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Achieving sustainable cultivation of temperate zone tree fruits and berries

Volume 2: Case studies

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Contents

Introduction

Temperate fruits include stone/drupe fruits (such as peach), pome fruits (such as apple) and berries (such as strawberries). Like other crops, cultivation of these fruits faces a number of challenges. These include the need to optimize yields, sensory and nutritional quality; the dynamic threats from biotic and abiotic stresses in a changing climate; the increasing cost and decreasing availability of labour; and the need for more efficient use of resources to minimise environmental impact. This second volume of *Achieving sustainable cultivation of temperate zone tree fruits and berries* includes case studies of individual fruits that illuminate the specific challenges they face and ways these are being addressed.

Part 1 Stone and pome fruits

The first part of the volume summarises research in improving the production of stone and pome fruits. Chapter 1 addresses advances and challenges in peach breeding. Characteristics such as a relatively short juvenile period, self-pollination and small genome size have made peach a model fruit for breeding and genetics research. The chapter reviews the moderate chill peach variety development program involving the USDA-ARS, the University of Georgia and the University of Florida. It shows how the program addressed the challenge of developing new early season varieties using low chilling genotypes with the appropriate sensory quality and firmness required for long-distance shipping. As the chapter explains, the improved firmness realized by the shift to non-melting germplasm has made it possible to leave ripening fruit on the tree longer, resulting in improved fruit size and appearance as well as eating quality. The chapter also reviews ways of improving disease resistance, focusing on peach fungal gummosis (PFG). It describes the steps involved in developing interspecific hybrids with improved resistance, as well as progress in understanding the genetics of PFG resistance and linkage mapping for marker-assisted selection.

Chapter 2 shifts the focus from breeding to improving sustainability in peach production. By adopting precision management techniques, growers can reduce the environmental impact of fruit growing without sacrificing quality and yields, while maintaining income. The chapter discusses how improvements in sustainable peach production can be achieved by adopting an interdisciplinary approach. Research on plant physiology provides the foundations for mechanistic models to predict crop performance in real time, allowing growers to fine-tune their orchard management. The chapter illustrates this by describing the importance of vascular flows to peach fruit growth, including factors such as vapour pressure deficit (VPD), and how this can be used to develop deficit irrigation programs, as well as mulches to reduce soil evaporation, to optimize both fruit development and water use. The chapter also reviews the latest research on the role of photosynthesis in peach production, including the effects of temperature, light and water availability. It shows how this understanding can be used to develop methods to modulate the light environment of the orchard (e.g. via shading hail nets) in order to reduce evapotranspiration, photoinhibition and heat stress which reduce yields. The chapter also discusses how recent advances in sensor technologies can be used, for example, to improve water stress management in peach crops.

Moving from peaches to cherries, the subject of Chapter 3 is advances and challenges in cherry breeding. Cherry breeding is currently carried out in many countries, by public and private programs, and sweet cherry cultivars are continuously being released. However, classification into clear-cut groups of existing cultivars is difficult, because there is a vast continuum of morphological diversity and many traits are influenced by differences in environmental factors among growing locations, including climate and soil characteristics as well as cultural practices. Despite the high number of available commercial cultivars, both sweet and sour cherry cultivation are still based on a small number of cultivars. After offering a historical overview of cherry breeding, the chapter describes the main achievements in conventional breeding, before considering methodologies and the latest advances and key cultivars. The chapter considers new approaches and phenotyping protocols.

Continuing to examine cherries, the subject of Chapter 4 is advances and challenges in sustainable cherry cultivation. Sweet cherries are an inherently challenging crop to produce sustainably, given the significant risks of crop loss from weather events, birds, insects and diseases, and requiring extensive manual labour due to large tree canopies and small delicate fruits. Nevertheless, cherry production has increased dramatically worldwide for the past two decades, driven by strong consumer demand and innovations in plant materials, efficient orchard training systems, orchard microclimate modification technologies, and improved physiological knowledge. The chapter examines the optimization of orchard tree development and fruit yields/quality by developing a foundational understanding of cherry morphology, growth, fruiting, cultivars and rootstocks, and how to utilize these components to re-design canopy architecture and orchard production systems for more labour-efficient, sustainable production.

Moving from cherries to pears, Chapter 5 considers advances and challenges in pear breeding. Although pear (*Pyrus* spp.) is an economically important fruit worldwide, pear cultivars and production practices have been among the slowest of the temperate fruits to change to meet modern consumer demands and labour-efficient orchard production. In the USA, the majority of the pear orchards are low-density plantings with large trees of long-standing cultivars that can reach up to 15 feet in height. Large vigorous trees require labour-intensive management and are relatively inefficient in terms of application of inputs such as water, pesticides, and bio-regulators. The chapter reviews the range of pear cultivars and pear rootstocks, and includes a discussion on germplasm resources. Breeding techniques and improvement of particular traits are considered, including dwarfing, precocity, cold hardiness, fire blight resistance, tree architecture and self-incompatibility.

Staying with the theme of pears, Chapter 6 examines advances and challenges in sustainable pear cultivation. Excessive vigour of European pear varieties and a dearth of dwarfing rootstocks pose significant challenges to the establishment and management of modern high-density orchards. The pronounced negative relationship between pear tree vigour and precocity requires intensive horticultural intervention to expedite a return on investment and to achieve maximum yield potential. Plantings of low to moderate tree densities are no longer economically sustainable given their characteristically inconsistent fruit quality and suboptimal yields. Nascent technologies and novel horticultural strategies have the potential to balance reproductive and vegetative development of pear trees and facilitate the cultural management of high-density orchards. The chapter provides a review of pear floral biology, and fruit setting habits and their complex interaction with environmental factors, along with practical horticultural strategies to promote balanced canopies.

Passing from pears to apples, Chapter 7 examines advances and challenges in apple breeding. Breeding new apple varieties is costly and time-consuming, often selecting for consumer-preference traits at the expense of other traits of agronomic importance. However, combining both sustainable cultivation with market acceptability would benefit growers, consumers and the environment. The chapter summarises the current status of apple breeding and genomics research, taking a forward look at the key factors that may improve selection efficiency within apple breeding programmes to simultaneously enhance both resource use efficiency traits and resilience to biotic and abiotic stress. The chapter discusses how coupling enhanced automated phenotyping, rapid cycling through generations, genome-assisted selection and genome editing using CRISPR-Cas9 can improve breeding programme productivity. The chapter also covers advances in genetic characterization of key rootstock traits.

Chapter 8 deals with advances and challenges in sustainable apple cultivation. Developing sustainable apple cultivation is dependent on both a better knowledge of tree architecture and physiology in relation to fruiting, and on how the tree interacts with its abiotic and biotic environments. Improving knowledge in these areas is crucial to take into account for more sustainable, low-input production. The chapter provides an overview of apple tree growth and fruiting, and explores methods for more sustainable apple training and pruning management.

The final chapter of the section, Chapter 9, addresses advances and challenges in sustainable plum and apricot cultivation. Sustainable fruit cultivation may depend on the combination of a number of factors, including optimal growing conditions, correct selection of cultivars and rootstocks, and application of modern crop cultivation techniques. Sustainability also implies promotion of biodiversity, improvement of microbiological processes in the soil, and protection of the environment (e.g. by avoiding pollution from fertilizer and pesticide run-off). It has been estimated that fruit production may need to increase two- to three-fold to meet future demand, but this needs to be achieved in a sustainable way. The chapter explores ways this might be achieved for plum and apricot production. The chapter covers the genetic resources available for cultivation of these fruits, and the environmental factors affecting plum and apricot cultivation.

Part 2 Berry fruits

The second part of the volume summarises challenges for sustainably cultivating berry fruits. Chapter 10 is focussed on advances and challenges in strawberry breeding. The commercial strawberry (*Fragaria* × *ananassa*) is a popular temperate fruit that is both nutritious and widely appreciated for flavour. The chapter highlights some of the newest innovations in strawberry production, with particular emphasis on genetic improvement of the crop. The trend for developing more robust and sustainable strawberry cultivated varieties via genetics is discussed in detail and useful technologies are reviewed, including high-throughput genotyping and quantitative trait locus (QTL) analysis, targeted sequence capture, third generation sequencing and expression QTL studies. High-throughput phenotyping is also covered, which is an increasingly important area of interest, both to improve breeding through traditional selection and for integration with genomics data for discovery of novel traits.

Going into greater depth on strawberries, Chapter 11 is a case study of how evolving market expectations impact strawberry sustainability. The strawberry industry is facing the reality that it has been built on an unsustainable foundation. First, water is increasingly scarce in some of the key regions where strawberries are grown. Aquifers continue to be depleted and land is subsiding in some areas as water is withdrawn. The chapter offers a case study of the impact of market expectations on the US strawberry industry. After an introductory survey of the history of strawberry production in the USA, the chapter examines the development of an annual strawberry production system. This includes looking at the impact of shifting markets on the sustainability of strawberry production and the challenge of increasing inputs with expansion of annual production in favorable locations. Finally, the chapter assesses the sustainability of the current model of strawberry production.

The subject of Chapter 12 is advances and challenges in raspberry and blackberry breeding. Raspberries and blackberries (*Rubus* spp.) are important fruit crops with increasing levels of production. The chapter focuses on key challenges in achieving more sustainable production, the tools available to breeders, and the future of breeding for sustainability of raspberry and blackberry crops. The chapter examines desirable traits for sustainability, molecular tools and resources.

Continuing to focus on brambles, Chapter 13 considers advances and challenges in sustainable raspberry/blackberry cultivation. *Rubus* crops are important for human health and for rural economies. As demand for these berry crops increases at a time of changing climate and increasing consumer concerns about sustainability, new breeding strategies and cultivation practices are needed. The chapter addresses some of the challenges and solutions to continued sustainable growth, including managing pest and disease stresses and the effects of climate change, as well as reducing environmental impacts.

The volume's concluding chapter, Chapter 14, deals with advances and challenges in blueberry breeding, There is a growing body of research on the biological processes underlying key physiological traits in blueberry (*Vaccinium corymbosum*). Studies have shown high levels of genetic diversity are present within this species, much of which remains to be harnessed. The chapter introduces both the recent advances and current challenges in the breeding of blueberries, with particular focus on demand and production in the UK. Key cultivars currently used in the industry are listed and their advantages and disadvantages are discussed. The genetic material available and its use in breeding programmes is covered, including crossing with other species within the genus *Vaccinium* to obtain desirable traits. The chapter includes sections on phenotyping and marker-assisted breeding, and an extensive discussion on the improvement of flavour in blueberry is also provided.

Chapter 1

Advances and challenges in peach breeding

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1 Introduction

The genus *Prunus* belongs to the family Rosaceae and contains approximately 230 species divided into five subgenera: *Prunophora* (*Prunus*), *Amygdalus*, *Cerasus*, *Padus* and *Laurocerasus* (Rehder, 1940), which includes peaches and nectarines (*Prunus persica*), plums (*P. salacina* and *P. domestica*), cherries (*P. avium* and *P. cerasus*), almonds (*P. dulcis*) and apricots (*P. armeniaca*). In 2015, the production of *Prunus* edible fruits and seeds surpassed 43 million metric tons with production found across Asia, Europe, North America, South America, Australia and South Africa (FAOSTAT, 2016).

Peach is a member of subgenus *Amygdalus*, which includes almond, Gansu peach (*P. kansuensis*), Tibetan peach (*P. mira*), mountain peach (*P. davidiana*) and *P. ferganensis*. These species are sexually compatible with each other and produce viable and fertile hybrids (Martínez-Gómez et al., 2003). *Prunus* breeding programmes have used hybridization among these species for improvement of genetic resistance to insect, nematodes and pathogens (Gradziel et al., 2001).

The centre of origin and domestication for peach and almond is southeastern and eastern Asia (Hedrick, 1911). Peach domestication dates back to more than 4000 years with peach genetics evolving by inbreeding, random

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drift from a reduced number of founders in the breeding programmes and heterosis (Faust and Timon, 2010; Li et al., 2013). During peach domestication in China, three main groups were recognized (Scorza and Okie, 1991; Wang, 1985). The southern group of peaches are found along the Yangtze River in the provinces of Jiangsu, Zhejiang, Jiangxi, Hubei, Hunan and Sichuan, and are characterized by their adaptation to mild winters and hot wet summers, similar to the climate of the southeastern United States. The northern group is found along the Yellow River in Shandong, Hebei, Henan, Shanxi, Shaanxi and Gansu provinces, and are characterized by their adaptation to cold winters and hot dry summers. The third group is adapted to arid northwest China.

From China, peaches were spread through Persia to Europe by the Romans (Scorza and Okie, 1991; Wang, 1985). Peaches made their way to North America via Spanish explorers, first through St. Augustine, Florida, United States, and Mexico (Scorza and Okie, 1991), and then were spread by Native Americans. These peaches were early ripening yellow non-melting flesh types. Later, an additional introduction occurred in the 1800s by the French and English, who brought white melting flesh peaches to the United States. However, all these materials lacked commercial quality (Scorza and Okie, 1991; Sharpe et al., 1954; Sherman et al., 1996; Wang, 1985). The first superior peach varieties in the United States came in the late 1800s and early 1900s from peach producers who identified and selected chance seedlings recovered from open pollinated (OP) seed of plants grown on their farms (Floyd, 1920; Layne and Bassi, 2008). Once these first selections were made and their superior benefits during production were observed, breeding and selection started in state and federal breeding programmes using hybridization between desired parents. However, cultivation and commercialization in the United States did not change until 1850, with the introduction of a superior cultivar, 'Chinese Cling', from China. After that, other superior cultivars followed 'Chinese Cling', such as its OP seedlings 'Georgia Belle' and 'Elberta' (Scorza and Okie, 1991). 'Elberta' had been widely used as a breeding parent in peach breeding programmes across the United States and can be found in the pedigree of most commercial peaches (Layne and Bassi, 2008; Scorza and Okie, 1991; Wang, 1985).

The diverse climates and growing regions in which peaches are grown successfully, plus its relatively short juvenile period (2–3 years), self-pollinated behaviour, small genome size and the identification of important Mendelian traits, have made peach a model fruit for breeding and genetics research (Abbott et al., 2002; Bielenberg et al., 2009). The assembled peach scaffolds cover nearly 99% of the peach genome and over 92% of its orientation has been confirmed. Furthermore, 74 757 *Prunus* ESTs have been queried against the genome at 90% identity and 85% coverage. The peach reference genome contains 27 852 predicted protein-coding genes with a mean percentage of between about 60% A + T bases and 40% G + C [(A+T)/(G+C): 1.5] (Verde et al., 2013). This GC content is slightly higher than that observed in other species such as *Arabidopsis thaliana* (about 36%), indicating relatively high stability and high percentage of protein-coding genes (Verde et al., 2013).

There are a number of public and private peach breeding programmes in the United States, and their geographic locations and chilling requirements generally are classified as northern (high-chill), western (mid- to high-chill), southern-central (mid-chill) and southern (low-chill) (Layne and Bassi, 2008). In this context, few breeding programmes have focused on mid- and low-chill variety development in the United States until recently.

2 History of the cooperative regional moderate chill peach variety development project

A moderate chill peach breeding project commenced in 1986 as a cooperative regional effort involving the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS, Byron, Georgia), the University of Georgia (Tifton and, later, Griffin, Georgia) and the University of Florida (Gainesville, Florida). Originally, the project's evaluation site was located near Quitman, Georgia, but was moved in 1991 to its current location at the University of Georgia Research and Education Center outside of Attapulgus in southwest Georgia. The main goal of this collaboration is to develop new peach and nectarine varieties adapted to the lower coastal plain shipping industry of the southeastern United States. Potentially this geographical area is broad, running from coastal South Carolina southward and then westward across South Georgia and north Florida following the Gulf coast west into Texas and then south to the Mexican border. At present, the primary production centre is in South Georgia along its border with Florida, with the largest production volume typically coming from the Quitman area in Brooks county. At the time the project started, this production area was usually the first long-distance shipping industry to send peaches to market in the spring, typically commencing in late April or early May. This industry, though small, representing at most ~5% of Georgia's peach acreage in the 1990s (Hubbard et al., 1998), has, nevertheless, significant economic impact due to the premium paid for early season fruit. Nonetheless, there was little breeding support in terms of new variety development, and the industry relied primarily on two varieties, 'Flordaking' and 'June Gold', for much of its production volume. Both of these varieties were produced as spin-offs by breeding programmes (the University of Florida and Armstrong Nurseries in California, respectively) focused on distinctively different production areas and markets.

2.1 Breeding priorities and approach

The cooperative regional breeding project is focused on the development of early season fresh market varieties. Hence, they must meet minimum size and appearance requirements, and also possess sufficient firmness for long-distance shipping. Quality is important, but the varieties this industry relied upon initially, like most early season varieties in other production areas, presented a decidedly 'low bar' with respect to quality. Initially, fruit smaller than 2 inches were occasionally accepted in the market (though at a much-reduced price); however, over time, fruit smaller than 2.25 inches were no longer marketed due to consumer preferences for larger fruit. Breeding to improve size, appearance and quality is straightforward in its approach, relying primarily on careful selection of breeding parents that offer improvements in one or more desired characteristics, but whose weak points can be offset by the other parent used in the cross.

The market window that this industry targets is both narrow, typically just six weeks in duration, and early, starting in late April and running through the end of May when the main production areas in central Georgia and South Carolina typically begin to ship in volume. Addressing these two issues requires careful manipulation of chilling requirement (which in turn largely determines bloom date) and fruit development period (days from bloom to harvest). Appropriate chilling requirement genetics are important in order to minimize spring frost risk and to adequately break endodormancy for a strong bloom and vegetative bud break. Low chilling requirement genotypes can ensure routine fulfilment of chilling requirement in this climatic region (nominally USDA zone 8b-9), but also are at risk of blooming too early and suffering frequent crop losses to spring frosts. Conversely, while higher chilling requirement genotypes might delay bloom and thereby ensure little or no spring frost damage in most years, they risk the possibility of inadequate breaking of endodormancy in low-chill years, resulting in delayed and extended bloom during warmer weather and possibly incompletely formed flowers that result in low fruit set and poor fruit shape. Additionally, a substantial bloom delay typically translates into a delayed harvest date, thereby potentially creating a gap in the production stream, possibly missing the variety's market window altogether.

The general rule for selecting varieties appropriate to a production area is to choose those with a chilling requirement no higher than 75% of the long-term (i.e. 50 years) chilling average (to ensure regular breaking of endodormancy) and no lower than 50% of the long-term chilling average (to avoid spring frost injury). In practice this is not always as easy as it sounds; recent winters have varied significantly from the long-term average (~675 chill hours) at the project's evaluation site in Attapulgus (T.G. Beckman, *unpublished data*). The long-term chilling average suggests that a chilling requirement between 350 and 500 chill hours is desirable; however, over the last 10 years, the average chill accumulation has declined to 590 chill hours, suggesting a range of 300–450 h might be more prudent.

As a rule, early ripening fruit (with a typically short fruit development period) softens more quickly than does mid- or late-season fruit (Beckman and Krewer, 1999). This issue was initially a major problem for the moderate chill peach breeding project. The first crosses were made with conventional melting flesh-type germplasm like that used in most fresh market peach breeding programmes. However, when the fruit development period was shortened to hit the needed harvest window, it resulted in progeny that often were too soft for shipping and were, therefore, discarded. The resultant heavy culling of the hybrid seedling populations profoundly slowed progress and nearly caused the project to collapse (Rahn, 1997). The search for an alternative strategy focused on other flesh types, such as stonyhard (a novel 'non-ripening' type) and non-melting (a 'slow to soften' type typically used in the development of processing peaches). Both were tried initially, but non-melting germplasm proved more useful and adaptable to the development of fresh market types, which thereby moved the project forward. It is now being augmented by slow ripening 'crispy' types (as exemplified by 'Big Top' nectarine) which provide excellent firmness as fruit approach ripeness. Crispy types are superior to the typical melting type, but then ultimately soften in the hands of consumers to a product similar to that provided by main season melting-type varieties.

Disease resistance is also a breeding priority. Bacterial spot (*Xanthomonas campestris* pv. *pruni*) is of primary importance in most Eastern U.S. breeding programmes, given its potential to significantly degrade the marketability of a crop. Unfortunately, test years for bacterial spot resistance are quite variable for screening germplasm. Nonetheless, the programme utilizes several highly susceptible selections as sentinels for high disease pressure. Peach fungal gummosis (PFG), incited by *Botryosphaeria dothidea* is another disease endemic to the southeastern U.S. peach industry with the potential to cause yield losses of 25–40% with susceptible cultivars (Beckman et al., 2003; Ezra et al., 2017). This disease pressure is particularly strong in the hot and humid lower coastal plain. Periodic evaluation of cultivar releases and advanced breeding lines for susceptibility to PFG has been the standard methodology in breeding programmes (Beckman and Reilly, 2005; Beckman et al., 2011). However, the recent identification of potential markers for resistance to this debilitating disease (Mancero-Castillo et al., 2018) should allow more rapid elimination of selections and potential breeding lines having unacceptable susceptibility.

Tree architecture is a recent, increasingly interesting genetic selection priority in this programme, which was prompted by the discovery of a distinctive spur-type growth habit in a hybrid population that presented a much more open canopy form that required substantially less pruning than normal types (T.G. Beckman, *personal observation*). Although the inheritance of this trait is still not fully characterized, it appears to be a suite of traits under the control of

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