole insects (untreated)	☒	☒	☒	☒	☑***	☑***
Whole insects (treated, e.g. freeze dried)	☒	☒	☒	☒	☑***	☑***
Live insects	☒	☑*	☑*	☑*	☑***	☑***
Hydrolysed insect proteins	☑	☑	☑	☑	☑	☑

Notes: * Member States' authorities shall continue to ensure that operators comply with general safety and marketing requirements in accordance with applicable European Union law. ** Limited to Black Soldier Fly (*Hermetia illucens*), Common Housefly (*Musca domestica*), Yellow Mealworm (*Tenebrio molitor*), Lesser Mealworm (*Alphitobius diaperinus*), House cricket (*Acheta domesticus*), Banded cricket (*Gryllodes sigillatus*), Field Cricket (G*ryllus assimilis*) and Silkworm (*Bombyx mori*). *** If authorized by the national competent authority of the Member State where the product is being commercialized, under the specific conditions applicable to processed pet food (in case the product is intended for use as processed pet food. † Restrictions apply to the species, processing plants and processing methods that can be used. In other cases there is no restriction on the insect species used provided they are not pathogenic to humans or animals.

Source: Adapted from IPIFF. 2024. Live insects in animal feed: what European Regulation says (and what it does not). In: *International Platform of Insects for Food and Feed*. [Cited 9 February 2025]. https://ipiff.org/live-insects/

In Europe, the insect industry is interested in setting its own high standards for food and feed safety. As noted above, the private-sector platform IPIFF has written its own guidelines on hygiene and safety for foods and feeds derived from insects (IPIFF, 2024). European insect producers must comply with all European Union food- and feed-safety rules, not just the ones specifically for insects. Insects reared in the European Union are "farmed animals" and cannot be fed on faeces, sewage, manure, hide or other animal byproducts, seed, wood, waste of any kind or packaging. All food-labelling requirements also apply to insects, for example those related to traceability. Guidance on contaminants in animal feed in general also applies to farmed insects used as feed (IPIFF, 2024; FAO 2021). IPIFF strongly advises that labels should state the similarity of allergenicity between insects and crustaceans and dust mites (FAO, 2021).

According to Section XI of EU Regulation 853 (2004), snail meat for human consumption must be prepared exclusively in establishments built and equipped for that purpose. Snail products must receive organoleptic (taste test) examinations and the animal's hepatopancreas (a digestive organ) must be removed (Pissia, Matsakidou and Kiosseoglou, 2021).

In the United States of America, edible insects fall under the FDA, and must comply with the Federal Food, Drug and Cosmetic Act. Insect-based products must not be adulterated, and their processing, packaging, storage and transportation must occur under proper sanitary conditions; the label must include the common name (e.g. "crickets") of the product and its ingredients (FAO, 2021). In Canada, insects are considered non-novel. Silkworms, house crickets and mealworms must meet the same safety and hygiene standards as other foods sold in Canada. Dried, whole black soldier fly larvae were authorized as a feed ingredient for poultry in 2016 (FAO, 2021). There are no regulations governing the harvesting, processing or food safety of wild edible insects in Mexico (Piña-Domínguez *et al.*, 2022). The country has no specific regulations governing the use of insects in feed, but policies

covering the safety of animal feed in general also apply to insects (FAO, 2021). In Australia and New Zealand, insects must comply with the countries' regular Food Standards Code. They are fed to poultry and fish and are used in some pet foods, but insect-based products are not fed to ruminants (FAO, 2021).

Insects are part of the food culture in many Asian countries, including China, Cambodia, the Lao Peoples' Democratic Republic, Malaysia, the Republic of Korea, Thailand and Viet Nam. Most of these countries lack specific regulations for the use of insects as food, but producers, processors and handlers generally have to follow the standards accepted for other foods (FAO, 2021). In the absence of national standards and given a lack of relevant published information, FAO developed a manual on sustainable cricket farming that includes material intended to serve as a framework that government agencies can use to monitor cricket production and ensure food safety (Hanboonsong and Durst, 2020). In China, silkworm pupae were listed as food by the Ministry of Health in 2014. There are local standards but no nationwide laws for edible insects (FAO, 2021).

In 2024, the Singapore Food Agency approved 16 insect species to be used as food, including four crickets, two grasshoppers, a locust, three mealworms, a white grub, the giant rhino beetle grub, silkworm pupae and drones of the European honey bee. Approved products include insect oil, uncooked pasta containing insects, and chocolate and other confectionary with a maximum of 20 percent insect content (Sullivan, 2024).

Regulation of wild harvesting

LOCAL NORMS. Formal regulations are not always the optimal approach to wild harvesting. Customary laws often provide a more nuanced approach to regulation, integrating unique local cultural, ecological and economic conditions in ways that better suit NWFPs (Laird, Wynberg and Mclain, 2009). Subsistence use of NWFPs need not always be regulated, except in cases where there is risk of overharvesting (Laird, Wynberg and Mclain, 2009).

Local people may have rules, usually unwritten ones, that govern the use of resources such as terrestrial invertebrates. For example, in the miombo woodlands of Zambia, the Bisa people harvested two species of caterpillars (*Gynanisa maja* and *Imbrasia zambesina*). The Bisa regulated harvesting by monitoring host-plant abundance, protecting the earliest instars and preventing fires in the season when the eggs and the caterpillars appeared. These rules were enforced by local leaders and by taboos. However, population pressure, poverty and high demand for caterpillars from outside buyers led to unsustainable practices, such as cutting down trees to obtain the caterpillars (van Huis and Oonincx, 2017). In another example, in the Bas-Congo of the Democratic Republic of the Congo, "it used to be the custom that if a child discovered these caterpillars *Aframomum alboviolaceum*, he took them to the chief who would decide whether it was time to start collecting. Now, unfortunately, everyone collects without seeking the chief's authority, and the species is becoming rare" (Latham, 2015). Local norms may shed light on the sustainable practices that should be written into regulations.

NATIONAL REGULATIONS. There is still little specific legislation on the conservation of edible terrestrial invertebrates, although these organisms may be covered in laws governing wildlife in general (Dzerefos, 2018; Lautenschläger, 2022). Where gathering insects for food is a tradition, national governments are starting to develop policies and regulations. For example, in Kenya, insects can be eaten but cannot be sold unless they are registered with the National Bureau of Standards (Halloran *et al.*, 2015). Most African countries do not regulate the harvesting of insects as food. However, wildlife regulations are more highly developed, and sometimes include insects (Grabowski *et al.*, 2020).

Regulations and policies tend to be inconsistent between countries and are usually over-restrictive, constraining the promotion of insects as food and feed (Lähteenmäki-Uutela, Marimuthu and Meijer, 2021). Only a few African countries (such as Kenya, Rwanda and Uganda) have standards for wild or farmed insects used as food and feed (Niassy *et al.*, 2022). ICIPE is partnering with the African

Organisation for Standardisation (ARSO)[76] to support the harmonization of standards for edible insects, especially those that are farmed, in Africa (ICIPE, 2024).

As Laird, Wynberg and Mclean (2009) wrote of NWFPs in general, the greatest attention in the regulation of wild harvesting should be paid to internationally traded industrial-scale products, as these generate the greatest risk of overharvesting. However, most insect species are not protected by international trade regulations (Fukushima, 2024). Seventy-four insect taxa in 15 genera are listed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), and all are Coleoptera or Lepidoptera. These are mostly large or flashy species, the sort favoured by collectors (Fukushima, 2024).

The greatest value of wild-harvested terrestrial invertebrate products is often in subsistence use and local trade. As with other NWFPs, policy should encourage the participation of small-scale producers and reduce the monopolistic tendencies of processors and traders. Lawmakers require a vast amount of information about the species in question before crafting legislation. Laird, Wynberg and Mclean (2009) argue that "existing customary and local laws are often better suited to this diverse set of products and activities."

Increasing trade in mopane caterpillars has led to stiff competition in South Africa and to imports from Botswana (Sekonya and Wynberg, 2022). Regulation has been marred by rigid rules, combined with lax enforcement (Sekonya and Wynberg, 2022). For example, harvesters in Botswana are required to obtain permits from the Department of Environment, Forestry and Fisheries (DEFF). Impoverished and elderly people often have to travel 200 km to obtain the costly permits. The DEFF may open the harvest season several days after the caterpillars have reached their last instar and are ready to harvest. Such regulations have forced out many compliant actors, while weak regulation means that many transgressors are unpunished. There are also conflicts between customary and formal norms. For example, customary chiefs try to ensure that outside harvesters with permits do not litter, camp in the forest or harvest insects prematurely or too late. The outsiders often feel that their permit allows them to harvest caterpillars anywhere in the country and to avoid customary authorities (Sekonya 2021). These and other conflicts are threatening the sustainable harvest of commercial mopane caterpillar harvesting (Sekonya, 2021; Sekonya and Wynberg, 2022).

Collection of wild Roman snails (*Helix pomatia*), along with habitat degradation, led to their depletion in western Europe by the early twentieth century. This was eventually addressed by bans on their commercial collection, first in France and by 1979 in the rest of western Europe. In line with the Bern Convention of 1979, most European countries prohibit collection of these snails during their reproductive season (1 April to 30 June) and only permit collection of individuals with a shell diameter of at least 30 mm (Gheoca, 2013). In Romania, snails are not part of the local cuisine, but they have been collected commercially since 1956, mainly by elderly people, youths and the unemployed, for export to western Europe. Snail exports were allowed only with the approval of local environmental agencies, and were usually restricted to animals with a shell diameter of 28–36 mm. This preserved larger breeding adults. Since 2008, Romanian law (Order 410/2008) has allowed the collection of snails with a shell diameter of 30 mm or greater – as per the Bern Convention, which Romania has signed (Gheoca, 2013). While the 30 mm rule follows European standards, Roman snails only reach sexual maturity at a shell diameter of 35 mm, so the current regulations allow all adult snails to be collected in Romania. Most collectors, especially older ones, have observed that snail populations are declining (Gheoca, 2013).

[76] https://www.arso-oran.org

Grasshoppers on sale in Uganda. © Eric Boa.

3.7 Policy frameworks

Farming and wild gathering of terrestrial invertebrates are influenced by policies in a variety of fields. With regard to insect farming, Stull and Patz (2020) identify the need to support research on optimal farming techniques, food safety, the health impacts of eating invertebrates, consumer acceptance and economic profitability, and conclude that policy should provide guidance for industry on food safety, encourage stakeholder collaboration in the development of production standards and promote knowledge-sharing networks.

Terrestrial edible invertebrates often receive little attention in national policy. In the case of sub-Saharan Africa, for example, Musundire *et al.* (2021) report that "coherent policies regarding safety, sustainability, trade and regulation of insects as food and animal feed are lacking." The Madagascar Nutrition Action Plan calls for studies to develop (validate, incorporate) at least two insect-based products but does not mention snails or other non-insect terrestrial invertebrates (Republic of Madagascar, 2017). Harvesting of wild insects is permitted by law in Madagascar, including for commercial purposes (Arrete No. 25608/2014). The Malawi National Nutrition Policy mentions in passing that edible insects should be encouraged for home consumption, but again no mention is made of non-insect terrestrial invertebrates (Republic of Malawi, 2006). In the case of the Democratic Republic of the Congo, Ombeni *et al.* (2022) report that legislation and policy for edible insects are lacking and note the need for legislators and decision-makers "to deliberate and include insects as feed and food in existing national policy and legal frameworks covering the food, health and feed sectors."

A comprehensive review of the state of integration of edible terrestrial invertebrates into national policies is beyond the scope of this study.

Insects on sale in Oaxaca, Mexico. © Eric Boa.

4. GAPS, NEEDS AND OPPORTUNITIES

Although edible mushrooms and invertebrates are different in biology and ecology, they face similar threats, including overharvesting. This section highlights actions that could be taken to support the sustainable use and conservation of both groups. There are many gaps in knowledge of how species are used and their importance to people. There has, however, been encouraging progress in conservation efforts and in promoting sustainable wild harvesting, suggesting that there are opportunities for wider sharing of information and experiences. Communicating proven ideas will support future actions to balance sustainable wild harvesting and effective conservation.

Gaps and needs

1. STATUS AND TRENDS: Preliminary assessments of several edible mushrooms appear in the IUCN Global Red List of Fungi, part of a welcome trend towards more attention being paid to the conservation status of macrofungi in general. There is a need for these efforts to continue and for greater priority to be given to edible species. The status and trends of edible invertebrates are less well known, and also need greater attention. A major challenge in the case of both edible fungi and edible invertebrates is understanding the impacts of habitat degradation and climate change on the status and trends of different species, as this would help to clarify which species are most at risk and should be prioritized for monitoring. To inform the breeding of potentially farmed species of insects, research is needed to characterize native vs. non-native ranges, to evaluate the need for conservation or invasion monitoring, and to recognize signatures of domestication.

2. PRODUCTION: Private companies continue to develop new and more sustainable substrates for a small but economically important group of saprobic edible mushrooms. It is difficult to assess gaps and needs in this field because of commercial confidentiality. Advances in technology development in China, the leading commercial producer, are not widely known outside the country.

The feasibility of using semi-cultivation techniques at scale for wild edible mushrooms is untested, other than for high-value truffles. A review of published trial results for selected species, including chanterelles and porcini (*Boletus edulis* group), is needed to assess priorities for further research and to assess the likely contribution semi-cultivation could make to the conservation of wild edible mushrooms.

Techniques for large-scale farming of terrestrial invertebrates for food and feed are improving rapidly (especially for insects farmed for animal feed). Important knowledge gaps still exist, however, for example in relation to how to improve mechanization of production and develop cheaper substrates that are free of harmful chemicals, heavy metals and other contaminants.

3. SUSTAINABLE WILD HARVESTING: The impacts of commercializing wild-harvested edible mushrooms and terrestrial invertebrates are not fully understood. There is a lack of consensus among different interest groups on what sustainable means in this context. There is a need for better evidence, but also for wider awareness of existing studies, most of which show little or no negative environmental impact from intensive collecting of edible mushrooms. There is also a need to distinguish the effects of the intensity of harvesting from those of adverse harvesting practices, such as raking the soil. Commercial harvesting is a threat to species of edible terrestrial invertebrates where local knowledge is disregarded. Such knowledge needs to be better documented and shared.

4. FOOD SAFETY: Many national authorities have yet to fully incorporate edible mushrooms and terrestrial invertebrates into legislation on food safety, particularly in the case of species of wild origin. The perceived risks of eating poisonous mushrooms continues to dampen consumers' enthusiasm for edible mushrooms in general, and especially wild-harvested ones. Some countries have published lists of the mushrooms that are "suitable for commercialization", but much remains to be done in terms of determining and regulating which species can be safely sold. A standardized method is needed for assessing the quality and reliability of evidence on edibility and resolving inconsistent case reports.

Consumers have less fear of eating toxic terrestrial invertebrates, but when target organisms are overexploited, some poisonous ones may be erroneously sold as food. Knowledge about how to correctly identify and label edible insects is weak and variable. There is a need to improve labelling and to develop measures and procedures that guarantee the safety of terrestrial invertebrate-based food and feed. This includes potential threats from allergies, especially for consumers who are allergic to other arthropods, such as marine crustaceans or dust mites. Better advice, and ideally national legislation, is needed on how to produce and market high-quality edible mushrooms and terrestrial invertebrates free from contaminants and other impurities.

5. CONSERVATION MEASURES: There is limited evidence with which to judge the effectiveness of permits as means of conserving edible fungi and terrestrial invertebrates. More information is needed about the negative as well as positive impacts of regulating wild harvesting. There is a strong need to monitor the effectiveness of regulations, particularly those on the issuing of permits and policing of harvesters. Few studies have been carried out to measure the impact of education campaigns on the conservation of edible species. There is a need for regulations to anticipate conservation issues that have the potential to arise as wild terrestrial invertebrates begin to be commercialized.

The physical and ecological conditions that favour production of wild mushrooms are better understood for temperate forests in Europe and North America than for ecosystems elsewhere. Further effort is needed to find out how improved forest management techniques identified from modelling would work in practice. Modelling approaches would help to address major gaps in knowledge about which conditions help to sustain the production of wild mushrooms in other locations, for example across the extensive miombo woodlands of southern Africa.

Information about local collectors, their practices and their knowledge of wild edible mushrooms and terrestrial invertebrates is uneven, with case studies having been published only in a few countries. Understanding this knowledge and behaviour is crucial for the design of functional conservation measures. There is a need for effective legislation on wild harvesting and cross-border trade, and for improved harvesting techniques for edible insects that are also pests (e.g. grasshoppers and locusts).

6. COLLABORATIONS: Research supported by projects on wild edible mushrooms and invertebrates in developing countries often depends on funding from international donors. Wider collaborations with, and connections to, relevant interest groups, for example those working on forest conservation and biodiversity monitoring, biologists studying macrofungi and terrestrial invertebrates, users of NWFPs, environmental and conservation groups, and food standards authorities, would help to strengthen the continuity of efforts and research capacity.

Opportunities

1. STATUS AND TRENDS: New molecular techniques for analysing genetic diversity *in situ*, for example next-generation sequencing, offer new ways to improve knowledge of the genetic diversity of edible mushroom species at population level. There are also opportunities to apply new techniques to edible terrestrial invertebrates and to improve understanding of their genetic diversity.

2. PRODUCTION: Gains in production could be achieved by wider sharing of available data on best practices in the breeding and genetic improvement of farmed mushrooms and terrestrial invertebrates, while respecting the need for commercial confidentiality.

Expanding the sources of information used to compile trade-flow data on wild-harvested edible mushrooms and terrestrial invertebrates from major sources (countries) would provide stronger evidence for the value of such trade at local, national and international levels and help to ensure adequate government support for these sectors.

Enabling research on appropriate cultivation technology for small farms and supporting studies on marketing, particularly at a local level, would help strengthen the livelihood contributions of edible mushrooms and terrestrial invertebrates. For edible insects (especially those used for feed), there are

significant opportunities for research on how to lower substrate costs. There are also opportunities for research on how to exploit the ability of the black soldier fly and the house fly and others that are yet to be exploited (e.g. the flesh fly, Sarcophagidae) to remove antimicrobials, mycotoxins and pathogens from substrates (such as rubbish and livestock manure). Enabling research on genetic modification of farmed insects would facilitate progress on the use of edible insects to process waste.

Wider sharing of information on the breeding of captive terrestrial invertebrates (such as black soldier flies) within and between the industry, research institutions and government bodies would bolster the development of the sector.

As the edible insect industry grows and trade increases, international standardization of regulations in areas such as food and feed safety (see below) become increasingly important. Regulations should cover the entire production chain, starting from wild harvesting and farming.

3. SUSTAINABLE WILD HARVESTING: Raising awareness of existing evidence about the impacts of wild harvesting on populations of wild edible mushrooms would encourage informed debate about the need to introduce restrictive measures. The aim should be to avoid adverse reactions to restrictive regulations on collecting from local communities that rely on wild harvesting for food and income.

Graduate students and other young professionals could be encouraged to conduct market studies, document and develop harvesting practices, and analyse the nutritional contribution made by edible mushrooms and terrestrial invertebrates in poorer countries. Sustainable harvesting could also be promoted by sharing best practices through the educational system (e.g. agricultural universities and vocational schools) and through government extension. Better assessments of smallholders' needs would help to reveal directions for future research and development as well their requirements for training on marketing (e.g. on group organization, packaging, labelling and food safety).

4. FOOD SAFETY: Advantage should be taken of the opportunity to adapt measures that are already in place in some countries and introduce them into new countries. A classification scheme for assessing case reports and establishing a common protocol on edible properties could be introduced under the Codex Alimentarius.

5. CONSERVATION MEASURES: Reviewing the evidence base for bans on wild harvesting in selected countries would allow lessons to be learned for future conservation measures. Including wild edible mushrooms and terrestrial invertebrates in wider policies on forest management, especially in the Global South, would help promote their conservation. Wider sharing of lessons learned from the formulation and implementation of regulations would promote understanding of how solutions from one area could be modified for implementation in other areas. Clear and well-informed norms that respect local knowledge could be used as models by different countries. There may also be opportunities to adapt regulations and rules that have been successfully applied in fishing and hunting.

Opportunities should be taken to deploy proven conservation measures, such as creating and managing wildlife refuges and national parks, to support the maintenance of edible mushroom and terrestrial invertebrate populations. Better gathering of information on conservation experiences and better sharing of information between countries would help to identify potential improvements. Appropriate education campaigns would increase support for conservation measures and the effectiveness of their implementation.

Opportunities to transfer experimental results on forest management approaches for maximizing the health of wild edible mushroom populations into real life should be explored.

Developing new techniques for growing edible mushrooms *in vivo* (cultures) would facilitate *ex situ* conservation.

6. COLLABORATION: Developing collaboration along the lines of the participatory market chain approach (PMCA) would help foster livelihood opportunities. This could, for example, be used to help determine which species enjoy market demand, identify experts from university and government

who could help smallholders and businesses, determine which species should be targeted for sustainable harvesting or cultivation, and devise improved methods for processing and marketing these species.

Strengthening existing networks (e.g. the Joint Network on Wild Fungi and the International Platform of Insects for Food and Feed) as well as new collaborative initiatives would improve contact between researchers, policymakers and producers, foster wider sharing of new knowledge and techniques, and promote awareness of relevant social and environmental issues. Such efforts could allow leading countries to interact regularly with colleagues, institutions and government bodies elsewhere that have a shared interest in the sustainable use and conservation of edible mushrooms, snails, insects or other terrestrial invertebrates.

References

Abou-Shaara, H.F. 2020**.** How can honey bees explain the process of animal domestication by humans? *Arthropods*, 9: 32.

Adamaki-Sotiraki, C., Rumbos, C.I. & Athanassiou, C.G. 2022. Developmental plasticity among strains of the yellow mealworm, *Tenebrio molitor* L., under dry conditions. *Journal of Insects as Food and Feed*, 8: 281–288. https://doi.org/10.3920/JIFF2021.0087

Adamolekun, B. 1992. A seasonal ataxic syndrome in southwestern Nigeria: an etiological hypothesis of acute thiamine deficiency. *Ethnicity and Disease*, 2: 185–6. https://doi.org/10.1016/0022-510X(94)90017-5

Adla, K., Dejan, K., Neira, D. & Dragana, Š. 2022. Degradation of ecosystems and loss of ecosystem services. In: J.C. Prata, A.I. Ribeiro & T. Rocha-Santos, eds. *One Health. Integrated approaches to 21st century challenges to health*, pp. 281–327. Amsterdam, Academic Press. https://doi.org/10.1016/B978-0-12-822794-7.00008-3

AFDO (Association of Food and Drug Officials). 2021. *Regulatory guidelines for wild mushrooms*. 1st Edition. York, USA, Association of Food and Drug Officials (AFDO). https://www.afdo.org/product/regulatory-guidelines-for-wild-harvested-mushrooms/

Alexander, S.J., Mclain, R.J., Jones, E.T. & Oswalt, S.N. 2011. Challenges and approaches to assessing the market value of wild fungi. In: A.B Cunningham & Z. Yang, eds. *Mushrooms in forests and woodlands*, pp. 87–106. London, Earthscan.

Alyagor, I. 2023. FreezeM launches enhanced genetic line of Black Soldier Flies. In: *Feed & Additive. International Magazine for Animal Feed & Additives Industry*. [Cited 1 August 2024]. https://www.feedandadditive.com/freezem-launches-enhanced-genetic-line-of-black-soldier-flies/

Amara, A.A. & El-Baky, N.A. 2023. Fungi as a source of edible proteins and animal feed. *Journal of Fungi*, 9: 73. https://doi.org/10.3390/jof9010073

Amedd, Mobiom, Nawaya & Songhaï Centre. 2017. Feeding snails [video]. In: *Access Agriculture*. [Cited 1 August 2024] https://www.accessagriculture.org/feeding-snails

Amulen, D.R., Vudriko, P., Mwangi, J., Pechal, J.L. & Benbow, M.E. 2022. Local and regional black soldier fly rearing potential in Uganda. *Journal of Insects as Food and Feed*, 8: S33.

Antonelli, A., Fry, C., Smith, R.J., Eden, J., Govaerts, R.H.A., Kersey, P., Nic Lughadha, E. *et al*. 2023. *State of the World's Plants and Fungi 2023*. Kew, UK, Royal Botanic Gardens, Kew. https://doi.org/10.34885/wnwn-6s63

Arora, D. 2008. The houses that matsutake built. *Economic Botany*, 62(3): 278–290. https://doi.org/10.1007/s12231-008-9048-1

Ashour, M. 2022. The alternative protein landscape: promises and challenges faced transitioning from start-up to scale-up. *Journal of Insects as Food and Feed*, 8: S7.

Athanassiou, C., Coudron, C.L., Deruytter, D., Rumbos, C., Gasco, L., Gai, F., Sandrock, C. *et al*. 2024. A decade of advances in black soldier fly research: from genetics to sustainability. *Journal of Insects as Food and Feed*, 24: 1–28. https://doi.org/10.1163/23524588-00001122

ATIA (Australian Truffle Industry Association). 2021. Growing truffles: In: *ATIA*. [Cited 22 January 2025]. https://truffleindustry.com.au/growing-truffles/

Auriol, C. 2022. The first novel food authorisation for insect: Paving the way for the booming market of insect as food. *Journal of Insects as Food and Feed*, 8: S140.

Bahrndorff, S., Ruiz-González, A., de Jonge, N., Nielsen, J.L., Skovgård, H. & Pertoldi, C. 2020. Integrated genome-wide investigations of the housefly, a global vector of diseases reveal unique dispersal patterns and bacterial communities across farms. *BMC Genomics*, 21: 66. https://doi.org/10.1186/s12864-020-6445-z

Barret, M., Chia, S.Y., Fischer, B. & Tomerlin, J.K. 2023. Welfare considerations for farming black soldier flies, *Hermetia illucens* (Diptera: Stratiomyidae): a model for the insects as food and feed industry. *Journal of Insects as Food and Feed*, 9(2): 119–148. https://doi.org/10.3920/JIFF2022.0041

Bederska-Lojewska, D., Swiatkiewicz, S. & Muszynska, B. 2017. The use of Basiodiomycota mushrooms in poultry nutrition – a review. *Animal Feed Science and Technology*, 230: 59–69. https://doi.org/10.1016/j.anifeedsci.2017.06.001

Berggren, Å. & Low, M. 2024. Conservation benefits and threats from insects as food. In: J.S. Pryke, M.J. Samways, T.R. New, P. Cardoso & R. Gaigher, eds. *Routledge handbook of insect conservation*, pp. 210–220. New York, USA, Taylor & Francis.

Biteau, C., Bry-Chevalier, T., Crummett, D., Ryba, R. & St. Jules, M. 2024. Insect-based livestock feeds are unlikely to become economically viable in the near future. *Food and Humanity*, 3: 100383. https://doi.org/10.1016/j.foohum.2024.100383.

Boa, E.R. 2004. *Wild edible fungi: their global importance and used to people*. Rome, FAO. https://www.fao.org/4/y5489e/y5489e00.htm

Boafo, H.A., Affedzie-Obresi, S., Gbemavo, D.S.J.C., Clottey, V.A., Nkegbe, E., Adu-Aboagye, G. & Kenis, M. 2019. Use of termites by farmers as poultry feed in Ghana. *Insects*, 10(3): 69. https://doi.org/10.3390/insects10030069

Boatta, F., Jansen, W.L., Beukeboom, L.W. & Ellers, J. 2023. Lipid quantity and composition vary between three European house fly strains. *Entomologia Experimentalis et Applicata*, 171: 248–257. https://doi.org/10.1111/eea.13279

Bonet, J.A., Pukkala, T., Fischer, C.R., Palahí, M., Martínez de Aragón, J. & Colinas, C. 2008. Empirical models for predicting the production of wild mushrooms in Scots Pine (*Pinus sylvestris*) forests in the Central Pyrenees. *Annals of Forest Science*, 65: 206 https://doi.org/10.1051/forest:2007089

Bonet, J.A., Egli S., Krisai-Greilhuber I., Bouriaud, L., Castaño, C., Colinas, C. & de-Miguel, S. 2020. Mushrooms and truffles. In: H. Vacik, M. Hale, H. Spiecker, D. Pettenella & M. Tomé, eds. *Non-Wood Forest Products in Europe. Ecology and management of mushrooms, tree products, understory plants and animal products. Outcomes of the COST Action FP1203 on European NWFPs*, pp. 213–261. Norderstedt, Germany, BoD.

Boongird, S. 2010. Honey and non-honey foods from bees in Thailand. In: P.B. Durst, D.V. Johnson, R.N. Leslie & K. Shono, eds. *Forest insects as food: humans bite back*. Bangkok, FAO Regional Office for Asia and the Pacific. https://www.fao.org/4/i1380e/I1380e00.pdf

Bourdon, O., Ekeland, C. & Brion, F. 2008. Pharmacy education in France. *American Journal of Pharmaceutical Education*, 72(6): 132. https://doi.org/10.5688/aj7206132

Broadbent, B. 2024. Insects as food. In: *Select Articles by Bill Broadbent*. [Cited 2 August 2024]. https://broadbent.ws/edible-insects/

Broeckx L., Frooninckx, L., Berrens, S., Wuyts, A. Sandrock, C. & Van Miert, S. 2022. Influence of strain genetics on larval performance and bioconversion efficiency for *Hermetia illucens. Journal of Insects as Food and Feed*, 8: S50.

Brickey, P.M. & Gorham, J.R. 1989 Preliminary comments on federal regulations pertaining to insects as food. *The Food Insects Newsletter*, 2(1): 1,7.

Buyck, B. 1994. *Ubwoba: les champignons comestibles du Burundi*. Publication Agricole 34. Brussels, Adminstration générale de la Coopération au Développement.

Buyck, B. 2008. The edible mushrooms of Madagascar: an evolving enigma. *Economic Botany*, 62, 509–520. https://doi.org/10.1007/s12231-008-9029-4

Cai, Z., Hansen, L.S., Laursen, S.F., Nielsen, H.M., Bahrndorff, S., Tomberlin, J.K., Kristensen, T.N., Sørensen J.G. & Sahana, G. 2024. Whole-genome sequencing of two captive black soldier fly populations: implications for commercial production. *Genomics*, 116(5): 110891. https://doi.org/10.1016/j.ygeno.2024.110891

Cardoso, P., Barton, P.S., Birkhofer, K., Chichorro, F. Deacon, C., Fartmann, T., Fukushima, C.S. *et al*. 2020. Scientists' warning to humanity on insect extinctions. *Biological Conservation*, *2*42: 108426. https://doi.org/10.1016/j.biocon.2020.10842

Carpenter, M.H. & Harpur, B.A. 2021. Genetic past, present, and future of the honey bee (*Apis mellifera*) in the United States of America. *Apidologie*, 52: 63–79. https://doi.org/10.1007/s13592-020-00836-4

Carpio, A.J., García, M., Hillström, L., Lönn, M., Carvalho, J., Acevedo, P. & Bueno, C.G. 2022. Wild boar effects on fungal abundance and guilds from sporocarp sampling in a boreal forest ecosystem. *Animals*, 12, 2521. https://doi.org/ 10.3390/ani12192521

Cattaneo-Vietti, R., Doneddu, M. & Trainito, E. 2016. *Man and shells: molluscs in the history*. Sharjah, United Arab Emirates, Bentham Science Publishers.

CEFA (China Edible Fungus Association). 2022. Analysis of the results of the 2020 national edible fungi statistical survey. *Edible Fungi of China*, 45: 81–96**.** (In Chinese).

CEFA. 2024. Analysis of the results of the 2022 national edible fungi statistical survey. *Edible Fungi of China*, 43: 118–126. (In Chinese).

Cerritos, R. 2009. Insects as food: an ecological, social and economical approach. *CAB Reviews*, 4: 27. https://doi.org/10.1079/pavsnnr20094027

Chirps. 2024. *Chirps: our story*. [Cited 3 August 2024]. https://eatchirps.com/pages/our-story-2

Cobbinah, J.R., Vink A. & Onwuka, B. 2008. *Snail farming: production, processing and marketing*. Wageningen, the Netherlands, Agromisa Foundation.

Collen, B., Böhm, M., Kemp, R. & Baillie, J.E.M. 2012. *Spineless: status and trends of the world's invertebrates*. London, Zoological Society of London. https://cms.zsl.org/sites/default/files/2022-12/spineless-lr-2039.pdf

Cook, L. 2013. *The mushroom hunters on the trail of an underground America*. New York, USA, Ballantine Books.

Côté-Andreetti, C. 2024. How the farming of edible insects takes pressure off protected primates. In: *FAO*. [Cited 10 February 2025]. https://www.fao.org/newsroom/story/how-insects-are-helping-to-save-the-lemur-in-madagascar/en

Cunningham, A.B. & Yang, X., eds. 2011. *Mushrooms in forests and woodlands: resource management, values and local livelihoods*. London, Earthscan.

de Kesel, A., Codjia, J.T.C. & Yorou, N.S. 2002. *Guide des champignons comestibles du Bénin*. Brussels, Jardin Botanique de Belgique.

de Miguel, S., Bonet, J.A., Pukkala, T. & Martínez de Aragón, J. 2014. Impact of forest management intensity on landscape-level mushroom productivity: a regional model-based scenario analysis. *Forest Ecology and Management*, 330: 218–227. https://doi.org/10.1016/j.foreco.2014.07.014

de Roman, M. & Boa, E.R. 2006. The marketing of *Lactarius deliciosus* in Northern Spain. *Economic Botany*, 60, 284–290. https://doi.org/10.1663/0013-0001(2006)60[284:TMOLDI]2.0.CO;2

de Roman, M., Boa, E.R. & Woodward, S. 2006. Wild-gathered fungi for health and rural livelihoods. *Proceedings of the Nutrition Society*, 65(2): 190–197. https://doi.org/10.1079/PNS2006491

Degreef, J., Kasongo, B., Niyongabo, E. & De Kesel, A. 2020. Edible mushrooms, a vulnerable ecosystem service from African miombo woodlands. *Biotechnology, Agronomy, Society and Environment*. 24(2): 70–80. https://doi.org/10.25518/1780-4507.18508

Dejene, T., Oria-de-Rueda, J.A. & Martín-Pinto, P. 2017. Edible wild mushrooms of Ethiopia: neglected non-timber forest products. *Revista Fitotecnia Mexicana*, 40(4): 391–397.

Diritto Vitivinicolo. 2022. Tartufi piano nazionale filiera 2017-2020. In: *Diritto Vitivinicolo*. [Cited 13 August 2024]. https://dirittovitivinicolo.eu/tag/piano-nazionale-filiera

Ditchkoff, S.S. & Mayer, J.J. 2009.Wild pig food habits. In: J.J. Mayer & I. Lehr Brisbin, Jr, eds. *Wild pigs: biology, damage, control techniques, and management*, pp. 105–143, Aiken, USA, Savanna River National Laboratory.

Dörper, A., Berman, H.M., Gort, G., Dicke, M. & Veldkamp, T. 2022. Effect of feeding black soldier fly larvae products to slow growing broilers on performance and health. *Journal of Insects as Food and Feed*, 8: S30.

Dossey, A.T., Oppert, B., Chu, F.C., Lorenzen, M.D., Scheffler, B., Simpson, S., Koren, S., Johnston, J.S., Kataoka, K. & Ide, K. 2023. Genome and genetic engineering of the house cricket (*Acheta domesticus*): A resource for sustainable agriculture. *Biomolecules*, 13(4): 589. https://doi.org/10.3390/biom13040589

Downer, R.G.H. & Matthews, J.R. 1976. Lipid distribution and utilization in insects. *American Zoologist*, 16(4): 733–745.

Du Bois, C.M. 2018. *The story of soy*. London, Reaktion Books.

Dufour, D.L. 1987. Insects as food: a case study from the northwest Amazon. *American Anthropologist*, 89(2): 383–397. https://www.jstor.org/stable/677762

Dufour, D.L. & Sander, J.B. 2000. Insects. In: K.F. Kiple & K.C. Ornelas, eds. *The Cambridge world history of food*, pp. 546–554. Cambridge, UK, Cambridge University Press.

Dzerefos, C.M. 2018. Conservation of edible insects in sub-Saharan Africa. In: A. Halloran, R. Flore, P. Vantomme & N. Roos, eds. *Edible insects in sustainable food systems*, pp. 181–197. Cham, Switzerland, Springer.

EFSA (European Food Standards Agency). 2024. Modification of the temporary maximum residue levels for mepiquat in cultivated fungi and oyster mushrooms. In: *EFSA*. [Cited 4 August 2024]. https://www.efsa.europa.eu/en/efsajournal/pub/8476#:~:text=Based%20on%20the%20risk%20assessment,agricultural%20practices%20is%20unlikely%20to

Egli, S., Peter, M., Buser, C., Stahel,W. & Ayer, F. 2006. Mushroom picking does not impair future harvests—results of a long-term study in Switzerland. *Biological Conservation*, 129(2): 271–276. https://doi.org/10.1016/j.biocon.2005.10.042

Egli, S. 2011. Mycorrhizal mushroom diversity and productivity – an indicator of forest health? *Annals of Forest Science*, 68, 81–88. https://doi.org/10.1007/s13595-010-0009-3

Egonyu, J.P., Subramanian, S., Tanga, C.M., Dubois, T., Ekesi, S. & Telemu, S. 2021. Global overview of locusts as food, feed and other uses. *Food Security*, 31: 100574. https://doi.org/10.1016/j.gfs.2021.100574

Egonyu, J.P., Wanjala, M.N., Olubowa, R.R., Orinda, M., Nyongesah, J.M., Tanga, C.M., Cheseto, X., Kassie, M. & Subramanian S. 2022. Beetle grubs as a source of food and feed in western Kenya: cultural practices and nutritional status. *Journal of Insects as Food and Feed*, 8: S112.

Eleftheriou, E., Vacherie, B., Labadie, K., Athanassiou, C.G., Rigaud, T., Moret, Y., Lefebvre, T. & Madoui, M.A. 2022. *Tenebrio molitor* genomic structure among available populations. In: R.F. Veerkamp & Y. de Haas, eds. *Proceedings of 12th World Congress on Genetics Applied to Livestock Production (WCGALP)*, pp. 2549–2551. Wageningen, the Netherlands, Wageningen Academic. https://doi.org/10.3920/978-90-8686-940-4

European Commission. 2023. Approval of fourth insect as a Novel Food. In: *Food Safety*. [Cited 3 August 2024]. https://food.ec.europa.eu/safety/novel-food/authorisations/approval-insect-novel-food_en

Facchini, E., Shrestha, K., Van Den Boer, E., Junes, P. Sader, G. Peeters, K. & Schmitt, E. 2022. Results of a genetic improvement program of *Hermetia illucens* for increased larval weight – industrial applications. *Journal of Insects as Food and Feed*, 8: S58.

FAO (Food and Agriculture Organization of the United Nations). 2009. *Eucalyptus in East Africa: the socioeconomic and environmental issues*. Addis Ababa, FAO Sub-regional Office Eastern Africa.

FAO. 2019a. *Report of the Seventeenth Regular Session of the Commission on Genetic Resources for Food and Agriculture. Rome, Rome, 18–22 February 2019*. CGRFA-17/19/Report. Rome. https://openknowledge.fao.org/handle/20.500.14283/mz618en

FAO. 2019b. *The State of the World's Biodiversity for Food and Agriculture*, J. Bélanger & D. Pilling eds. FAO Commission on Genetic Resources for Food and Agriculture Assessments. Rome. https://doi.org/10.4060/CA3129EN

FAO. 2021. *Looking at edible insects from a food safety perspective. Challenges and opportunities for the sector*. Rome. https://doi.org/10.4060/cb4094en

FAO. 2023. *Contribution of terrestrial animal source food to healthy diets for improved nutrition and health outcomes – An evidence and policy overview on the state of knowledge and gaps*. Rome. https://doi.org/10.4060/cc3912en

FAO. 2024. *Desert locust.* [Cited 3 August 2024]. https://www.fao.org/locusts/en/

Ferreira, M.P., Cuerrier, A., Giroux, M. & Norton, C.H. 2018 Insect consumption in the Arctic. In: A. Halloran, R. Flore, P. Vantomme & N. Roos, eds. *Edible insects in sustainable food systems*, pp. 19–34. Cham, Switzerland, Springer.

Floccia, F., Ercole, S., Eyjólfsdóttir, G.G., Fodor, L.K., Giacanelli, V., Gonçalves, S.C., Madesis P. *et al*. 2024. *JoNeF survey report: survey of macrofungi conservation and data collection in*

Europe. Brussels, European Union Network for the Implementation and Enforcement of Environmental Law. https://www.impel.eu/en/projects/joint-network-for-wild-fungi-jonef

Fortuna, T.M., Le Gall, P., Mezdour, S. & Calatayud, P.A. 2022. Impact of invasive insects on native insect communities. *Current Opinion in Insect Science*, 51: 100904. https://doi.org/10.1016/j.cois.2022.100904

Fowles, T.M. & Nansen, C. 2020. Insect-based bioconversion: value from food waste. In: E. Närvänen, N. Mesiranta, M. Mattila, & A. Heikkinen, eds. *Food waste management*, pp. 321–346. Cham, Switzerland, Palgrave Macmillan.

Franklin, A., Sandrin, F., Asaha, S., Abid, C. & Kabangu, N. 2022. Insect farming in support of wildlife conservation efforts in the Okapi Wildlife Reserve, D.R. Congo. *Journal of Insects as Food and Feed*, 8: S29.

Frankopan, P. 2023. *The Earth transformed: an untold story*. New York, USA. Alfred A. Knopf.

FSN (Food Safety News). 2024. *Woman pleads not guilty in Australian mushroom case.* [Cited 7 August 2024]. https://www.foodsafetynews.com/2024/05/woman-pleads-not-guilty-in-australian-mushroom-case/

Fukushima, C.S. 2024. Legal and illegal trade in insects. In: J.S. Pryke, M.J. Samways, T.R. New, P. Cardoso & R. Gaigher, eds. *Routledge handbook of insect conservation*, pp. 502–515. New York, USA, Taylor & Francis.

Gadzama, I.U. & Ndudim, R.K. 2022. Deep-fried grasshoppers a delicacy in Maiduguri north eastern Nigeria. *Journal of Insects as Food and Feed*, 8: S16.

Generalovic, T.N., Sandrock, C., Roberts, B., Hauser, M., Pippan, M., Durbin, R. & Jiggins, C.D. 2022. Population genetics and domestication of the black soldier fly (*Hermetia illucens*). *Journal of Insects as Food and Feed*, 8: S59.

Generalovic, T.N., Sandrock, C., Roberts, B.J., Meier, J.I., Hauser, M., Warren, I.A., Pipan,M., Durbin, R. & Jiggins, C.D. 2023. Cryptic diversity and signatures of domestication in the Black Soldier Fly (*Hermetia illucens*). *bioRxiv*, 10.21.563413. https://doi.org/10.1101/2023.10.21.563413

Gheoca, V. 2013. Edible land snail *Helix pomatia*'s exploitation in Central Romania: Legislation, evolution, perspectives. In: *Advances in Environment, Ecosystems and Sustainable Tourism*. Proceedings of the 11th International Conference on Environment, Ecosystems and Development (EED '13). Proceedings of the 2nd International Conference on Sustainable Tourism and Cultural Heritage (STACH '13), Brasov, Romania, June 1–3, 2013, pp. 144–149. WSEAS Press.

Gowda, K.B. Jerry, D.R. & Zender, K.R. 2025**.** Genetic improvement of farmed insect species: programmes, progress, and prospects. *Journal of Insects as Food and Feed* ((published online ahead of print 2025). https://doi.org/10.1163/23524588-00001387

Grabowski N.T., Tchibozo S., Abdulmawjood, A., Acheuk, F., Guerfali, M.M. Sayed, W.A.A. & Plötz, M. 2020. Edible insects in Africa in terms of food, wildlife resource, and pest management legislation. *Foods*, 9(4): 502. https://doi.org/10.3390/foods9040502

Gruber, K., Melton, L. & Nature Magazine, 2023. How gene-edited insects are providing food, fuel and waste disposal. In: *Scientific American.* [Cited 3 August 2024]. https://www.scientificamerican.com/article/how-gene-edited-insects-are-providing-food-fuel-and-waste-disposal/

Guidou, C., Trespeuch, C., De Swaef, E. & Dantas Lima, J. 2022. Partially defatted black soldier fly meal inclusion in Pacific white shrimp diets: effects on growth performances. *Journal of Insects as Food and Feed*, 8: S35.

Guiné, R.P.F., Florença S.G., Correia P.M.R., Anjos, O., Coelho, C. & Costa, C.A. 2022. Honey bee (*Apis mellifera*) broods: composition, technology and gastronomic applicability. *Foods,* 11(18): 2750. https://doi.org/10.3390/foods11182750

Hall, I.R., Brown, G.T. & Zambonelli, A. 2007. *Taming the truffle: the history, lore, and science of the ultimate mushroom*. Portland, USA, Timber Press.

Halloran, A. 2014. *Discussion paper: Regulatory frameworks influencing insects as food and feed*. Rome, FAO. https://www.fao.org/edible-insects/39620-04ee142dbb758d9a521c619f31e28b004.pdf

Halloran, A., Vantomme, P., Hanboonsong, Y. & Ekesi, S. 2015. Regulating edible insects: The challenge of addressing food security, nature conservation, and the erosion of traditional food culture. *Food Security,* 7: 739–746. https://doi.org/10.1007/s12571-015-0463-8

Halsch, C.A., Shapiro, A.M., Fordyce, J.A., Nice, C.C., Thorne, J.H., Waetjen, D.P. & Forister, M.L. 2021. Insects and recent climate change. *Proceedings of the National Academy of Sciences,* 118: e2002543117. https://doi.org/10.1073/pnas.200254311

Hanboonsong, Y. & Durst, P. 2020. *Guidance on sustainable cricket farming: a practical manual*. Rome. FAO. https://openknowledge.fao.org/server/api/core/bitstreams/2043dd6d-0239-47e9-a93a-f1d750eb9be8/content

Hansen, L.S., Laursen, S.F., Bahrndorff, S., Sørensen, J.G., Sahana, G., Kristensen, T.N. & Nielsen, H.M. 2024. The unpaved road towards efficient selective breeding in insects for food and feed—A review. *Entomologia Experimentalis et Applicata*, 00: 1–24. https://doi.org/10.1111/eea.13526

Härkönen, M., Niemelä, T., Mbindo, K., Kotiranta, H. & Piearce, G, 2015. *Zambian mushrooms and myccology.* Norrlinia 29. Helsinki, Finnish Museum of Natural History.

Härkönen, M., Niemelä, T. & Mwasumbi, L. 2003. *Tanzanian mushrooms. Edible, harmful and other fungi.* Norrlinia 10. Helsinki, Finnish Museum of Natural History.

Harvey, J.A., Tougeron, K., Gols, R., Heinen, R.M., Abarca, M., Abram, P.K., Basset, Y. *et al*. 2023. Scientists' warning on climate change and insects. *Ecological Monographs,* 93: e1553. https://doi.org/10.1002/ecm.1553

Hernández-Rodríguez, D., Osorio-Carballo, B., Fernádez-Tepach, F. & Melgar-Lalanne, G. 2022. Pesticide residues were not found in the Mexican chapulin (*Sphenarium purpurascens*) harvested from cornfields. *Journal of Insects as Food and Feed,* 8: S117.

Heuel, M., Sandrock, C., Leiber, F., Mathys, A., Gold, M., Zurbrügg, C., Gagnat, I.D.M., Kreuzer, M. & Terranova, M. 2021. Black soldier fly larvae meal and fat can completely replace soybean cake and oil in diets for laying hens. *Poultry Science,* 100: 101034. https://doi.org/10.1016/j.psj.2021.101034

Hull, K.L., Greenwood, M.P., Lloyd, M., Brink-Hull, M., Bester-van der Merwe, A.E. & Rhode, C. 2024. Drivers of genomic diversity and phenotypic development in early phases of domestication in *Hermetia illucens*. *Insect Molecular Biology*, 33(6): 756–776. https://doi.org/10.1111/imb.12940

Hyde, K.D. 2022. The numbers of fungi. *Fungal Diversity,* 114: 1. https://doi.org/10.1007/s13225-022-00507-y

ICIPE (International Centre of Insect Physiology and Ecology). 2024. *ICIPE Annual Report 2023*. Nairobi. http://www.icipe.org/sites/default/files/icipe-Annual-Report2023.pdf.

Illgner, P. & Nel, E. 2000. The geography of edible insects in sub-Saharan Africa: a study of the mopane caterpillar. *Geographical Journal,* 166(4): 336–351. https://doi.org/10.1111/j.1475-4959.2000.tb00035.x

Incredible Project. 2020. *Regulation of mycological harvesting in Castilla y León MICOCYL.* Soria, Spain. https://www.nwfps.org/wp-content/uploads/2021/03/Regulation-of-mycological-harvesting-in-Castilla-y-Leon-MICOCYL-min.pdf

INSECTINOV-Sud. 2024. Innover pour produire et valoriser les insectes et leurs productions. In: *Institut de Recherche pour le Développement*. [Cited 3 August 2024]. https://www.ird.fr/irn-insectinov-sud-innover-pour-produire-et-valoriser-les-insectes-et-leurs-productions

IPIFF (International Platform of Insects for Food and Feed). 2024. Insects as food. [Cited 3 August 2024]. https://ipiff.org

Jensen A.B. & Lecocq, A. 2022. Diseases of black soldier flies, research and diagnostic tools. *Journal of Insects as Food and Feed,* 8: S144.

Jensen, K., Kristensen, T.N., Heckmann, L.H. & Sørensen, J.G. 2017. Breeding and maintaining high-quality insects. In: A. van Huis & J.K. Tomberlin, eds. *Insects as food and feed: from production to consumption*, pp. 174–198. Wageningen, the Netherlands, Wageningen Academic Publishers.

Jongema, Y. 2017. *List of edible insects of the world*. Wageningen, the Netherlands, Wageningen University and Research. https://www.wur.nl/en/research-results/chair-groups/plant-sciences/laboratory-of-entomology/edible-insects/worldwide-species-list.htm

Jyothi, K.R. & Thara, S.S. 2021. Development of improved strain in species of *Pleurotus* by gamma irradiation. *Journal of Food Science and Technology*, 58, 3540–3547. https://doi.org/10.1007/s13197-021-05059-8

Kauserud, H., Stige L.C., Vik, J.O., Økland, R.H. & Høiland, K. 2008. Mushroom fruiting and climate change. *PNAS*, 105 (10): 3811–3814. https://doi.org/10.1073/pnas.0709037105

Kaya, C., Generalovic, T.N., Ståhls, G., Hauser, M., Samayoa, A.C. Nunes-Silva, C.G. Roxburgh, H. *et al*. 2021. Global population genetic structure and demographic trajectories of the black soldier fly, *Hermetia illucens. BMC Biology*, 19: 94. https://doi.org/10.1186/s12915-021-01029-w

Kelemu, S. 2015. Insects: an overlooked food source. *International Journal of Tropical Insect Science,* 35: 1–2. https://doi.org/10.1017/S174275841500003X

Kenis, M., Sileshi, G., Mbata, K. Chidumayo, E., Meke, G. & Muatinte B. 2006. *Towards conservation and sustainable utilization of edible caterpillars of the miombo*. Presentation to the SIL Annual Conference on Trees for Poverty Alleviation, 9 June 2006, Zürich, Switzerland. https://apps.worldagroforestry.org/downloads/Publications/PDFS/PP06315.pdf

Kirk, J & Kirk, K. 2021. Controlled indoor cultivation of Black Morel (Morchella sp.) All-year-round. In: *Danish Morel Project*. [Cited 7 August 2024]. https://thedanishmorelproject.com/

Kinyuru, J. & Ndung'u, N. 2022. Edible insects regulatory national standards in Kenya: an incentive or a deterrent? *Journal of Agriculture Science & Technology*, 21(40): 1–3. https://doi.org/10.4314/jagst.v21i4.1

Klimaszyk, P. & Rzymski, P. 2018 The yellow knight fights back: toxicological, epidemiological, and survey studies defend edibility of *Tricholoma equestre* . *Toxins* 10(11): 468. https://doi.org/10.3390/toxins10110468

Krafsur, E.S., Cummings, M.A., Endsley, M. ., Marquez, J.G., & Nason, J.D. (2005). Geographic differentiation in the house fly estimated by microsatellite and mitochondrial variation. *Journal of Heredity*, 96(5), 502–512. doi:10.1093/jhered/esi093

Krongdang, S., Phokasem, P., Venkatachalam, K. & Charoenphun, N. 2023. Edible insects in Thailand: an overview of status, properties, processing, and utilization in the food industry. *Foods*, 12(11): 2162. https://doi.org/10.3390/foods12112162

Kumschick, S., Devenish, A., Kenis, M., Rabitsch, W., Richardson, D.M. & Wilson, J.R.U. 2016. Intentionally introduced terrestrial invertebrates: patterns, risks, and options for management. *Biological Invasions*, 18: 1077–1088. https://doi.org/10.1007/s10530-016-1086-5

Laessoe, T. & Petersen, J.H. 2019. *Fungi of temperate Europe.* Volumes 1 and 2. Princeton, USA, Princeton University Press.

Lähteenmäki-Uutela, A., Marimuthu, S.B. & Meijer, N. 2021. Regulations on insects as food and feed: A global comparison. *Journal of Insects as Food and Feed*, 7: 849–856. https://doi.org/10.3920/JIFF2020.0066

Laird, S.A., Wynberg, R. & Mclain, R.J. 2009. *Wild product governance: laws and policies for sustainable and equitable non-timber forest product use*. United Nations University, Centre for International Forestry Research, People and Plants International, University of Cape Town, Institute for Culture and Ecology.

Landsman, A.P., Schmit, J.P. & Matthews, E.R. 2021. Invasive plants differentially impact forest invertebrates, providing taxon-specific benefits by enhancing structural complexity. *Frontiers in Ecology and Evolution*, 9: 682140. https://doi.org/10.3389/fevo.2021.682140

Lange, K.W. & Nakamura, Y. 2021. Edible insects as future food: chances and challenges. *Journal of Future Foods*, 1(1): 38–46. https://doi.org/10.1016/j.jfutfo.2021.10.001

Latham, P. 2015. *Edible caterpillars and their food plants in Bas-Congo province, Democratic Republic of Congo*. Kinshasa, Salvation Army.

Latham, P., Malaisse, F., Mbuta, A.K.K., Razafimanantsoa, T.M., Mabossy-Mobouna, G., Malasi, F.M. & Bouyer, T. 2024. *Caterpillars and chrysalises eaten in Africa.* Published by P. Latham.

Lautenschläger, T. 2022. *Riquezas naturais de Uíge – Serra do Pingano. Uma nova área protegida no Norte de Angola*. Dresden, Germany, Technische Universität Dresden.

Ledbetter, M., Wilkin, J.D, Mubaiwa, J., Manditsera, FA., Mackeka, L., Ruzengwe, F.M. & Madimutsa, O.N. 2024. Development of a nutritious cereal-based instant porridge by the incorporation of protein-rich insect powder – an example from Zimbabwe. *Journal of Functional Foods*, 112: 105957. https://doi.org/10.1016/j.jff.2023.105957

Leonard, A. 2021. *The role of host plants, temperature and natural enemies in the development, survival and reproduction of edible grasshopper* Ruspolia differens *(Orthoptera: Tettigoniidae)*. Kampala, Makerere University. Doctoral dissertation.

Lesnik, J. 2019. *Edible insects and human evolution*. Gainesville, USA, University Press of Florida.

Li, H., Tian, Y., Menolli, N. Jr, Ye, L., Karunarathna, S.C., Perez-Moreno, J. & Rahman, M.M. 2021. Reviewing the world's edible mushrooms: a new evidence-based classification scheme. *Comprehensive Reviews in Food Science and Food Safety*, 20(2): 1982–2014. https://doi.org/10.1111/1541-4337.12708

Li, F., Zhang, J. & Cai, M. 2022. Characterisation of penicillin bio-degradation in solid waste treatment by *Hermetia illucens* L. larvae. *Journal of Insects as Food and Feed*, 8: S81.

Liceaga, A.M. 2021. Processing insects for use in the food and feed industry. *Current Opinion in Insect Science*, 48: 32–36. https://doi.org/10.1016/j.cois.2021.08.002

Lockwood, J.R. 2010. The fate of the Rocky Mountain locust, *Melanoplus spretus*: implications for conservation biology. *Terrestrial Arthropod Reviews*, 3(2), 129–160. https://doi.org/10.1163/187498310X523874

Luoma, D.L., Eberhart, J.L., Abbott, R., Moore, A., Amaranthus, M.P. & Pilz, D. 2006. Effects of mushroom harvest technique on subsequent American matsutake production. *Forest Ecology and Management*, 236(1), 65–75. https://doi.org/10.1016/j.foreco.2006.08.342

Lusheng, L., Zhang, J., Shang, R. & Wang, G. 2022. Influences of fish and defatted black soldier larvae meal diets on the growth of juvenile Chinese soft-shelled turtles. *Journal of Insects as Food and Feed*, 8: S36.

Madsen, D.B. 1989. A grasshopper in every pot. *Natural History*, 7(89): 22–25.

Madsen, D.B. & Kirkman J.E. 1988. Hunting hoppers. *American Antiquity*, 53(3): 593–604. https://doi.org/10.2307/281220

Martinez de Arano, I., Maltoni, S., Picardo, A. & Mutke, S. 2021. *Non-wood products for people, nature and the green economy. Recommendations for policy priorities in Europe. A white paper based on lessons learned from around the Mediterranean.* EFI and FAO, Barcelona. https://doi.org/10.36333/k2a05

Mayett, Y., Martínez-Carrera, D., Sánchez, M., Macías, A., Mora, S. & Estrada-Torres, A. 2006. Consumption trends of edible mushrooms in developing countries: the case of Mexico. *Journal of International Food & Agribusiness Marketing*, 18(1/2): 151–177. https://doi.org/10.1300/J047v18n01_08

McGavin, G. 2024. *The good bug: a celebration of insects (and what we can do to protect them).* London, Michael O'Mara.

Melkov, A. 2024. Leveraging sustainable genetic technologies to expand and improve the black soldier fly market and products. Beta Bugs News. In: *Better Bugs*. [Cited 20 November 2024]. https://www.betabugs.uk/leveraging-sustainable-genetic-technologies-to-improve-the-black-soldier-fly/

Mhemdi, H. & Mezdour, S. 2022. Extraction of protein from caterpillar larvae by mechanical pressing assisted by pulsed electric field treatment. *Journal of Insects as Food and Feed*, 8: S13.

Middle East Eye. 2023. The murders of Syrian truffle hunters are not all they seem. In: *Middle East Eye*. [Cited 4 August 2024]. https://www.middleeasteye.net/news/syria-truffle-hunters-murders-not-all-seem

Moir, M.L., Vesk, P.A., Brennan, K.E., Poulin, R., Hughes, L., Keith, D.A., McCarthy, M.A. & Coates, D.J. 2012. Considering extinction of dependent species during translocation, ex situ conservation and assisted migration of threatened hosts. *Conservation Biology*, *2*6(2): 199–207. https://doi.org/10.1111/j.1523-1739.2012.01826.x

Morera, A., LeBlan, H., Martínez de Aragón, J., Bonet, J. & de Miguel, S. 2024. Analysis of climate change impacts on the biogeographical patterns of species-specific productivity of socioeconomically important edible fungi in Mediterranean forest ecosystems. *Ecological Informatics*, 81: 102557. https://doi.org/10.1016/j.ecoinf.2024.102557

Morte, A., Kagan-Zur, V., Navarro-Ródenas, A. & Sitrit, Y. 2021. Cultivation of desert truffles – a crop suitable for arid and semi-arid zones. *Agronomy,* 11(8): 1462. https://doi.org/10.3390/agronomy11081462

Moyet, M., Kinney, M., Bernard, E. & Alyokhin, A. 2022. Suppression of methicillin-resistant *Staphylococcus aureus* by larvae of black soldier fly, *Hermetia illucens. Journal of Insects as Food and Feed,* 8: S26.

Mueller, G.M., Cunha, K.M., May, T.W., Allen, J.L., Westrip, J.R.S., Canteiro, C., Costa-Rezende, D.H. *et al*. 2022. What do the first 597 global fungal red list assessments tell us about the threat status of fungi? *Diversity,* 14(9): 736. https://doi.org/10.3390/d14090736

Muir, G.F., Sorrenti, S., Vantomme, P., Vidale, E. & Masiero, M. 2020. Into the wild: Disentangling non-wood terms and definitions for improved forest statistics. *International Forestry Review, 2*2(1): 101–119. https://doi.org/10.1505/146554820828671553

Musundire, R., Ngonyama, D., Chemura, A., Ngadze R.T., Jackson, J., Matanda, M.J., Tarakini, T., Langton, M. & Chiwona-Karltun, L. 2021. Stewardship of wild and farmed edible insects as food and feed in sub-Saharan Africa: a perspective. *Frontiers in Veterinary Science,* 8: 601386. https://doi.org/10.3389/fvets.2021.601386

Mushroom Initiative. 2025. Ectomycorrhizal reforestation - projects in Southeast Asia. In: *Mushroom Initiative*. [Cited 21 January 2025]. https://www.ecomushrooms.org/en/ectomycorrhizal-reforestation-2/

Mvodo Meyo, E.S., Nkemasong, Z.A., Shu G., Ngono, J.P.N. & Ngosong, C. 2021. Snail farming as an alternative profitable livestock system for sustainable development. In: W. Leal Filho, R. Pretorius & L.O. de Sousa, eds. *Sustainable development in Africa: fostering sustainability in one of the world's most promising continents,* pp. 477–490. Cham, Switzerland, Springer.

Nalunga, J. 2023. Rearing crickets for food and feed [video]. In: *Access Agriculture.* https://www.accessagriculture.org/rearing-crickets-food-and-feed

Ndiaye, W.N., Brehmer, P., Deschamps, M.-H., Corréa, M., Diédhiou, F., Kantoussan, J., Braham, C.B. *et al*. 2022. West African context call for rapid implementation of insect meal for fishmeal substitution. *Journal of Insects as Food and Feed,* 8: S137.

Niassy, S., Omuse, R., Roos, N., Halloran, A., Eilenberg, Egonyu, J.P., Tanga, C. *et al*. 2022. Safety, regulatory and environmental issues related to breeding and international trade of edible insects in Africa. *Scientific and Technical Review,* 41: 117–131. https://doi.org/10.20506/rst.41.1.3309

Niego, A.G.T., Lambert, C., Mortimer, P. Thongklang, N., Rapior, S., Grosse, M., Schrey, H. *et al*. 2023. The contribution of fungi to the global economy. *Fungal Diversity,* 121: 95–137. https://doi.org/10.1007/s13225-023-00520-9

Niskanen, T. Lücking, R., Dahlberg, A., Gaya, E., Suz, L.M. Mikryukov, V., Liimatainen, K. *et al*. 2023. Pushing the frontiers of biodiversity research: unveiling the global diversity, distribution, and conservation of fungi. *Annual Review of Environment and Resources,* 8: 149–176. https://doi.org/10.1146/annurev-environ-112621-090937

Nordic Council of Ministers. 2012. *Mushrooms traded as food*. Copenhagen. https://norden.diva-portal.org/smash/get/diva2:701732/FULLTEXT01.pdf

Oldroyd, B.P. 2012. Domestication of honey bees was associated with expansion of genetic diversity. *Molecular Ecology,* 21: 4409–4411. https://doi.org/10.1111/j.1365-294x.2012.05641.x

Ombeni, J.B., Mabossy-Mobouna, G., Boyombe, L.L., Latham, P., Malaisse, F., Monzenga, J.-C. & Munyuli, T.B.M. 2022. Entomophagy in the Democratic Republic of Congo: challenges and ways forward for the edible insect sector. *African Journal of Tropical Entomology Research,* 1: 116–139. https://doi.org/10.5281/zenodo.6968717

Omuse, E.R., Tonnang, H.E.Z., Yusuf, A.A. Machekano, H., Egonyu, J.P., Kimathi, E., Mohamed, S.F. *et al*. 2024. The global atlas of edible insects: analysis of diversity and commonality contributing to food systems and sustainability. *Scientific Reports,* 14: 5045. https://doi.org/10.1038/s41598-024-55603-7

Oonincx, D.G.A.B. & Finke, M.D. 2021. Nutritional value of insects and ways to manipulate their composition. *Journal of Insects as Food and Feed,* 7: 639–659. https://doi.org/10.3920/JIFF2020.0050

Pechal, J.L., Valle De Souza, S., Benbow, M.E., Bennett, A., Adedeji, O.B. & Omonona, B.T. 2022. Piloting insect-to-fish farming systems in Nigeria. *Journal of Insects as Food and Feed,* 8: S32.

Peintner, U., Schwarz, S., Mešić, A., Moreau, P.-A., Moreno, G. & Saviuc, P. 2013. Mycophilic or mycophobic? Legislation and guidelines on wild mushroom commerce reveal different consumption behaviour in European countries. *PLoS ONE,* 8(5): e63926. https://doi.org/10.1371/journal.pone.0063926

Pérez-Moreno, J., Guerin-Laguette, A., Flores Arzú, R., Yu, F.Q. & Verbeken, A. 2020. Setting the scene. In: A. Guerin-Laguette, R. Flores Arzú & F.Q. Yu, eds. *Mushrooms, humans and nature in a changing world perspectives from ecological, agricultural and social sciences.* Cham, Switzerland, Springer.

Perreault, V., Haddad, C. & Doyen, A. 2022. Production of a mealworm protein ingredients by using food processes applied in the pulse and legume industries. *Journal of Insects as Food and Feed,* 8: S24.

Picard, C., Tomberlin, J.K., Jordan, H. & Preyer, C. 2022. Genotype-phenotype correlations in optimising biology: Lessons learned from other domesticated systems. *Journal of Insects as Food and Feed,* 8: S7.

Piggott, N. 2022. Unlocking the real value of insect meal. *Feed & Additive. International Magazine for Animal Feed and Additives Industry,* 2(21): 34–36.

Piña-Domínguez, I.A., Ruiz-May, E., Hernández-Rodríguez, D., Zepeda, R.C. & Melgar-Lalanne, G. 2022. Environmental effects of harvesting some Mexican wild edible insects: an overview. *Frontiers in Sustainable Food Systems,* 6: 1021861. https://doi.org/10.3389/fsufs.2022.1021861

Pissia, M.A., Matsakidou, A. & Kiosseoglou, V. 2021. Raw materials from snails for food preparation. *Future Foods,* 3: 100034. https://doi.org/10.1016/j.fufo.2021.100034

Precedence Research. 2024. *Edible insects market size, share, and trends 2024 to 2033*. [Cited 5 August]. https://www.precedenceresearch.com/edible-insects-market

Preteseille, N., Deguerry, A., Reverberi, M. & Weigel, T. 2018. Insects in Thailand: national leadership and regional development, from standards to regulations through association. In: A. Halloran, R. Flore, P. Vantomme & N. Roos, eds. *Edible insects in sustainable food systems,* pp. 435–442. Cham, Switzerland, Springer.

Presstv. 2021. Iran's customs seizes record $105 mln haul of truffle bound for Slovenia. In: Presstv. [Cited 4 August 2024]. https://www.presstv.ir/Detail/2021/08/21/664900/Iran-truffle-seizure-customs-office

Price, M.R., Sischo, D., Pascua, M. & Hadfield, M.G. 2015. Demographic and genetic factors in the recovery or demise of *ex situ* populations following a severe bottleneck in fifteen species of Hawaiian tree snails. *PeerJ* 3: e1406. https://doi.org/10.7717/peerj.1406

Procházka, P., Spukupva, J., Tomšik, K., Mullen, K.J. & Čabelková I. 2023. Climatic factors affecting wild mushroom foraging in Central Europe. *Forests,* 14: 382. https://doi.org/10.3390/f14020382

Prokofieva, I., Górriz-Mifsud, E., Bonet J.A. & Martínez de Aragón, J.. 2016. Viability of introducing payments for the collection of wild forest mushrooms in Catalonia (North-East Spain). *Small-scale forestry,* 16: 147–167. https://doi.org/10.1007/s11842-016-9348-8

Puliga, F., Illice, M., Iotti, M., Leonardi, P., Baghdadi, A., Mozafari, A.A. & Zambonelli, A. 2021. True truffle diversity in Iran. *Italian Journal of Mycology,* 50(1): 52–62. https://doi.org/10.6092/

Ramos-Elorduy, J. 2006.Threatened edible insects in Hidalgo, Mexico and some measures to preserve them. *Journal of Ethnobiology and Ethnomedicine,* 2: 51. https://doi.org/10.1186/1746-4269-2-51

Republic of Madagascar. 2017. *Plan National d'Action pour la Nutrition-III 2017-2021*. Antananarivo, Office National de Nutrition. https://faolex.fao.org/docs/pdf/Mad172682.pdf

Republic of Malawi. 2006. *National Nutrition Policy*. Lilongwe, Office of the President and Cabinet, Department of Nutrition, HIV and AIDS. https://faolex.fao.org/docs/pdf/mlw141072.pdf

Rhode, C., Badenhorst, R., Hull, K.L., Greenwood, M.P., Bester-van der Merwe, A.E., Andere, A.A., Picard**, C.J &** Richards**, C.** 2020. Genetic and phenotypic consequences of early domestication in black soldier flies (*Hermetia illucens*). *Animal Genetics,* 51: 752–762. https://doi.org/10.1111/age.12961

Roos, N. 2018.Insects and human nutrition. In: A. Halloran, R. Flore, P. Vantomme & N. Roos, eds. *Edible insects in sustainable food systems,* pp. 83–91. Cham, Switzerland, Springer.

Royse, D.J., Baars, J. &Tan, Q. 2017. Current overview of mushroom production in the world. In: D.C. Zied, & A. Pardo-Giménex. eds. *Edible and Medicinal Mushrooms: Technology and Applications,* pp. 5-13. New York, USA. Wiley.

Rosenberg, G. 2014 A new critical estimate of named species-level diversity of the recent Mollusca. *American Malacological Bulletin,* 32: 308–322. http://dx.doi.org/10.4003/006.032.0204

Rubel, W.D. & Arora, D. 2008. A study of cultural bias in field guide determinations of mushroom edibility using the iconic mushroom, *Amanita muscaria,* as an example. *Economic Botany,* 62: 223–243. https://doi.org/10.1007/s12231-008-9040-9

Rygało-Galewska, A., Zglińska, K. & Niemiec, T. 2022. Edible snail production in Europe. *Animals,* 12: 2732. https://doi.org/10.3390/ani12202732

Sánchez-Bayo, F. & Wyckhuys, K.A. 2019. Worldwide decline of the entomofauna: a review of its drivers. *Biological Conservation,* 232: 8–27. https://doi.org/10.1016/j.biocon.2019.01.020

Schunko, C. Li, X., Klappoth, B., Lesi, F., Porcher, V., Porcuna-Ferrer, A. & Reyes-García, V. 2022. Local communities' perceptions of wild edible plant and mushroom change: a systematic review. *Global Food Security,* 32. https://doi.org/10.1016/j.gfs.2021.100601

Sekonya, J.G. 2021. *Governance, Informality and Agency in the Making of Cross-Border Mopane Worm Livelihoods in Southern Africa.* Cape Town, South Africa, University of Cape Town. PhD Thesis.

Sekonya, J.G. & Wynberg, R.P. 2022. Navigating the governance and commercialisation pitfalls in edible insect informal crossborder trade. *Journal of Insects as Food and Feed,* 8: S124.

Sellem, E., Paul, K., Donkpegan, A., Li, Q., Masseron, A., Chauveau, A., Gagnepain-Germain, F. & Lefebvre, T. 2024. Multitrait genetic parameter estimates in a *Tenebrio molitor* reference population: high potential for breeding gains. *Animal,* 18(6): 101197. https://doi.org/10.1016/j.animal.2024.101197

Senn-Irlet, B., Heilmann-Clausen, J., Genney, D. & Dahlberg, A. 2007. *Guidance on conservation of macrofungi in Europe.* Prepared for the European Council for Conservation of Macrofungi. Strasbourg, France. http://www.eccf.eu/Guidance_Fungi.pdf.

Sheldrake, M. 2020. *Entangled Life: How fungi make our worlds, change our minds and shape our futures.* London, Bodley Head.

Siddiqui1, S.A., Asante, K., Ngah, N., Saraswati, Y.R., Wu, Y.S., Lahan, M., Aidoo, O.F., Fernando, I., Povetkin, S.N. & Castro-Muñoz, R. 2024. Edible dragonflies and damselflies (order Odonata) as human food – A comprehensive review. *Journal of Insects as Food and Feed,* 10(12): 1947–1972. https://doi.org/10.1163/23524588-20230097

Sileshi, G.W., Tibuhwa, D.D. & Mlambo, A. 2023. Underutilized wild edible fungi and their undervalued ecosystem services in Africa. *CABI Agriculture and Bioscience* 4: 3. https://doi.org/10.1186/s43170-023-00145-7

Silva, G.M., Thiengo, S.C., Jeraldo, V.S., Rego, M.I.F., Silva A.B.P., Rodrigues P.S. & Gomes S.R. 2022. The invasive giant African land snail, *Achatina fulica* (Gastropoda: Pulmonata): global geographical distribution of this species as host of nematodes of medical and veterinary importance. *Journal of Helminthology,* 96: e86. https://doi.org/10.1017/S0022149X22000761

Sitta, N. & Davoli, P. 2012. *Edible mycorrhizal mushrooms: international markets and regulation.* In: A. Zambonelli & G.M. Bonito, eds. Edible ectomycorrhizal mushrooms. Current knowledge and future prospects. London, Springer.

Slagboom, M., Nielsen, H.M., Kargo, M., Henryon, M. & Hansen, L.S. 2024. The effect of phenotyping, adult selection, and mating strategies on genetic gain and rate of inbreeding in black soldier fly breeding programs. *Genetics Selection Evolution,* 56: 71. https://doi.org/10.1186/s12711-024-00938-y

Song, J. H., Chang, G. D., Ji, S., Kim, S.Y., & Kim, W. 2022. Selective breeding and characterization of a black mealworm strain of *Tenebrio molito*r Linnaeus (Coleoptera: Tenebrionidae). *Journal of Asia-Pacific Entomology,* 25(4): 101978. https://doi.org/10.1016/j.aspen.2022.101978

Sonntag, E., Vidal, A., Grimm, D., Rahmann, G., van Groenigen, J.W., van Zanten H. & Parodi A. 2023. Positioning earthworms in the future foods debate: A systematic review of earthworm nutritional composition in comparison to edible insects. *Journal of Insects as Food and Feed,* 10(5): 33–75. https://doi.org/10.1163/23524588-20230163

Stork, N.E. 2018. How many species of insects and other terrestrial arthropods are there on Earth? *Annual Review of Entomology,* 63: 31–45. https://doi.org/10.1146/annurev-ento-020117-043348

Stull, V. & Patz, J. 2020. Research and policy priorities for edible insects. *Sustainability Science,* 15(2): 633–645. https://doi.org/10.1007/s11625-019-00709-5

Sullivan, H. 2024. Singapore has approved 16 insects to eat as food: here's everything you need to know. *The Guardian.* 10 July 2024. London. [Cited 9 August 2024]. https://www.theguardian.com/environment/article/2024/jul/10/singapore-approves-insects-eat-food

SUSINCHAIN. 2023. *Sectoral roadmap and policy recommendations for supporting large-scale commercialisation of high-quality insect products in Europe*. Berlin. https://susinchain.eu/wp-content/uploads/2023/10/SUSINCHAIN-Roadmap-final2.pdf

Tahvanainen, V., Milna, J. & Kurttila, M. 2019. Climatic and economic factors affecting the annual supply of wild edible mushrooms and berries in Finland. *Forests*, 10(5): 385. https://doi.org/10.3390/f10050385

Tahvanainen, V., Milna, J., Kurttila, M. & Salo, K. 2016. Modelling the yields of marketed mushrooms in *Picea abies* stands in eastern Finland. *Forest Ecology and Management*, 362: 79–88. https://doi.org/10.1016/j.foreco.2015.11.040

Tang, C., Yang, D., Liao, H., Sun, H., Liu, C., Wei, L. & Li, F. 2019. Edible insects as a food source: a review. *Food Production, Processing and Nutrition*, 1: 8. https://doi.org/10.1186/s43014-019-0008-1

Tanga, C.M. & Kababu, M.O. 2023. New insights into the emerging edible insect industry in Africa. *Animal Frontiers*, 13(4): 26–40. https://doi.org/10.1093/af/vfad039

Tanga, C.M., Wamai, L.K., Osuga, I.M., Kidoido, M.M., Subramanian, S. & Ekesi, S. 2022. Insect meal in layer chicken diet enhances growth, egg production, egg quality, meat quality and farmer profitability. *Journal of Insects as Food and Feed*, 8: S36.

Taylor, G.S., Braby, M.F., Moir, M.L., Harvey, M.S., Sands, D.P.A., New, T.T., Kitching, R.L. *et al*. 2018. Strategic national approach for improving the conservation management of insects and allied invertebrates in Australia. *Austral Entomology*, 57: 124–149. https://doi.org/10.1111/aen.12343

Torres, G., Diaz, F., Okamura, Y., Messori, S. & Hutchinson, J. 2022. The World Organisation for Animal Health – current and potential roles in safe international trade of bees and other insects. *Revue Scientifique et Technique Office international des epizooties*, 41(1): 211–218. https://doi.org/10.20506/rst.41.1.3318

Turtiainen, M. & Nuutinen, T. 2011. Evaluation of information on wild berry and mushroom markets in European Countries. *Small-Scale Forestry*, 11: 131–145. https://doi.org/10.1007/s11842-011-9173-z

USDA (United States Department of Agriculture). 2024. Mushroom harvesting. In: *USDA*. [Cited 13 August 2024]. https://www.fs.usda.gov/detail/willamette/passes-permits/forestproducts/?cid=FSEPRD538700#:~:text=Everyone%20must%20have%20a%20valid,valid%20on%20all%20four%20forests

van den Eshof, S. 2022. Insect protein: A sustainable alternative. *Feed & Additive. International Magazine for Animal Feed and Additives Industry*, 2(21): 52–54.

van Huis, A. 2022a. Edible insects: challenges and prospects. *Entomological Research*, 52(4): 161–177. https://doi.org/10.1111/1748-5967.12582

van Huis, A. 2022b. Progress and prospects. *Journal of Insects as Food and Feed*, 8: S5.

van Huis, A. & Oonincx, D.G.A.B. 2017. The environmental sustainability of insects as food and feed. A review. *Agronomy for Sustainable Development*, 37: 43. https://doi.org/10.1007/s13593-017-0452-8.

van Huis, A., Van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G. & Vantomme, P. 2013. *Edible insects: future prospects for food and feed security*. FAO Forestry Paper 171. FAO, Rome. https://openknowledge.fao.org/server/api/core/bitstreams/c7851ad8-1b4b-4917-b1a1-104f07ab830d/content

Vargas-Sáncheza, R.D., Torrescano-Urrutiab, G.R., Ibarra-Ariasc, F.J., Portillo-Loeraa, J.J., Ríos-Rincóa F.G. & Sánchez-Escalante, A. 2018. Effect of dietary supplementation with *Pleurotus ostreatus* on growth performance and meat quality of Japanese quail. *Livestock Science*, 207: 117–125. https://doi.org/10.1016/j.livsci.2017.11.015

Veldkamp, T., Meijer, N., Alleweldt, F., Deruytter, D., Van Campenhout, L., Gasco, L., Roos, N., Smetana, S., Fernandes, A., & Van der Fels-Klerx, H.J. 2022. Overcoming technical and market barriers to enable sustainable large-scale production and consumption of insect proteins in Europe: a SUSINCHAIN perspective. *Insects*, 12: 281. https://doi.org/10.3390/insects13030281

Wade, M. 2023. Insects are food (for the other?): MacKenzie Wade on edible insects and cultural attitudes. (Episode 4). [Audio recording]. In: *Get the Bug Podcast*. [Cited 9 August 2024]. https://shows.acast.com/get-the-bug-podcast/episodes/04-insects-are-food-for-the-other-mackenzie-wade-on-edible-i

Wade, M. & Hoelle, J. 2020. A review of edible insect industrialization: scales of production and implications for sustainability. *Environmental Research Letters*, 15: 123013. https://doi.org/10.1088/1748-9326/aba1c1

Weist, E.F. 2023. Roasted grasshoppers, native potatoes: Salt Lake menus tell new, old Native story. In: *Utah Division of Indian Affairs*. [Cited 9 August 2023]. https://indian.utah.gov/roasted-grasshoppers-native-potatos-salt-lake-menus-tell-new-old-native-story/

Winkler, D. 2008. Yartsa Gunbu *(Cordyceps sinensis)* and the fungal commodification of Tibet's rural economy, *Economic Botany*, 62(3): 291–305. https://doi.org/10.1007/s12231-008-9038-3

Winkler, D. 2022. *Fruits of the forest: a field guide to Pacific Northwest edible mushrooms.* Seattle, USA, Mountaineers Books.

WWF (World Wide Fund for Nature). 2021. *The future of feed: A WWF roadmap to accelerating insect protein in UK Feeds*. WWF-UK. https://www.wwf.org.uk/sites/default/files/2021-06/The_future_of_feed_July_2021.pdf

Xu, Y., Tang J., Wang, Y., He, X.,·Tan, H., Yu, Y., Chen, Y. & Peng, W. 2022. Large-scale commercial cultivation of morels: current state and perspectives. *Applied Microbiology and Biotechnology*, 106: 4401–4412. https://doi.org/10.1007/s00253-022-12012-y

Yen, A.L. 2009. Entomophagy and insect conservation: some thoughts for digestion. *Journal of Insect Conservation*, 13: 667–670. https://doi.org/10.1007/s10841-008-9208-8

Zambonelli, A., Ioti, M. & Murat, C., eds. 2015. *True truffle (*Tuber *spp.) in the world*. Switzerland, Springer.

Zhou, F., Tomberlin, J.K., Zheng, L., Yu, Z. & Zhang, J. 2013. Developmental and waste reduction plasticity of three black soldier fly strains (Diptera: Stratiomyidae) raised on different livestock manures. *Journal of Medical Entomology*, 50: 1224–1230. https://doi.org/10.1603/me13021

Żuk-Gołaszewska, K., Gałęck, R., Obremski, K., Smetana S., Fiegel, S. & Gołaszewski, J. 2022. Edible insect farming in the context of the EU regulations and marketing—An overview. *Insects* 13(5): 446. https://doi.org/10.3390/insects13050446