

Chapter 2

Science Drives Horticulture's Progress and Profit

Geoffrey R. Dixon, Ian J. Warrington, R. Drew and G. Buck-Sorlin

Abstract Horticultural science linked with basic studies in biology, chemistry, physics and engineering has laid the foundation for advances in applied knowledge which are at the heart of commercial, environmental and social horticulture. In few disciplines is science more rapidly translated into applicable technologies than in the huge range of man's activities embraced within horticulture which are discussed in this Trilogy. This chapter surveys the origins of horticultural science developing as an integral part of the sixteenth century "Scientific Revolution". It identifies early discoveries during the latter part of the nineteenth and early twentieth centuries which rationalized the control of plant growth, flowering and fruiting and the media in which crops could be cultivated. The products of these discoveries formed the basis on which huge current industries of worldwide significance are founded in fruit, vegetable and ornamental production. More recent examples of the application of horticultural science are used in an explanation of how the integration of plant breeding, crop selection and astute marketing highlighted by the New Zealand industry have retained and expanded the viability of production which supplies huge volumes of fruit into the world's markets. This is followed by an examination of science applied to tissue and cell culture as an example of technologies which have already produced massive industrial applications but hold the prospect for generating even greater advances in the future. Finally, examples are given of

G. R. Dixon (✉)

School of Agriculture, Earley Gate, University of Reading,
Berkshire RG6 6AR, Reading, UK
e-mail: geoffrdixon@btinternet.com

GreenGene International, Hill Rising, Sherborne, Dorset, UK

I. J. Warrington

Massey University, Palmerston North 4474, New Zealand
e-mail: ianjw@xtra.co.nz

R. Drew

School of Biomolecular and Physical Sciences, Griffith University,
Nathan Campus, Nathan, Queensland 4111, Australia
e-mail: r.drew@griffith.edu.au

G. Buck-Sorlin

AGROCAMPUS WEST Angers Centre, National Institute of Horticulture and Landscape,
UMR1345 Research Institute of Horticulture and Seeds (IRHS), 49045, Angers, France
e-mail: Gerhard.buck-sorlin@agrocampus-ouest.fr

nascent scientific discoveries which hold the prospect for generating horticultural industries with considerable future impact. These include systems modeling and biology, nanotechnology, robotics, automation and electronics, genetics and plant breeding, and more efficient and effective use of resources and the employment of benign microbes. In conclusion there is an estimation of the value of horticultural science to society.

Keywords Applied science · Impact · Industrial application · Environmental value · Social value · Food supply · Dietary provision

Introduction

Horticulture is the controlled manipulation of plant reproduction, growth and fruiting applied to crop production, environmental care or social benefit. The word “profit” is deliberately used in the title indicating that scientific discovery is the basis for future profitability in the commercial sense but also in pursuit of environmental and social sustainability. This belief draws on the profits which have already accrued from discoveries and applications in horticulture and horticultural science and which are elaborated as part of this chapter. This may seem to be a utilitarian approach from the perspective of purist researchers but accurately reflects the desire of horticultural scientists for close collaboration with end-users. The definition does not however, adequately convey the intellectual depth of horticultural science which takes basic and fundamental discoveries and translates these into applicable and useful knowledge.

Controlled manipulation of plants requires access to and an understanding of scientific knowledge across multiple disciplines and then its synthesis into applied science and ultimately technological expertise. Horticultural science’s reservoir of knowledge firstly evolved over many centuries from the original gathering of empirical principles garnered by mankind’s founding social cultures. The advent of the sixteenth century “Scientific Revolution” ultimately produced qualitative and quantitative hypothesis and data-driven studies founded on basic research in biology, chemistry, physics, mathematics, electronics and social and economic disciplines. As a result, horticultural science has become an applied science which flourishes by cross-fertilization between itself and other disciplines. Excellence in horticultural science demands scholastic, intellectual capacities which are capable of identifying nascent discoveries across the basic sciences and integrating them into processes and procedures which possess industrial, environmental and social value. Horticultural science deals in both “why” natural processes happen and “how” they may be manipulated thereby producing ecologically sustainable social and economic growth. The knowledge gained in itself often contributes back to the fundamental sciences and enhances basic understanding.

Knowledge of the controlled manipulation of plants emerged long before the modern era of scientific experimentation. Horticulture is the oldest of all mankind’s arts and sciences. From our earliest civilizations in Babylon, China and South

America mankind developed an understanding of the cultivation of food, medicinal and decorative plants. Knowledge of how plant form and function could be manipulated was passed firstly verbally and subsequently in written texts through into the sixteenth century. Quite probably forms of simple experimentation existed prior to this date. Initially it is quite likely that this involved the segregation of higher yielding forms of food plants and the evolution in cultivation of cropping variants which would, in turn, become semi-stable land races. This would have been supplemented with an understanding of the use and effects of irrigation water and animal fertilisers, seed saving and forms of asexual propagation, and plant protection. The identification of plants containing useful and beneficial compounds and their description required forms of systematic thinking and enquiry which culminated in the great herbals which were initially hand-written in monasteries and other religious establishments.

The first systematically recorded experimentally-based horticultural enquiry was that of Stephen Hales (1727). He carried through a series of well planned experiments, and demonstrated that a plant takes in large volumes of water through its roots provided that it has leaves from which the water may subsequently evaporate. He went so far as to suggest that “may not light also, by freely entering the expanded surfaces of leaves and flowers, contribute much to the ennobling the principles of vegetables?” A glimpse of an understanding of what much later was termed photosynthesis perhaps? Certainly, Hales provided the first scientific basis for the horticultural processes of irrigation, nutrition and plant manipulation and protection. That technology had been utilised empirically by mankind for centuries, possibly millennia. The ensuing “Scientific Revolution” produced increasing understanding of biological principles and processes. John Ray and Carl Linnaeus provided scientific structures for the nomenclature and taxonomic assessment of plants and their properties. That step related plant identification with structure and function (Dixon and Brishammar 2007a, b). Charles Darwin’s seminal qualitative development of an understanding of evolution and speciation offered a logical basis for biological thought which is reverberating now as molecular science with ever increasing impacts in horticulture (Darwin 1862). Microbiology and mycology began emerging as important elements in horticultural thinking with Pasteur’s recognition of the causal agents of vine diseases and subsequent studies which founded plant pathology. Along with entomology, the basis was laid for the emergence of key areas of biological science with enormous impact on the successful control of healthy plant growth.

A major step in quantitative understanding was Mendel’s discovery of the principles of heredity using peas as an experimental model (Mendel 1866; Stern and Sherwood 1966; Orel 1996). Particular benefits come from the integration of physical and chemical scientific thinking into biology and subsequently leading to developments in horticultural science. An early example of this is the influence of Professor John Henslow’s quantitative approach to speciation (Henslow 1830) which Kohn et al. (2005) postulated influenced Darwin’s thinking. The rise of horticulture’s productive capacities towards the end of the nineteenth century is firmly rooted also in industrial discoveries. Nitrogen fixation by artificial means allowed

the manufacture of commercial quantities of fertilisers which resulted in increased levels of crop productivity of previously unachievable dimensions (Smil 2001). At about the same time, Mendel's work was rediscovered in 1900 (Bateson 1909) and formed a scientific basis for genetics and plant breeding leading to the development of higher yielding and better quality crop cultivars. This is a classic example of the convergence of commercial research and development providing fertilisers on the one hand and more basic academic studies providing new genetic forms capable of profiting from added nutrients on the other.

Throughout the ensuing twentieth and now twenty-first centuries, fundamental science has been and continues to be the foundation from which most developments and innovations in the art and science of horticulture spring. The pathways by which fundamental science is turned into horticultural science and subsequent technology are neither straightforward nor short term. Although many years may elapse between an initial basic "blue-skies" discovery and its translation into applied science and related technologies once these offer increased efficiency then changes are adopted by industry very quickly. The pathways for the thinking which translates science into application are complex, frequently indirect and most certainly not linear as some pundits regrettably and damagingly pretended in the 1980s. Horticulture, and agriculture and forestry for that matter, are rooted in industrial practice. Not infrequently that means that information derived by practitioners unlocks an understanding of science which then turns full circle formulating novel processes which resolve a practical problem.

The organisational structures within which horticultural science uses basic science and turns it into technology are changing in parallel with worldwide social, religious and political evolution. Nonetheless, the requirement for new basic scientific discoveries remains continuous. Without new science, horticulture itself cannot evolve and move forward, continuing the processes of wealth creation for society, conserving and safeguarding the environment, and enhancing human health and welfare. It is foolhardy in the extreme to pretend that mankind's urgent needs for horticultural production can be met by anything other than continuous evolution of new scientifically-based knowledge. This is exemplified by the huge advances that studies of molecular biology have brought in our basic understanding of how organisms are constructed and the delicate metabolisms which control their activities as, for example, described by Enrico Coen (1999). Horticulture has an enviable reputation for being capable of turning new science into technological improvements at least on a par with the pharmaceutical industry. This perhaps should not be surprising given the close origins and evolution of horticulture and pharmacy.

Social change is placing new demands on horticulture and satisfying these demands means altering the requirements for science and technology. In a very perceptive prediction Oosten (1999) (echoed by Warrington 2011) argued that major shifts in the world economy (globalization), society and technology would cause dramatic changes in Dutch horticulture and the attitude of the government towards research by 2010. He contended that the horticulture industry would change from a product-driven to customer-driven strategy while developing market-oriented product chains. Knowledge would become a critical factor in competition and applied

research closely linked to industry would become the responsibility of private enterprise. In particular, he highlighted four developments in science and technology of great significance to the horticultural industry: molecular biology; information technology (IT); new concepts in the marketing chain; dynamics in health food relations and production ecology. The need for strengthening basic sciences was emphasised and those which he called "knowledge institutes" (universities and research institutes) would be faced with repositioning themselves for three roles:- knowledge creation; co-operating innovator; and knowledge brokering.

Horticultural Science's Changing Focus

The marketing of horticultural produce has changed rapidly and monumentally in the past 25 years (Shepherd 2008) and continues doing so. Chains linking growers, traders, processors, retailers and consumers are now controlled to a very large degree by supermarket retailers. Supply systems are likely to evolve from largely price-based competition to innovation-based competition. Consumers are seeking increased localisation, regionality and identification of origin, as well as safe and healthy nutritional foods. Electronics, nanotechnology and robotics offer opportunities for interaction between primary producers and the ultimate consumers. Customers and producers will interact directly with confidence and trust. Only the largest producers will be capable of managing the infrastructure capable of servicing this relationship and its dialogue which will reach beyond national borders. These producers will own the intellectual property rights to production and supply systems and commission their own R&D from these assets. This applies currently with greatest impact on the supply of fresh and processed produce in food chains. As a result, applied horticultural science is moving towards private sector provision at the same time as the role of the crop producer is becoming more prominent in the consumer's mind as responsible for the delivery of safe, reliable and health-enhancing products. At the same time, aspects of research and development needed for environmental and social horticulture, as described in other chapters of this Trilogy, are emerging through economic evaluations of areas such as natural ecosystem services and the quantification of social care within communities. An example of this approach is the framework for environmental-economic decision-making which includes ecological sustainability criteria, environmental costs, natural resource scarcity prices and local peoples' preferences developed by Tiwari (2000). Here the geographic information system (GIS) technique was used for evaluating ecological criteria and integrating information for use in cost-benefit analysis. A cost-benefit analysis (CBA) embraced external costs, such as environmental costs and scarcity value of water, and ecological sustainability criteria. As stated by Hughes (2007), the *raison d'être* of the global food industry is to satisfy the ever evolving requirements of consumers worldwide. The dominating trends affecting consumer behaviour include: demographic changes; concerns about safety, health, well-being and nutrition; and an inexorable search for convenience, particularly in urbanised communities. Across

the globe, starting in developed and migrating to emerging countries, the growth of supermarket retailing is forming a principal link between food producing industries and their consumers. A relatively few, sophisticated international retailers are establishing businesses in both geographic hemispheres and, in doing so, are transforming the nature and operations of international supply chains. The implications of international horticultural supply chains being transformed from “supply push” to “demand pull” are profound for all stakeholders, including growers, exporters and importers, and the international research and development (R&D) community. Commodity markets are fragmenting into specific consumer segments. The R&D focus is shifting from input traits (e.g. yield or pest and pathogen resistance) to consumer-led output traits (e.g. taste, size, shape), and is becoming an increasingly private sector function. The challenge is to identify and commercialize product attributes that consumers’ value and will pay premiums for.

Those businesses capturing the intellectual property associated with value-added products will take the lion’s share of the consumers’ dollars. The trend towards “privatization” of R&D will cause current supply chains, which are open and commodity-orientated to become closed, with exclusive providers of genetics and associated production systems linking with specific producers, exporters, importers and retailers. The horticultural industry will come under increasing price pressure in the future, as fewer, larger businesses control access to higher income consumers. Competition will evolve however, from solely price-based to innovation-based systems providing novelty in products, processes, and services. Successful horticultural businesses around the world will seek to build trust and longer-term commercial relationships with those who have immediate contact with the grower and consumer, bringing in an era of interdependence, rather than independence. This will steadily manifest itself in closer relationships between producers and the consumers. The latter are making it abundantly plain that they wish for contact with producers through increasing consumer demand for information regarding the origins and qualities of food. The internationalised food chains will have to accommodate growing demands by consumers for localisation of production, the provision of fresh and processed products carrying health and welfare benefits, minimisation of adverse environmental impacts in the production and delivery of food and other services, and a desire for a reconnection between urban and rural societies. Overlaying all of this will be the increasingly severe impacts of climate change, water scarcity and increased urbanisation on opportunities for horticultural production. This echoes Sumner’s (2007) contention, that horticultural science has a dichotomy of purpose of serving the requirements of transnational corporations and supporting basic human needs, community survival and environmental sustainability.

Possibly a solution lies in what Larsson et al. (2009) now describe as their Triple Helix Concept of co-operation between academia, industry and government. That revives the founding principles of the American Land Grant Colleges and what were once the Scottish Schools of Agriculture. They resolved the dilemma whereby industry requires short term problem-solving research while there must be a provision of basic seed-corn research investing in studies which will only ripen into industrial technology over an indeterminate period. To some extent, in pursuit of these goals

in the USA, Bewick et al. (2011) reported that the USDA has created a Specialty Crop Research Initiative (SCRI) for research, education and economics receiving \$US 230 million over 5 years addressing the scientific needs of horticulture. The focus is to discover new knowledge and technologies which ensure a sustainable supply of horticultural products and services. Additionally, this programme emphasizes the need for education and training of both the current and future workforce. This is achieved through planning from university graduate to primary education which aims at inspiring youth into choosing horticulture as a career as described elsewhere in this Trilogy.

Horticultural Industries Created by Science

The application of basic science into horticulture has succeeded by providing tools for the control of germination, growth, reproduction and post-harvest handling for commodity crops, the design, construction and maintenance of macro- and micro-landscapes, and the provision of plants which enhance physical and psychological health. In this section are examined a series of science-led advances in horticulture which have had and continue having enormous impact on profitability and sustainability. These are but a few of the many such advances that have taken place over past decades. The perspective of history provides the identification of seminal advances in horticultural science in the early part of the twentieth century which laid the basis for industrial practices which have subsequently become common commercial uses. Much early scientific effort was invested in attempts to produce uniformity of growth in experimental material with the initial aim of providing regularity and reliability for research studies. The early researchers wished, in particular, for control and regularity with perennial crops. Darwin (1859) pointed to the two key sources of variation in biological systems, characteristics which are inherited from two parents in the genotype and the impact of the environment on their expression in the phenotype. Hence genotype (G) x environment (E) interaction results in the phenotype (P).

Refinement and Development of Top Fruit Rootstocks

All top fruit trees, both pip and stone, consist of a rootstock onto which the scion fruiting cultivar is budded or grafted and which results in two sources of genotypic variation. The husbandry required for producing fruit trees formed from the union of a rootstock and a scion has been known in Europe at least since the fourteenth century and was developed to very high degrees of skill, particularly in part of the Spanish Netherlands in what is now separately Belgium and The Netherlands. Both the rootstock and the scion are influenced individually and collectively by the environments in which they grow and by interactions between them. Scion cultivars, the source of edible fruit, result from lengthy breeding and selection programmes and

consequently possess highly defined characteristics. Rootstocks mainly result from even more lengthy selection programmes and are retained in commercial use for decades. Many of their characteristics began being identified in the late nineteenth century and variation within rootstocks is noted in Bedford and Pickering (1919) and amplified by Bunyard (1920) and Hatton (1920). Scion growth control via the manipulation of pip and stone rootstock vigour played and still plays a major role in increasing fruit quality and quantity. Bunyard (1920) noted the history of Paradise rootstocks and their origins. This was followed by several years of careful analysis of selections of these stocks demonstrating how the yield of the scion varied with different stocks. ‘Lane’s Prince Albert’ when grafted and budded on stock number IX was the highest yielding (Hatton 1927). This work led on to the subsequent development of the ‘Malling (M)’, ‘Malling-Merton (MM)’ and ‘East Malling-Long Ashton (EMLA)’ clones as described, for example, by Preston (1955). Apple rootstocks selected by British research stations (East Malling, John Innes and Long Ashton) in the early part of the twentieth century currently still dominate commercial practice internationally. The rootstock known as Malling no. 9 (M9) is still to be found in almost every apple orchard worldwide. The studies of rootstock vigour and stabilisation of original selections taken from commercial material resulted in rootstocks with predictable and reliable properties. Recently, further sources of rootstocks have appeared from Eastern Europe and North America resulting from continuing studies aimed at engendering improved performance of the scion cultivars. None of these, however, have achieved the market dominance of the original British material, especially M9, to date. These rootstocks quite literally support a worldwide market in the single largest internationally-traded fruit commodity, the apple, and have done so for nearly a century.

Scion Sterility and Fertility Barriers

Explanations of the biological processes of scion pollination across barriers of self-sterility and incompatibility were elucidated by Hatton, Amos, Hoblyn, Crane and Lawrence (Dixon 2006). These workers founded the science of cytogenetics resulting in an understanding of underlying incompatibility of fertilisation between cultivars of apple, pear and, in particular, cherries and plums. They recognised groups of cultivars which could be planted successfully so that pollination would be successful and those where it would fail. The result of this work has provided generations of fruitgrowers worldwide with the ability for designing orchard layouts which would ensure cross-pollination and successful high yielding and high quality cropping. Consequently, cultivars are now specified into their compatibility groups even where they are destined for hobby gardeners. Working out these groups required dedicated laboratory studies of the growth or failure of the pollen tube into the ovary and transmission of male gametes for successful pollination. This work extended into field vegetables in the 1950s showing that in *Brassica* spp. in particular the presence of specific sterility (S) alleles in the genotype regulated the success or failure of fertilisation and resultant development of seed crops. Prior to

that step however, it was essential to understand what constitutes a brassica species. Detailed research by a Korean-born scientist working in Japan in the 1930s uncovered the plasticity of brassicas and the natural formation of new species through allopolyploidy (U 1935). As a consequence, brassicas now constitute the world's most important fresh food and industrial processing crops second only to the cereals in their importance in the diets of humans and domesticated animals (Dixon 2007).

Photoperiodism and the Control of Vegetative and Flowering Phases

Investigations beginning in the 1920s revealed that plants may react to the duration of the light environment by reproducing or remaining vegetative (Garner and Allard 1920, 1923). Subsequently, plants were divided into short-day responsive, long-day responsive or day-neutral forms (Wareing 1956; Schwabbe 1950, 1951, 1952). Since these original discoveries, botanical science has invested huge amounts of time and effort into understanding the manner by which variations in light quality and quantity are perceived and translated into signals which result in the initiation of flowering or the retention of a vegetative state. Modern molecular biology explains these processes in terms of the genetic components of plants and the manner by which the signals are generated. In the intervening years however, huge multinational horticultural industries have developed which produce flower and foliage crops worldwide using artificial control of day-length (such as chrysanthemum, poinsettia, *Kalenchöe*, carnation and rose) (Bernier et al. 1981). Crops are grown on very precise schedules where flower production is predicted over the entire growing period to within a few hours to high degrees of quality and consequently financial value. Basic knowledge of the manner by which flowering is triggered created multibillion dollar, global industries growing cut flowers and flowering pot plants.

Rooting Media

Original studies at the John Innes Institute in the 1920s, aimed at providing a root environment for potted experimental plants and germinating seed, which offered standardised structure and texture combined with regulated nutrient supplies. This aimed at limiting one of the variables which beset geneticists when studying the effects of breeding experiments. The results produced the John Innes series of potting and seed composts (Darlington 1949) which remain in common use, especially in the huge hobby markets today and are increasingly used where peat composts are not acceptable (Carlile and Waller 2013). These composts are based on standardised mixtures of sand and loam-based compost into which precise quantities of nutrient fertilisers and calcium carbonate (lime) were mixed. John Innes composts remained as research standards into the 1950s. A new industry developed that manufactured these composts for sale to plant propagators, nurserymen and

hobby gardeners. This remains an active part of what has become the global plant media industry developed on the back of an initial desire by research workers for repeatable and regular growth patterns in their experimental material. The problem with John Innes mixtures is that the loam component is very difficult to standardise across large volumes of compost. Consequently, researchers in the University of California devised alternative formulations of media where loam is replaced by peat which became known quite simply as “UC mixes” (Baker et al. 1957). Mixtures of peat and sand are more easily standardised and formulated on a factory scale. They provide composts with better properties of air fill porosity and resultant reproducibility of crop growth. This Californian research initiative has resulted, over the last 50 years, in an entire revolution in the ornamental and nursery industries, whereby plant selling has changed from almost exclusively bare-root material which could only be sold in the period of plant dormancy, to almost year-round provision of container-grown and containerised shrubs, trees, perennials and annual plants. As a result, it is probably fair to claim that the entire shift from small local nurseries to massive garden centres has come about because of the characteristics of plants which the retail consumer can conveniently carry home and plant at any time of the year. This revolution, fired initially from the availability of convenient rooting media, has spawned a massive worldwide garden centre industry. The result is that this industry is now worth billions of dollars and has become part of the tourist industry in many countries, since retail customers use garden centres as part of their rest and relaxation during holidays and weekends. The revolution of continuously available plants permitted garden designers the freedom they needed for producing ever changing scenery in their urbanised clients’ regard as “garden rooms”.

Genetic Uniformity in Vegetable Crops

Genetic uniformity has become the hallmark of field and protected vegetable crops and underpins growers’ abilities for supplying supermarkets with high quality produce on a year-round basis. This has been achieved by an almost universal change to the use of F_1 hybrid cultivars. These provide uniformity of growth and maturity allowing the application of precision management techniques delivering controlled ripening and harvesting. Compared with open pollinated cultivars, where individual plants grew at differing rates and maturities and which were very unpredictable, F_1 hybrid crops have resulted in substantial financial gains across the industry worldwide and down the supply chain to retailers. From the plant breeders’ perspective they also offer much greater security for their intellectual property rights (IPR) because they are far less accessible for duplication and copying. The seed of F_1 cultivars must be produced annually by crossing the inbred parental lines and self-saved seed from a commercial crop cannot easily reproduce the specified hybrid. Much of the development of F_1 hybrid vegetables can be traced back to genetic studies in Japan in the 1930s which resulted in the production of the Brussels sprout (*Brassica oleracea* var *gemifera*) cv Green Jade. This could not have come about without an

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