BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Achieving sustainable cultivation of apples

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Introduction

The apple is an iconic fruit recognized in most countries of the world and is produced in many. China is the biggest producer by far, producing around 40% of the world's 63 million tons of apples, almost ten times that of the second largest producer, the United States. Production levels and advances in storage technologies have resulted in the availability of apples year round in many markets. As a fruit with a high content of flavonoids and dietary fibre, apple has been linked to many health benefits. Indeed, apple has achieved what most other fruits have not in that it has successfully made its way into the fast food industry and can be frequently found, typically sliced, accompanying a considerably less healthy burger.

We have been cultivating apples for thousands of years, but the last century has seen the biggest changes in our production systems. Like other crops, we have moved into intensive agriculture. Dwarfing rootstocks for apple have enabled intensive, more efficient plantings of almost-two-dimensional trees before most other tree fruits. Such high-density plantings are moving apple production towards precision horticulture and provide orchard structure that fits mechanization and automation, rapidly becoming a requirement as labour shortage is the principal challenge currently facing sustainability of apple in many areas of the world. Our ability to optimize cultural practices through integrated pest management, biocontrol, and measured irrigation and nutrition, increases the sustainability of the orchard systems. Growers and pack-houses worldwide are striving to achieve Global GAP certification of farm assurance leading to Good Agricultural Practice status; apple precision horticulture is perfectly aligned.

Apple cultivation can be challenging in many ways; growers need the orchard to remain in the ground often for decades to recoup their very high initial investments. In addition, they must develop and execute careful management plans. However, while complex, working with a composite tree brings a level of flexibility and purposefully intensive management that is not present in some other production systems. As opposed to most annual crop producers, skilled apple growers can literally 'build' the tree to their requirements by carefully choosing a rootstock to suit their soil conditions and fitness for their preferred production system, and a scion to suit their climate and the available market. Once the tree is planted, the growers can train it into a structure that is desired by themand manipulate the leaf canopy and crop load to achieve the optimum balance of fruit quality and yield. Of course, none of this is easy, so perhaps the key skill for a grower is the ability to forecast 10–20 years ahead and prepare for change. Will it be hotter and drier, or will our precipitation patterns change dramatically? What will new technology bring and will it fit the current orchard training system? Will the variety still be profitable? And of course, there is the constant threat of new exotic pests. While apple growers using conventional farming practices confront these challenges, those utilizing organic systems must follow appropriate, and often quite different, practices. Nonetheless many are doing so successfully.

More growers are moving towards the physical protection of their crop using netting, initially for mitigation of hail but now also to filter potentially damaging levels of light that can damage fruit and stress vegetative growth, and in some areas, are also being considered for pest protection. Such investments in infrastructure add to the already expensive establishment costs, so obviously the grower has to take into account the market price and typical grade-out of the variety to recover their initial costs and generate a revenue stream.

Ultimately, in my view, it is consumer demand that will sustain apple production as long as we can produce and deliver quality pieces of fruit consistently throughout the year. One thing that sets apple apart from most other fruit crops is the range of fruit types that are in demand, in terms of both internal eating quality and, of course, appearance. Another advantage for apple is that new varieties are clearly named and can easily be distinguished, providing the retailer with a marketing incentive and ensuring consumers can be confident that the ones they chose to purchase again have the characteristics that they prefer. We can offer the consumer more than simply fresh fruit by extending the sliced apple market, developing high-quality juices, sauces, dried apple and other lightly processed products.

Worldwide, consumers prefer different fruit flavour and texture attributes. Breeders are challenged to combine those diverse consumer-preferred attributes with varieties that also enable producer- and environmentally-friendly production practices. Continued breeding and selection to feed the demand for new improved eating experiences as well as to develop varieties that will face the challenges of a changing climate is essential for long-term sustainability. Cultivated *Malus* are only a few generations removed from wild progenitors compared to many other crop species, so we have plenty of opportunities for genetic gain to develop superior new cultivars. Further, we have widely diverse genetic resources available to us and, with new DNA-based tools, breeders are becoming better enabled to access this diversity and attempt the introgression of new traits.

The authors and topics in the book have been carefully chosen to provide the reader with an introduction to apple as a crop species plus present updates from leading international scientists on multiple aspects of apple production. Each chapter contributes to the ultimate aim of achieving sustainable cultivation, whether the word sustainable is interpreted as meaning economically viable, environmentally sound and/or socially acceptable, or the more general definition to endure or last indefinitely. Specific chapters on environmental impact assessment, economics of production and consumer trends in apple sales add to the bigger picture of the current position of global apple sustainability. Our goal was not just to provide a current review, but also to provide a useful resource for further information in terms of publications, research groups and conference series. Apple cultivation is certainly heading in a more sustainable direction. Advances over recent years have been dramatic. This book is a unique, timely and comprehensive review of these scientific advances and their potential implementation by apple producers worldwide.

Part 1 Plant physiology and breeding

The first group of chapters looks at advances in understanding apple physiology and breeding. Chapter 1 highlights the critical importance of genetic diversity. Widely used apple cultivars exhibit low resistance to pathogens and low tolerance to climatic threats. Apple breeding programmes therefore need to develop new cultivars which are more resilient in the face of key threats, while also selecting for other important qualities. Previously, it was difficult to use wild apple species for breeding because typically they have undesirable fruit, non-uniform ripening times, and other traits that are not amenable to commercial apple production. Apple progenitor species, *M. sieversii*, *M. orientalis*, *M. sylvestris*, *M. prunifolia*, and *M. baccata* offer desirable variation, and are more amenable to use in breeding programmes because they are diploid and often have fruit traits more similar to *M.* × *domestica* than many of the more distant wild *Malus* species. The chapter explores the opportunities and challenges of using progenitor species of *Malus* × *domestica* in traditional breeding programmes.

Key challenges include understanding *Malus* diversity, capturing and maintaining this diversity, and ensuring that researchers and breeders have access to living apple accessions. The chapter highlights the role of genebanks, such as the USDA-ARS National Plant Germplasm System. Genebanks provide breeders access to *Malus* wild species and local cultivars (which may also have desirable traits). The USDA-ARS National Plant Germplasm System, for example, maintains an apple collection with 3070 unique grafted trees representing *M.* × *domestica* cultivars and 33 *Malus* species, and 15 hybrid species that are available to breeding programmes.

It is important to note that many wild *Malus* species are, however, poorly represented in genebank collections, and phytosanitary restrictions and treaty agreements may limit access to wild materials, particularly at the international level. Ongoing coordinated efforts among genebanks to compare collections at the phenotypic and genetic levels as well as confirm cultivar identities will facilitate use of genebank collections in the future. These efforts will enable future researchers specializing in apple improvement to provide consumers with higher quality fruit that can be produced more sustainably. Finally, new technologies that make use of marker-assisted selection, genomic selection, genetic engineering, genome-wide association mapping, high-throughput genotyping and/or rapid-cycling plants are paving the way toward the increased use of wild *Malus* species in apple breeding.

Chapter 2 provides an overview of the development of genome sequencing technology, reviews the process of sequencing the apple genome and then considers how this information can be employed, both to develop new and better varieties of apple and, in the shorter term, to improve current horticultural practices. In the future, knowledge of specific genes can be used to improve vegetative growth and development, biotic and abiotic disease tolerance or resistance, pre-harvest stages of fruit development, postharvest fruit storage, shelf-life and organoleptic traits.

The next group of chapters reviews the latest research in understanding apple tree growth and its implications for cultivation practice, starting with rootstocks and planting systems. Chapter 3 discusses the importance of rootstocks, with an emphasis on the mechanisms and morphological effects of dwarfing. This chapter outlines the key attributes of widely used dwarfing and semi-dwarfing rootstocks including relatively recent releases that confer resistance to economically important pests and diseases and tolerance to abiotic conditions of drought, low temperature and waterlogging. These traits significantly widen the potential sites and regions that can potentially support modern apple systems.

Understanding how rootstocks and scions interact to manifest in various growth attributes of size, architecture and precocity (earliness of flowering and bearing) has been a major focus of research. Understanding of growth attributes also enables managers to design growing systems that allow the tree to fill the allocated canopy space to optimise light capture early in the life of the orchard (and prevent excessive shading after establishment) in order to produce better yields. The chapter summarises recent research on the manipulation of tree growth and development, with an emphasis on the use of plant growth regulators, followed by a discussion of the effects of different planting systems.

Chapter 4 provides a detailed discussion of the practices which affect canopy development, dormancy release, bud break and vegetative growth. As an example, the chapter explores how application of branching agents has become standard nursery practice while notching has gained acceptance for branch induction in older trees, particularly in combination with cytokinin. Under conditions of inadequate winter chilling, bud break can be manipulated by cultural practices or application of chemical rest-breaking agents. Understanding how scion cultivars interact with rootstocks has driven studies on training and pruning, underpinned by knowledge of architectural traits and tree physiology. The chapter ends by presenting two case studies which show the importance of post-planting apple tree management, and illustrate how it can interact with choice of rootstock and planting system to determine yield, including artificial spur extinction and chemical thinning for crop load control.

Chapter 5 looks at recent research on the biology and horticultural aspects of flowering with a particular focus on pollination. Fruit production begins with the transition of a bud from vegetative to floral state. The bud differentiates, overwinters, and emerges as a flower the following spring. Flowers are then pollinated, fertilized, and the fruit grows firstly by cell division and later by cell enlargement. All of these processes are vital to the development of high-quality fruit. Sub-optimal environmental, biological or cultural conditions during any of these stages can reduce both productivity and fruit quality. The chapter discusses the biological processes and genetic controls of these developmental stages. It also highlights some of the key environmental effects and how these processes can be manipulated by cultural management.

As with earlier processes, understanding the ways in which apple fruit grow and develop is crucial for achieving sustainable apple cultivation. Chapter 6 examines how apples grow and ripen, what we know about the factors that support or limit growth, why fruit abscise and how growers can manipulate fruit growth and abscission to optimize cropping. Amongst other topics, the chapter explores in detail seasonal growth patterns, the chemical composition of apples in different seasons, the role of hormones in abscission, and seasonal ripening patterns as well as competition within the flower/fruit cluster. The chapter suggests ways to model optimal crop load and suggests future trends for research in this area.

The foundations of a productive and healthy orchard are the rootstocks that provide anchorage, water and nutrients essential to the above-ground portions of the trees. Utilization of composite trees has increased the efficiency of breeding productive apple trees by dividing the selection of scion traits and rootstock traits into two genetically (and functionally) different specimens which are then brought together through grafting. As part of the tree, the rootstock influences many factors in addition to tree size, particularly productivity, fruit quality, pest resistance and stress tolerance. Understanding how scion properties are modulated by rootstocks allows targeting of traits that may be selected to improve whole tree performance by improving rootstock performance. Chapter 7 examines apple breeding methods and explores how rootstocks affect scion traits, before addressing the impact of rootstocks on disease and pest resistance.

Breeding and selecting new, improved cultivars by exploiting natural genetic diversity is an essential route forward in ensuring sustained and sustainable apple production. There can be no doubt that breeders have an expanding set of tools at their disposal to achieve these goals with the advent of marker-assisted (and DNA-informed) breeding. Chapter 8 discusses the promise of marker-assisted breeding in apple and reviews the advances that have been made, particularly over the last two decades, in practical application of genetic markers to breeding programmes, current tools, and the impacts of this technology. A case study of genetic marker application in the Washington State University apple breeding programme is also described. The chapter suggests what the near future may hold for marker-assisted breeding in apple. The rapid increase in genomic data will present its own challenges in terms of managing decision-making although the result will be enhanced efficiency, accuracy and pace of new apple cultivar development.

Part 2 Cultivation techniques

The next group of chapters reviews improvements in cultivation techniques. Chapter 9 provides a summary of recent innovations in orchard training system design, pruning techniques, thinning, plant growth regulators and fruit finishing with the aim of identifying more sustainable practices. New training systems like the 'bi-axis' are described to achieve planar, vertical or angle canopies, as well as mechanical and other pruning and thinning techniques to minimize labour requirements. It is now possible to purchase specific typologies of tree that are more compatible with training techniques which will further improve production. New uses of plant growth regulators to manipulate tree growth and fruit finish are also analysed.

Chapter 10 explores the emerging issues that will influence future approaches to soil and nutrient management in apple orchards. These include climate change and variability, the degradation of soil and water resources, and the future availability and cost of fertilizers. The chapter then reviews strategies for precision nutrient and water management. These include fertigation and targeted foliar application as well as improved types of fertilizer and technologies for sensing nutrient limitations. Improved irrigation scheduling and conservation irrigation techniques, including partial and deficit irrigation, are also discussed. Finally, the chapter considers the prospects for alternative production systems and production areas given the changing climate.

As Chapter 11 points out, sustaining large-scale commercial apple production depends on the availability of a large, seasonal and suitably skilled workforce. Costs and overall productivity could be improved by mechanization of apple production operations. Chapter 11 begins by reviewing the levels of mechanization that may be introduced into apple production and then considers a variety of mechanization solutions for each of the four key operations in apple production: training and pruning, thinning, pest and disease control, and harvesting. In each case, the chapter first considers those solutions which employ lower levels of mechanization, and then moves up to solutions which involve a higher level of mechanization, including automation and robotics. The advantages and disadvantages of each solution and directions for further development are also discussed.

Use of fungicides to control disease in postharvest apples is becoming less acceptable to many consumers, and the search for alternative approaches that are more sustainable in controlling postharvest diseases of fruits has intensified during the last three decades. Chapter 12 describes various alternative approaches to synthetic fungicides for controlling postharvest diseases of apples that are potentially safer for human health and the environment. The main focus has been on exploring natural products and substances generally regarded as safe (GRAS) which have anti-fungal properties. The chapter also reviews physical treatments (such as heat treatment, irradiation or the use of controlled atmospheres), biological control and natural fruit resistance, either by induction in harvested fruit or through breeding programmes. When used in combination, these techniques can now rival fungicide treatments in effectiveness.

Postharvest handling of apples, as for most horticultural products, is largely concerned with the maintenance of product quality after harvest. Chapter 13 outlines recent advances in understanding the various factors affecting fruit maturation and ripening. It reviews harvest, handling and grading operations, and discusses postharvest storage technologies including refrigeration, controlled atmosphere (CA) storage and the use of 1-Methylcyclopropene (1-MCP). It also considers a range of postharvest treatments of apples and the physiological disorders to which apples are subject.

Part 3 Diseases and pests

Fungal plant pathogens cause significant economic losses in the field and during storage which decreases fruit quality. Several pathogens also produce mycotoxins that are harmful to human health. Pathogens include *Alternaria mali* (Alternaria leaf spot), *Colletotrichum* species (bitter rot), *Glomerella cingulata* (Glomerella leaf spot), *Gymnosporangium juniperi-virginianae* (cedar apple rust), *Podosphaera leucotricha* (powdery mildew), *Botryosphaeria dothidea* (white rot), *Schizathyrium pomi* (flyspeck) and, in particular, *Venturia inequalis* (apple scab). There have been a number of advances in biological, chemical and cultural methods of control which help to combat these diseases. Chapter 14 reviews these developments together with a discussion of the main pre- and postharvest apple pathogens and methods of integrated disease management.

Like fungal diseases, viruses and virus-like agents are a recurring problem in apple production. Viruses include so-called ‘latent viruses’, apple mosaic virus, flat apple disease and viroids. They are graft-transmissible, and are readily disseminated through the use of infected budwood. Since many of these agents do not have arthropod or nematode vectors, the most effective control strategy is to develop orchards with clean, virus-tested planting stock. As Chapter 15 states, the implementation of quarantine and certification programmes globally is essential to safeguard apple production and minimize the risk of spreading disease by removing virus-infected plants from the supply chain. Procedures for virus testing and elimination are constantly being revised to incorporate the best and most appropriate technologies, including developments in high-throughput sequencing techniques.

As Chapter 16 indicates, bacterial diseases remain an ongoing challenge to the sustainability of apple production. Fire blight, for example, is a serious economic threat to apple production. Chapter 16 uses it as an example to present the key issues and challenges which bacterial diseases raise for apple production. The chapter reviews the history of fire blight and its spread around the globe, economic impact, symptoms, disease biology and management. The chapter also includes a case study on current efforts to develop apple cultivars which are resistant to fire blight disease. Other apple diseases caused by bacteria, including blister spot, crown gall and hairy root, bacterial blister bark and apple proliferation are also considered.

Management of apple pests is a necessary and challenging part of crop production. Chapter 17 begins by covering key pests of apple such as the codling moth. The chapter then considers indirect pests, which may be tolerated in moderate densities, and are therefore more amenable to other control tactics, especially biological control. The chapter suggests that integrated pest management (IPM) tactics which control key pests without disrupting biological control of secondary pests are the best way forward for sustainable IPM in apple production. After considering the tools and tactics available as part of a sustainable IPM programme, the chapter considers the challenges facing IPM, such as pesticide resistance and invasive species, which require innovative solutions for future IPM systems.

Disease- and pest-resistant cultivars can significantly contribute to sustainable and resilient cultivation of apples. Chapter 18 reviews the development of apple varieties resistant to a number of important diseases, including apple scab, powdery mildew, fire blight, nectria canker and Marssonina apple blotch. The chapter also consider the development of pest-resistant apple varieties, before discussing DNA-based selection techniques for developing resistance and the mechanisms on which resistance depends.

Part 4 Sustainability

A viable business is a key element of sustainability. Chapter 19 reviews and compares costs in apple production worldwide. The chapter analyses the economics of apple production around the world, including in countries such as Germany, Italy, South Africa, Switzerland and Chile. A detailed case study of apple production in Washington State, USA, is also provided. The chapter includes a comparison of apple production costs by variety across the United States, Germany, Italy, and South Africa. Given the importance of international markets for major apple producing countries in the world, the chapter considers apple production in relation to global trends in production and international trade. It discusses structural changes in the apple industry around the world, as well as trends in production systems and technologies.

As Chapter 20 indicates, the world of apple marketing presents many complex challenges. Consumers have become increasingly disparate and selective in what they expect from the products they buy. They remain concerned about the intrinsic qualities of apples, such as colour, taste and texture, but continue to add new concerns such as social responsibility and environmental sustainability. The chapter reviews topics such as the influence of suppliers and retailers on apple sales, global forces affecting apple demand, recent trends in apple consumption, factors affecting consumer demand for apples and the challenges this creates in marketing apples.

As Chapter 21 suggests, the environmental impact of apple production can be managed through cultivation practices and inputs. Pesticides typically have the greatest environmental impact, but energy use from cultivation techniques (including the costs of nutrient, irrigation and pesticide inputs) is also substantial. This chapter shows that apple production sustainability has improved in the area of pest management and decreased for resource use. It demonstrates that high-density apple orchards require higher levels of infrastructure and resource inputs than older systems, and argues that enhancing biocontrol of pests and lengthening the usable life of equipment and infrastructure are important strategies for reducing the environmental impact of modern production systems.

The final chapter in the book, Chapter 22, reviews key research areas for those involved in organic apple production. It covers the development of suitable varieties and rootstocks, soil fertility management, and strategies for maintaining apple tree health.

The latter include weed and disease control as well as methods for regulating crop set and tree growth. A number of case studies are used to show how research can have real practical impacts, for example by adding to the organic farmer's toolbox of disease control strategies.

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