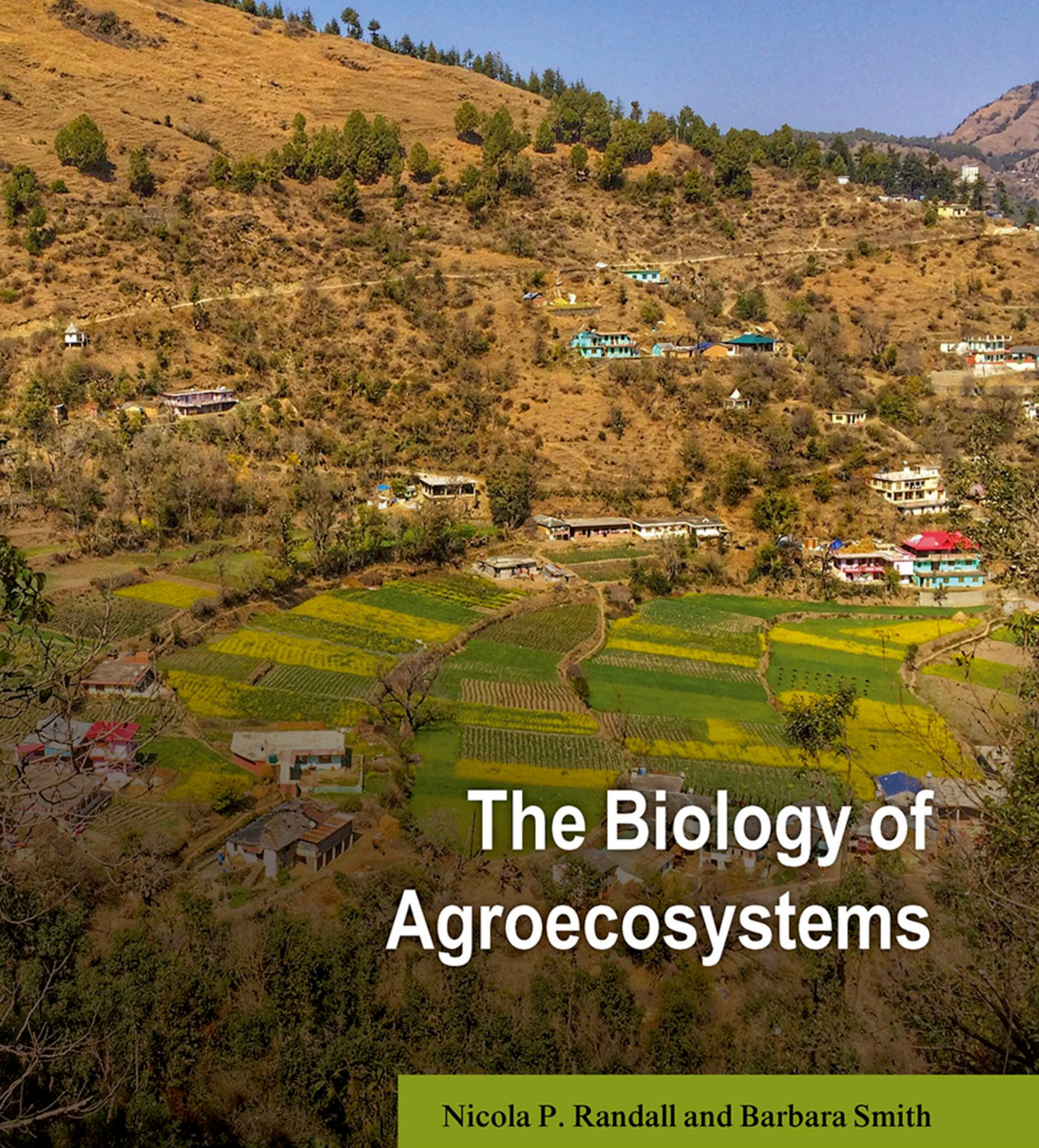

The Biology of Agroecosystems

Nicola P. Randall and Barbara Smith

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The Biology of Agroecosystems

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Contents

1
Introduction

1.1 What are agroecosystems?

An ecosystem is a community of living organisms, the abiotic environment, and the interactions that take place through flows of energy and nutrients, within a given area. The subset of a natural ecosystem that is managed for agricultural production is known as the agroecosystem. The limits of an agroecosystem are not easily defined, as the impact of agriculture is not limited to the land under production. Agroecosystems include cultivated areas (growing arable crops such as grains, rice, and oilseeds, or horticultural crops such as vegetables), pasture and leys that support livestock, permanent crops such as orchards or plantations, and mixed farming systems.

Agriculture takes place in three of the world's four climatic zones: temperate, tropical, and arid (but excluding polar) at a variety of altitudes. Agroecosystems are rarely homogenous and are usually a matrix of land managed for production and peripheral non-farmed areas, such as scrub, grasslands, woodland patches, and watercourses. Agroecosystems are highly variable, and their characteristics will depend on the regional and local context; some will be comprised largely of monocultures whereas others will be comprised of highly diverse mixed cropping and livestock systems. The amount of semi-natural habitat in the matrix will vary. All of these factors are also determined by environmental variables such as local climate, geology, and altitude. As a result, both globally and regionally, we find significant variation within and between agroecosystems. Individual agricultural sites range from small subsistence holdings to very large intensively managed farms. For example, the average landholding in Asia is about 1 hectare (ha), and these holdings are frequently even smaller in many regions (for example, holdings in Bangladesh are estimated to average only 0.3 ha). This contrasts with North America where the average size is nearly 120 ha (Asia and Pacific Commission on Agricultural Statistics 2010). The one factor that ties agroecosystems together is that all are managed, to a greater or lesser extent, for production (usually of food, fibre, or fuel).

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1.2 Why study the biology of agroecosystems?

The Royal Society of Biology considers biology to 'encompass all areas of the science of life from molecules, through whole organisms to ecosystems' (https://www.rsb.org.uk/). The extent and impact of agroecosystems on the global environment, and their importance for sustaining the human population means that a good understanding of agroecosystems and their functions is essential.

Most global landscapes have been impacted by agriculture, and even unmanaged or semi-natural biotopes are surrounded by agriculture of some kind. Agricultural practices have global and ever-changing impacts on the biology of ecosystems. It is important to remember that agricultural environments are anthropogenic habitats both in their origin and ongoing maintenance, and so are inherently unstable, even in the case of low impact subsistence agriculture. The management decisions that we make will impact on both food production and the condition of the wider environment.

1.2.1 The extent and characteristics of agroecosystems

Humans have managed land for food production for at least 10,000 years. Nearly 40 per cent of the global land area is currently classified as agricultural, although this percentage can vary widely between continents and countries. The Falkland Islands, for example, had over 90 per cent of its land area classified as agricultural in 2015, whereas in Egypt, where most of the country is desert, this figure was less than 4 per cent (FAO 2018). There is also great regional disparity between the proportion of agricultural land that is cultivated as opposed to under permanent crops or pasture, and the proportion of land that is used for food production rather than for other products. Plate 1 shows the disparity between regions that primarily grew crops for human food consumption and those where alternative products dominated in the year 2000.

Agriculture has expanded in line with global populations, and in the twentieth century farming was transformed by the development of world markets and technology. In what has been called the 'Green Revolution', agricultural change was characterized by the development and distribution of hybridized varieties of cereal grains, the improvement and expansion of irrigation, the introduction and distribution of synthetic fertilizers and pesticides, and the modernization of management techniques including increased mechanization.

Whilst achieving increased food production, this expansion and intensification of agriculture has resulted in environmental impacts, such as increased levels of diffuse pollution within water catchments and reduced heterogeneity within the landscape. Declines in farmland wildlife, have been frequently recorded (Benton et al. 2003), (including birds (Donald et al. 2001), invertebrates (Molina et al. 2014), and wildflowers (Sutcliffe and Kay 2000). Natural biotopes are increasingly fragmented as agricultural activities expand around them, and this trend is likely to continue.

Agroecosystems will continue to change in the future. Global human populations rose from 2.5 billion in 1950 to 7.6 billion in 2017 (United Nations, Department of Economic and Social Affairs, Population Division 2017), and this, coupled with changing dietary patterns, has led to pressures for further increases in food production. Scientists predict that global crop demand will have at least doubled between 2005 and 2050 (Tilman et al. 2011). Boosting productivity through new methods and technologies is one way to meet this challenge, but is unlikely to meet these increasing demands alone (Ray et al. 2013), and so further intensification of existing agricultural systems is likely to be combined with increased conversion of land for agriculture. The most intensive agriculture tends to be on arable land. Around 11 per cent of global land surface is currently either in arable land or under permanent crops. The FAO predicts that this only represents just over one-third of land that has crop production potential, although how much of this is likely to be brought under future cultivation is disputed (Bruinsma 2017).

This evolution of agriculture helps to ensure that increasing food production requirements are met, but the natural biological components that facilitate ecosystem services, such as clean water, pollination, and bio-control, are also essential to support this increase (Zavaleta et al. 2010; Blitzer et al. 2016). In order to understand how to best deliver sustainable agroecosystems for the future, an understanding of the relationships between land use, ecosystem services, and the related organisms that deliver them is necessary (Bommarco et al. 2012).

1.2.2 Studying the biology of agroecosystems

The study of agroecosystem biology necessarily includes a diverse range of topics. Studies of agroecosystems may focus on the crops and livestock farmed, or the physical changes facilitated, such as management of water tables through drainage, damming, or irrigation, or from reprofiling of the land itself such as in regions where terracing of hillsides is common. Agroecosystems and their components can be studied at a variety of scales, from specific organisms to the multiple interactions within a landscape and beyond.

In addition, agricultural activities may impact on non-agricultural ecosystems. For example, Tilman et al. (2001) predicted that agricultural growth would lead to a more than 2.4-fold increase in eutrophication of terrestrial fresh waters and of coastal marine systems due to nitrogen and phosphorus increases.

To complicate matters, food production has implications beyond biology. Societal, political, economic, and technological factors are as important in the consideration of sustainable agriculture as biodiversity and ecosystem services. These external drivers influence agricultural biology at a local and global scale, which in turn impacts on ecosystem functions. Likewise, it is the agroecosystems and the biological relationships that take place within them that often drive the social, economic, and political decisions that are made, from individual farmers to international bodies.

1.3 The purpose and organization of the book

This book focuses on the biological aspects of terrestrial agriculture, but will consider these in the wider agroecological context. The book provides an introduction to the biological and ecological attributes of agroecosystems, and the biological impacts of agriculture. It is designed to aid the reader's understanding of agroecosystems, the biological pressures that they face, and the issues that must be considered in their management.

The book introduces different types of farming systems and their associated biology. It illustrates some of the specific physiological and ecological issues associated with agriculture, together with potential management options for reconciling production of food and other commodities (fibre, medicines, energy, etc.) with conservation of natural resources and biodiversity.

Following on from this introductory chapter, Chapter 2 gives an overview of the historical context of modern agriculture and the key characteristics of agroecosystems. Chapter 3 examines general biodiversity within and between different types of farming systems, and outlines the relationship between agriculture and patterns of biodiversity in space and time, from the genetic to the landscape level. Chapter 4 builds on this by considering biotic interactions and the role of functional groups within agroecosystems. Chapters 5 and 6 address the specific key ecosystem components, soil and water, and consider how agricultural practices affect and are affected by these key components. Chapter 7 discusses the impact of the globalization of agriculture on the biology of agroecosystems. Chapters 8 and 9 discuss the sustainable management of agroecosystems and look to the future challenges for agroecosystem biology.

Case studies from around the world are used throughout the book to illustrate the wide variety of global farming systems and the biological issues and solutions associated with them.

2

Agricultural Environments

2.1 Introduction

This chapter outlines the origin and development of global agriculture. Agricultural systems around the world are extremely diverse, but all involve the management of land for the production of food and other commodities.

Agriculture is defined as the science of farming, which is itself defined as the activity of growing crops or raising livestock (Oxford English Dictionary 2004). Food is the most widely produced agricultural product, but diverse agricultural commodities are produced throughout the world. Non-food commodities include fibre for clothing, biomass crops for energy, wood for construction, ingredients for medicines and beauty products, and flowers for décor.

The global extent of agricultural land accounts for 37.6 per cent of the land area on Earth (FAO 2013; Roser 2016); this can be subdivided into three broad categories: arable land comprising 28 per cent, permanent crops 3 per cent, and permanent meadows and pastures 69 per cent. The number of hectares dedicated to agriculture has changed very little since 2009 and is not predicted to rise appreciably in the foreseeable future (Roser and Ritchie 2017). Arable production, however, has risen steeply; by 2012, just 32 per cent of the land area could produce the equivalent amount of crops to all of that needed in 1961 (Ausubel et al. 2013). A combination of agricultural technologies and changing tastes means that there has been downward pressure on croplands (Ausubel et al. 2013), and it is expected that further increases in crop production are also likely, frequently due to intensification of farming rather than range expansion.

2.2 The origins and historical development of agriculture

Agriculture requires the cultivation, domestication, and management of plants and animals. Before humans were farmers, they were hunter-gatherers. Some 15,000 years ago, humans foraged for fruits, seeds, and grains, supplementing these with protein from hunting and fishing. They led nomadic lifestyles, moving

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seasonally depending on food availability. The development of agriculture has been pieced together from archaeological and paleontological records, supplemented by anthropology and molecular studies. From these, we know that wild grains were collected and eaten from at least 20,000 BC, and it is generally agreed that agriculture spontaneously and independently arose in several regions somewhere between 15,000 and 10,000 BC, although estimates vary. Vasey (1992) outlines evidence of scattered agricultural practices that range from 8,500 years BC in Southwest Asia, Peru, and Mexico, to 12,000 BC in Taiwan based on evidence of regular forest burning, and as far back as 14,000 BC in the Nile valley based on the tools that have been found. Emmer wheat, einkorn wheat, hulled barley, peas, lentils, bitter vetch, chick peas, and flax (the eight Neolithic founder crops) were cultivated in the Eastern Mediterranean from around 9,500 BC.

At least 11 regions of the Old and New World have been identified as centres of domestication (Larson et al. 2014). The earliest examples are from Southwest Asia, where there is evidence of domestication of wheat, barley, lentils, peas, sheep, goats, pigs, and cattle. In Mesoamerica, squash was domesticated in the early Holocene (Larson et al. 2014). Domestication changes crop species traits, towards palatability and ease of management. There is evidence in the botanical remains from human teeth that suggest the loss of fruit bitterness in *Cucurbita moschata* (a squash species) had taken place by 11,500 BC (Larson et al. 2014). The selection for desirable traits was an ongoing process of both conscious and unconscious selection (Darwin 1868). For example, it has been suggested that the glutinous quality of rice was selected for its taste, but that the non-shattering of cereal seeds is due to the habit of harvesting of cereals by sickle, which favoured plants with seeds that do not fall from the stalk (Larson et al. 2014). In animals, domesticated traits include increased docility, altered reproduction patterns, and changes in body proportions (Hammer 1984). Pigs, native to Eurasia and Africa, were domesticated in Mesopotamia *circa* 11,000 BC; cattle are thought to have been domesticated from a type of wild cattle, aurochs, in two separate events in the Indian subcontinent and in Western Asia around 6,000 to 8,000 BC; and in South America people domesticated llamas, alpacas, and guinea pigs.

The widespread adoption of agriculture came with the Neolithic (approximately 1,000–2,000 BC). The first agricultural civilization was Sumerian, in southern Mesopotamia (a region in Western Asia). The Sumerians were living in villages by 8,000 BC and cities by 5,500 BC, having developed a system of irrigation that allowed them to grow grain at scale using the waters from the Tigris and the Euphrates, despite low rainfall in the area (Wilkinson 2013). However it was the Egyptians who practised agriculture on a large scale between 10,000 and 4,000 BC, allowing them to build an Empire on their agricultural wealth (Janick 2000). Subsequently, the Greeks and the Romans drew on the expertise of these early agrarian societies (Mazoyer and Roudart 2007).

The development of the plough was key to the growth of agriculture, but its origin is uncertain. The earliest archaeological evidence for a ploughed field is from the

Indus valley *circa* 2,800 BC (Lal 2003) and there are pictograms of ploughs from Sumaria in 3,000 BC. These early implements were largely wooden. When iron came into widespread use in 500 BC, mechanization, particularly the use of the plough, facilitated a profound change in both society and the environment by enabling rapid deforestation and cultivation of the land. Early Roman agriculture was based on small, hand-cultivated landholdings of 1–5 acres (0.4–2 ha). With the advent of ox and plough, a single individual was able to prepare a much larger plot. Increasingly, Roman agriculture specialized, particularly in vines and olives, and the many small farmers made way for fewer, large plantation owners. The small farmers, no longer occupied by agriculture and pushed into the cities, were then available to be incorporated into the armies that would be used to forge the Roman Empire (Montgomery 2007).

At the same time as the Romans, great cities were supported by agriculture in Meso- and South America. The Aztec, Maya, and Inca civilizations developed terracing, raised bed technologies, and irrigation systems, which supported population growth. Agriculture was based on corn in Mesoamerica and potato in South America, both crops which are still hugely important in modern agriculture and currently support a large proportion of the world's population (Mazoyer and Roudart 2007).

A suite of major advances in agriculture occurred during the 'Arab agricultural revolution', which refers to the development of agriculture in the medieval Arab empire and its diffusion from Europe to the borders of the Far East. The Arab trade routes enabled the exchange of novel crops. This was an era of scholastic enterprise. Islamic scholars, particularly botanists, experimented, taught widely, and published scholarly works such as the twelfth-century *Kitab al Filaha* 'Treatise on Agriculture', and offered practical advice, such as the Calendar of Cordoba, an agricultural calendar, which they translated and distributed. During this time, irrigation technologies were developed, understanding of soil fertility management advanced, and the introduction of high-value crops and animals proliferated, supported by the distribution of free seeds, advice, and education. Relatively liberal landownership laws were also introduced. Anyone was allowed to own, sell, and inherit land. In contrast to the Roman model where serfs were tied to (and sold with) land, those who directly worked the land had rights to a share of the produce. These circumstances, combined with central government policy to exploit undeveloped lands, resulted in advancements in agriculture (Idrisi 2005).

In northern Europe, the eleventh and twelfth centuries saw an expansion of the monastic system when the monasteries became centres of expertise for agriculture and forestry. The church had large landholdings and in conjunction with the manorial system, under which large landholders farmed using indentured serfs, landowners had control over large areas of land. New crops were imported via Arab traders. In 900 AD the introduction of the 'heavy plough' enabled deep ploughing of heavy, more clay-based soils which greatly increased productivity.

Land was drained and marginal lands were brought into production. The adoption of a three field rotation system (rather than two) added nitrogen-fixing legumes to the rotation which resulted in the improvement of soil fertility. Windmills and watermill technology improved, leading to increased efficiency of processing both food and fibre. Crop yields stabilized in the thirteenth century, with the next significant shift in agriculture coinciding with the 'discovery' of the Americas and the exchange of crops between the Old and New Worlds in the fifteenth century. Horses, cattle, sheep, and goats were introduced into the New World, which had few livestock species, and European traders introduced cassava and maize into Africa, replacing traditional African foods (Wambugu and Wafula 2000). In Europe, the introduction of the potato generated great change. Potatoes are calorie dense and the impact of their introduction was to double Europe's food supply (in terms of calories) and reduce famine (Mann 2011). A secondary impact was the necessity to adopt the intensive fertilization required by potatoes, which was helped by the introduction of guano from Peru. This set the direction for an agricultural system where fertility needs were met by the addition of imported nutrients.

The advent of what we might consider 'modern farming' arrived in the seventeenth to nineteenth centuries with the agricultural revolution, centred in Europe and largely in the UK, sometimes called the British Agricultural Revolution, which was a process of increasing mechanization (Overton 1996). There was an explosion of new technologies and changes to farming. In Britain, this period of change was underpinned by the 'Enclosure Acts' which enclosed common lands and passed them into private hands and removed the existing manorial system whereby tenant farmers were only able to farm small strips. This transfer of power and ownership gave a newfound confidence to landowners, who invested heavily in land that gave them the whole return (Overton 1996). However, it was a process that took place over many years; there were eleven Enclosure Acts, the first in 1773 and the last in 1859. In total, over 5,200 individual Enclosure Acts were passed, covering 2.75 million ha (House of Commons 1919). There were several key innovations in this period that led to great increases in productivity and efficiency:

- **The development of the seed drill**. Before the advent of the seed drill, seeds were broadcast by hand. The seed drill was imported into England from China, and developed by Jethro Tull in 1701; it distributed seeds evenly and at an optimum depth, and continued to be developed and improved over the next hundred years. It improved germination, allowed planting in rows to make husbandry easier, and, by sowing beneath the soil, minimized seed predation.
- **The development of mechanical threshers**. Threshing, the process of separating seed from stalks and husks after harvest, was a laborious and time-consuming process. In the 1780s, Andrew Meilkle, a Scottish engineer, developed a mechanical horse-powered alternative to traditional hand threshing. The model was improved and developed incrementally in the UK, Australia, and America and was the precursor of the combine harvester. It greatly reduced the labour associated with harvest, but at the expense of many rural jobs.