INTRODUCTION

THE AGE OF BIOLOGY

> An organism is the product of its genetic constitution and its environment . . . no matter how uniform plants are genotypically, they cannot be phenotypically uniform or reproducible, unless they have developed under strictly uniform conditions.
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> **— Frits Went, 1957**

A LITERARY and cinematic sensation, Andy Weir's *The Martian* is engineering erotica. The novel thrills with minute technical details of communications, rocket fuel, transplanetary orbital calculations, and botany. The action concerns a lone astronaut left on Mars struggling to survive for 1,425 days using only the materials that equipped a 6-person, 30-day mission. Food is an early crisis: the astronaut has only 400 days of meals plus 12 whole potatoes. Combining his expertise in botany and engineering, the astronaut first works to create in his Mars habitat the perfect Earth conditions for his particular potatoes, namely, a temperature of 25.5°C, plenty of light, and 250 liters of water. Consequently, his potatoes grow at a predicted rate to maturity in 40 days, thus successfully conjuring sufficient food to last until his ultimate rescue at the end of the novel. Unlike so many of the technical details deployed throughout the novel, the ideal conditions for growing potatoes are just a factoid. Whereas readers of the novel get to discover how to make water in a process occupying twenty pages, the discovery of the ideal growing conditions of the particular potatoes brought to Mars is given one line.[1] Undoubtedly, making water from rocket fuel is tough, but getting a potato's maximum growth in minimum time is also tough. Back on Earth, current consumers wandering supermarkets full of fruit and vegetables making decisions about a potato's or tomato's look and texture and guessing about taste perhaps barely appreciate that the discoveries of the incredibly complex processes of growing plants have constituted some of the most important knowledge of all time. For although the sciences and technologies of plants have not yet saved a single astronaut on Mars, they have helped feed the multiplying people of the Earth.

Starting around the eighteenth century, European empires went to great lengths to collect and cultivate new plants. In the nineteenth century, the science of agriculture emerged as a proper function of many states to produce new breeds of crops and livestock and to make productivity gains through the development of new farming practices.[2] As many sciences moved into laboratories, the study of plants moved into greenhouses. Under glass, experimenters sought to reveal how the environment regulates and controls elements of plant growth, flowering, and development; notably, Charles Darwin had his greenhouse heated. Subsequently, in the late nineteenth century, genetics and plant physiology emerged as the two great new experimental sciences for understanding plants. Although the story of the geneticists' discoveries of genes and their wondrous promise is widespread, the corresponding story of knowledge about the plant physiologists' technologies of plants' environments is far less well known. Yet today, the wealth, variety, and sheer uniformity of everything people eat from apples to zucchini owes much to both the pioneering efforts of commercial facilities that fixated on a few systems and variables of climatic control as well as those scientific institutions that experimented with plant varieties and variable environments. Quite simply, the sciences of genes and environments have underpinned the new agricultural revolutions through the Green Revolution to modern hydroponics.

Engineering the Environment tells the history of one class of laboratories that created artificial climates and helped make those discoveries possible. They were called *phytotrons,* a name that resounded with all the promise of the dawning atomic age. For plant scientists, especially botanists and plant physiologists, phytotrons offered to "make it possible to study plant behaviour in its broadest sense under a diversity of climatic conditions where it is possible to vary each factor without appreciably altering the others."[3] A phytotron was a facility consisting of any number of rooms or smaller cabinets, in each of which any desired set of environmental conditions could be produced and monitored by new computers. Plant scientists used the ability to produce and then reproduce any climate to conduct experiments on the environmental responses of plants. And for over sixty years now, phytotrons have continued to be part of the global experimental study of the effect of environments on growth and development. They now serve on the front lines to attack the growing threat of climate change and uncertainty about its effects on the planetary food supply and biosphere. In the near fictional future, Andy Weir's astronaut builds a phytotron on Mars to survive—as his potato crop nears maturity, Weir's astronaut thanks "the billions of dollars' worth of life support equipment" in his habitat, which "maintains perfect growing temperatures and moisture at all time."[4]

When it opened in 1949, the first phytotron at the California Institute of Technology (Caltech) was a wonder of environmental systems engineering. It possessed new fluorescent tube lighting that controlled light, new air-conditioning systems and thermostats that controlled temperature, new devices of humidity regulation and nutrient standardization. Postwar, the study of plants also required a radioactivity room and a wind tunnel for early experiments in airflow across single leaves, whole plants, and rooms of plants. In a second-generation phytotron like the one in Stockholm any temperature between +5°C and +40°C could be maintained to an accuracy of ±0.2°C, or 0.5 percent; a fivefold improvement over the original phytotron in just twenty years.[5] Subsequently, the third-generation phytotron, named the Biotron at the University of Wisconsin-Madison, went even farther building soundproof rooms, dark rooms, and below-freezing rooms, and extended controlled environment experimentation to animals as well as plants. In all, like the more familiar story of the cyberneticans of the Cold War era, plant scientists in phytotrons obsessed about control over everything from their experimental black boxes, to their professional lives, and the wider geopolitical struggle of the era.[6] To establish the biological response to the environment required control: "What is important in a phytotron," the deputy director of France's national phytotron, Jean Paul Nitsch, told an audience in 1969, "is *the degree of control* over the various environmental factors."[7] Importantly, early phytotrons sought not only to control the technologies that made environments but also to govern the scientist users themselves.

Centrally, new computer systems at the heart of every phytotron gave control of control. In recurrent images of the era, computer panels occupied prominent and visible spaces in the first phytotron at Caltech, the Climatron, and the Biotron.[8] Those computers were not the desktops and laptops of today, though; they were the room-sized mechanisms of electronic and social control.[9] Opening in 1965 at the Royal College of Forestry in Stockholm, the "control room" in the Swedish phytotron, for instance, centralized the "timers regulating the photo- and the thermoperiods in the individual climate rooms." At the same time, housed in the control room was the "control system using thermocouples and multipoint recorders [*sic*] the temperature, the humidity, and the light conditions at certain points in all climate rooms." Overseeing regulation and monitoring was a third control system, "an elaborate alarm system to warn of malfunction"; on nights and weekends, the alarm system could "by a telephone robot" alert "any desired home number."[10] Computerized, phytotrons realized one vision of high modernism where every season would be created, charted, and overseen by the central regulating equipment of the control room. Consequently, as this book shows, learning about plants meant learning about the technology to replicate any biological environment. Plant science in the phytotron was timed and recorded, monitored and warned, called and regulated—a science governed by machine.

New assemblages of technologies to produce and control artificial climates reshaped the very boundaries of being human and offered ever-greater control, notably as a few went into space, some went deep under the sea in atomic submarines for months on end, and most went to their new middle-class jobs high above the street in clean and modern air-conditioned high-rise office buildings.[11] Like spaceships, skyscrapers, and airports, phytotrons sat squarely within the architectural, artistic, and scientific movement known as modernism, which, as Peder Anker traced, saw technology as the key to just social and natural organizations.[12] It was some of the grandest thinking of the era. For a technocrat modernist such as the Lloyd Berkner, a "growing technological capability" led straightforwardly to "knowledge of nature" by which "man acquires greater control."[13] Le Corbusier's vision of his "plan" for a new architecture and a new city included notable new forms that would best encompass the totality of needs and wants, from his famed "City of Towers" to any single house that would, of course, have a controlled environment with "baths, sun, hot-water, cold-water, warmth at will, conservation of food, hygiene, beauty in the sense of good proportion."[14] Purposively designed to create a new experimental and ordered plant science, the designs of phytotrons resonate with such high modernist visionaries. Indeed, while Le Corbusier encapsulated the spirit of modernism in the bon mot, "a house is a machine for living in," for over thirty years it seemed to some scientists that a phytotron was a laboratory for doing plant science in.

Little wonder then that as ever grander facilities took shape around the world through the 1950s and 1960s, Pierre Chouard, the director of *le grand phytotron* outside Paris, upon his retirement in the 1970s announced that biology was "entering . . . a Phytotronic era."[15]

BEFORE THE PHYTOTRONIC ERA

A variety of efforts to control one or more elements of the environment arose as part of the broad turn toward experimentation across the biological sciences.[16] Alongside open-air field trials, those cheap and popular mainstays of agriculture and horticulture then and now, greenhouses could hold a climate approximately steady for the benefit of a whole range of plant species. Greenhouses and fields served as places of agricultural experimentation on new breeds as well as new techniques of farming.[17] Technology was celebrated as much as botany and agriculture in the grand Victorian palm house at Kew Gardens and the grander art-deco-styled greenhouses of the Jardin des Plantes in Paris of the 1920s. Prior to the Second World War and the widespread availability of air-conditioning, the "control of air temperature by heating" was the achievement that elevated the glasshouse above the field for commercial growers as well as for botanists and physiologists.[18] Greenhouse technology saw exotic plants grown en masse in unnatural locales, such as the tropical palms grown in London and Paris, or the roses grown by one Illinois producer who possessed nearly a million square feet under glass by the 1920s.[19] But by the middle of the twentieth century, according to one experimenter, greenhouse conditions might suffice for agricultural production but experimental science demanded repeatability and control: the "chief physical characteristic of the average glasshouse environment," he complained, "is its great variability." In ten minutes, light intensity could change by 50 percent, air temperature by 10 percent, and the air itself by

30 percent. Such environments, the experimenter denounced, were "not quite haphazard but prehistoric, or rather pre-scientific!"[20]

Since the scientific revolution, scientists have sought to control the experimental environment of their instruments, laboratories, and objects. One well-known example saw the mere body temperature of more than one experimenter in the room with the apparatus at one time undermined James Joule's measurement of specific heat.[21] The emergence of experimental biology in general, and the discipline of plant physiology in particular, gave rise to one of the first attempts to claim mastery over the biological environment. Called the Vivarium, the facility opened in Vienna in 1903, and offered innovative technologies and systems brought to bear on zoological and plant physiological problems.[22] Later in the 1920s, scientists at the Boyce Thompson Institute in New York built "two constant-condition rooms" to address emerging experimental work on environments after the landmark studies of W. W. Garner and H. A. Allard indicated that day length governed flowering.[23] Later still in the 1930s, German biochemists could lay claim to running the "best-equipped biochemical research facilities in Germany and the world," the director of the Kaiser Wilhelm Institute for Biochemistry in Berlin advertised, because they had built adjustable controlled chambers that stabilized the environments for their new ultracentrifuges and electrophoresis apparatuses.[24] By the mid-1950s controlled environment facilities had become plainly ubiquitous: as the leader of Australia's major plant research group, Otto Frankel, reported after a tour through the United States, "Controlled environment facilities are now, at least to some degree, part and parcel of every botanical institution."[25]

Phytotrons unified and extended earlier piecemeal efforts to claim total control of the whole environment. In both walk-in rooms and smaller reach-in cabinets, phytotrons produced and reproduced whole complex climates of many variables. In the first phytotrons each individual room was held at a constant unique temperature. As figure I.1 shows, the Australian phytotron, for example, had rooms maintaining 9°C, 12°C, 16°C, 20°C, 23°C, 26°C, 30°C, and 34°C. Because some of the earliest controlled-environment experiments showed that plants reacted differently in daytime temperatures and nighttime temperatures, the first experiments to observe the effect(s) of varying the daytime versus the nighttime temperature saw experimenters move their plants from higher to lower temperatures over the course of a daily, or any other variable or

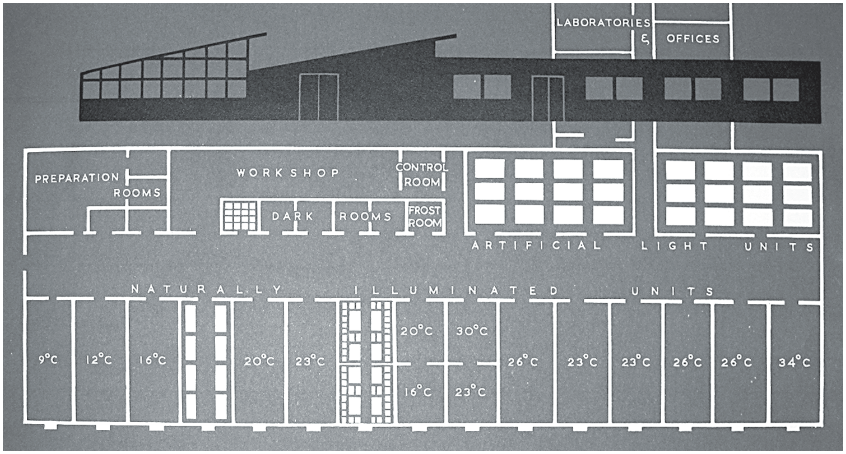

Figure I.1. "Plan of the Proposed Australian Phytotron." From "What Is Needed for an Australian Phytotron?" March 28, 1958. NAA Series A4940, file C2060. Image courtesy of the National Archives of Australia.

constant, routine. This rendered the variable "temperature" experimentally controllable. Even a brute force approach that tested each successive environmental variable and every variety of plant would serve to pinpoint specific environmental conditions to maximize growth. Expecting that more knowledge would surely come from greater technology, the next generation of phytotrons expanded in technological reach, in their ranges of environmental variables, and also in the degree of control over each variable. The phytotron in Stockholm offered a humidity-controlled room and a custom built computer, as well as a low-temperature room that extended the temperature range down to –25°C for the study of Nordic forests.[26] After that, phytotron technology compressed whole environments into smaller cabinets able to be set to any desired combination of environmental conditions, which are still in use today.

By the middle of the twentieth century, plenty of plant scientists, broadly including botanists, foresters, horticulturists, plant pathologists, and plant physiologists, used controlled and monitored environments to establish connections between specific environmental conditions and the mechanisms of flowering, trace elements and plant nutrition, photosynthesis, and plant heredity.[27] With control over the entire interrelated complex of the environment it seemed to many plant scientists that they had at last cracked the great puzzle, namely, the study of plant behavior

Figure I.2. "Glasshouse of Phytotron CSIRO, Canberra." 1967. NAA Series A1200, L66896. Courtesy of the National Archives of Australia.

from their genes as well as their environments. The plant breeder, phytotronists' advertised, already provided control over plants' "genetic constitution."[28] Phytotrons offered similar mastery over the environment through technology. While the control of temperature, humidity, airflow, and day length was achieved by the 1950s, the control and study of light has preoccupied the builders of phytotrons since the 1960s (and proved, as we shall see, to be a more complex technological and biological problem). Work in phytotrons helped botanists and plant physiologists better understand all the "hottest topics" of plant physiology of the 1920s and 1930s—phenomena such as photoperiodism (the response of plants to day length) and vernalization (the response of plants to temperature), as

Figure I.3. Kennebec potatoes grown . . . From Went, *The Experimental Control of Plant Growth,* plate XII. Reproduced with permission from John Wiley & Sons, Ltd.

well as the actions of auxins, plant hormones, and chemical herbicides.[29] Later, the name of phenomena of *phytochrome,* a photoreversible pigment came, the story went, from a "combination of *phytotron* and *Kodachrome*."[30]

One notable success of plant science in phytotrons was the ability "to determine the precise limits of productivity of plants."[31] The first phytotron, for instance, hosted two years of experiments on Kennebec potatoes and pinpointed that the greatest weight of tubers came from a combination of 20°C day temperatures with 14°C night temperatures (fig. I.3), in contrast to Andy Weir's astronaut's Idaho potatoes, which required an optimal temperature of 25.5°C. However, experiments in the phytotron also discovered that growth cannot be reduced to one environmental condition: the yield of Kennebec potatoes decreased by a fifth as the length of daylight went from eight to sixteen hours, and then decreased by four-fifths at twenty-four hours.[32] Remarkably, plants need nighttime, and thus, although unmentioned in the novel, Andy Weir's astronaut in fact helped his potatoes grow each time he turned out the lights.

Another celebrated "great discovery" by none other than the founder of the first phytotron, Frits Went, was that tomato fruit only set "over a limited and experimentally determinable range of night temperatures."[33] Went was a central figure in twentieth-century plant science.[34] Having achieved controlled conditions, Went spoke widely about how "with 3 parameters, . . . day temperature, night temperature and length of day, we can describe any climate at any particular time of the year in terms which are important for plant growth and plant distribution." To visualize the optimal climates for particular varieties, Went had three-dimensional models built, consisting of wire-frames forming lines that marked the growth of plants across several environmental measures, which were reproduced in a variety of publications (fig. I.4). What his model showed was revolutionary: in his new environmentally controlled laboratory, which had just gained its cognomen *phytotron*, plant science could now experiment on the "environment." Went spoke dramatically to the assembled audience of the International Botanical Congress in Stockholm in 1950, and illustrated his talk with results from several plants, but particularly highlighted the case of *Saintpaulia*, or the African violet. African violets required 25°C day temperatures and 22°C night temperatures, Went told his listeners, thus its optimal point existed outside the ellipse that described the climate in Pasadena, California, where he lived. However, the question of whether African violets could be grown inside their houses "sharply divided" the gardening public of Pasadena. Many swore they could be grown. Just as many dismissed even the possibility. The explanation, Went happily claimed, stemmed from the dependence of the plant's growth and development being intimately linked to three variables of climate, phototemperature (day temperature), nyctotemperature (night temperature), and photoperiod (length of light). People who left their windows open during the night could not grow African violets, but those who closed their windows could. And so the reveal: "you tell me which plants you grow in your house, [I will] tell you how you live."[35]

Such models dramatically illustrated the power of controlled-environment plant science everywhere from headline articles in *Science* magazine to popular picturesque 1960s coffee-table books.[36] Readers of *The World of Plants* (volume 3 of Doubleday's *Encyclopedia of the Life Sciences*)

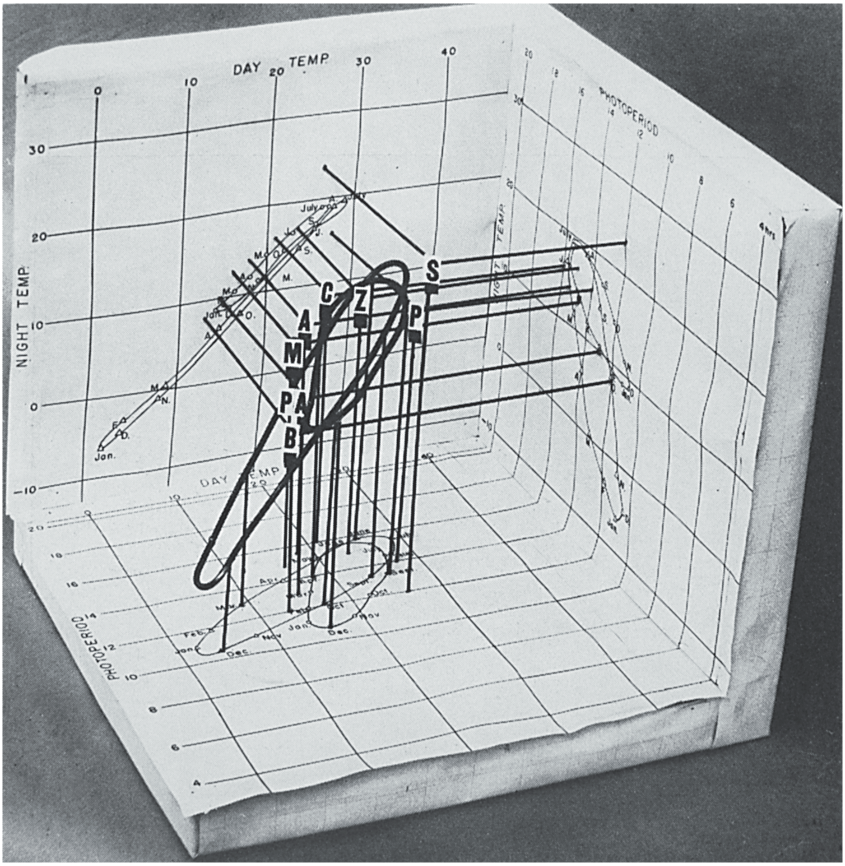

Figure I.4. Three-dimensional axis graph showing the relationship between phototemperature, nyctotemperature, and photoperiod for two locations, Pasadena, California, and Denver, Colorado for a number of garden flowers over an approximate 12 month period. The optimal growing conditions for various plants are indicated by the letters: S=Saintpaulia; Z=Zinnia; B-Bellis perennis; M=Mattiola; PA=Papaver nudicaule; A=Ageratum; C=Callistephus. From Went, *The Experimental Control of Plant Growth*, plate XXII. Reproduced with permission from John Wiley & Sons, Ltd.

were treated to color images of the newest facilities such as the Missouri Botanical Garden's Climatron and France's phytotron at Gif-sur-Yvette. They read how a phytotron's "reproducible . . . experimental conditions" gave the "basic laws of the physiology of plants." Readers noted how scientific methods of control were at work in agriculture and botany to render the world regular, stable, and wonderful. They were shown multidimensional graphs that displayed the point of maximum growth and photographs showing development across a range of environmental variables. They were offered startling facts of nature, for example, that "cold conditions are necessary to break the dormancy of seeds" in peaches and apples, and they saw photographs showing that apple seeds exposed to cold germinated while ones kept at constant temperature did not.[37] As Went said just after his phytotron opened, "modern research cannot do without such laboratories any more."[38]

THE PHYTOTRONIC ERA

The pursuit of technological control over organisms and experiments has been and remains a fundamental agent of change for biology in the twentieth century. To explain how scientists think about the world and how they create knowledge, historians have long followed and observed what technologies they have built and used, notably those famed biological technologies like electron microscopes, ultracentrifuges, electrophoresis apparatus, and radioisotopes that have shaped biologists' ability to see and trace molecular processes.[39] Running parallel to the technologies that have helped reveal genes, technologies that have revealed the biological environment have been equally important. Moreover, just like the instruments of the physicists "fix what it is to *be* an experimenter," so too have the use and embrace of molecular or environmental technologies defined what it meant to be a geneticist or molecular biologist as much as what it meant to be a botanist, plant physiologist, or ecologist.[40]

This book argues that the construction of technologies to control the biological environment had three immense consequences. First, control enabled the "environment" to be defined as a part of an experimental science of life. Second, phytotrons saw some biologists become technologists in their pursuit of biological knowledge. Third, the construction of new laboratories with elaborate technological systems to control and regulate elements of any climate saw feedback emerge as a powerful challenge to reductionism, not only because the technological control of one climatic variable destabilized another but also because it revealed organisms as complex products of genes and environments. In sum, the study of life became an exercise in technological control over both genes and environments and so the knowledge of the machine equaled knowledge of the plant.

Like so much in the early Cold War, phytotrons were built with fresh memories of depression, global war, and then widespread Malthusian predictions of population explosions, with "algae burgers" proposed to head off the world's "greatest single cause of unrest," namely, hunger.[41] Believing that a revolution in the scientific attack on the global issue of food was necessary, governments as well as the sugar, tobacco, forest, rice, and tomato industries all supported new phytotrons. Went's "great discovery," for example, underpinned the Campbell Soup Company's large research project in the late 1950s, including the building of new rooms in the Caltech phytotron to develop and test varieties of tomato to find those that would set fruit in the hot conditions of the southwest United States.

Phytotrons were the practical application of science to increase productivity. Testing progenies for potentially successful adaptations to particular climates, often far removed from their local climate, occupied much of the ordinary work in phytotrons after 1949. Caltech's physiologists lauded their facility as saving valuable time and money for breeders because far fewer plants up to the F_4 generation would need to be tested for far less time in the controlled conditions of a phytotron. Even better, breeders need no longer take the risk, Caltech biology division chairman James Bonner quipped, of not the right "kind of summers" ruining everything.[42] Likewise, several Australian plant physiologists maintained years afterward that phytotrons had made it possible "to accelerate and make more reproducible many kinds of research on plants at all levels of organization from the sub-cellular to the community."[43] Similarly, the Swedish Royal College of Forestry declared their phytotron to be a boon to the Nordic forest industry barely a year after the facility opened because it "made it possible to determine the various photo- and thermoperiodic systems controlling the growth of different provenances of European conifers."[44] Finally, by rationalizing the identification of new useful plants for particular environments, phytotrons played a small role in the now famous Green Revolution. The identification of best-correlated varieties and environments was considered so important that the Australian government donated a phytotron to the International Rice Research Institute in 1974 to study the most significant staple crop grown under the most diverse climatic conditions, namely, rice.[45] Whether for the forests of Sweden or for the agriculture of Australia, California, or France, something like an "engineering science" style of biology established control over genes and environments and promised a new biological world of economic and social benefits.[46]

At the same time, those scientists who built phytotrons believed that biological science ought to be ultimately directed toward gaining basic knowledge, not just increasing portion size. For many plant scientists the real revolution ignited by phytotrons was that the basic science study of living organisms under controlled environments might reveal biological laws. Historians of science have long noted the commonplace cultivation of an image as a basic science in many biological and physical sciences in the Cold War era, in part, because through the pursuit of "basic science" one might achieve an elevated status within the scientific community.[47] In the moral economy of most sciences, the pursuit of mere applications remains distinctly second-class, no matter how useful they might be, unless they are directed toward basic knowledge. For the plant physiologist Lloyd Evans, once a postdoctoral student of Went, and later the designer and director of the Australian phytotron, and later still the president of the Australian Academy of Science, the choice for a young scientist between "pure or applied" always remained "that old intellectual class distinction."[48]

The distinction sat at the heart of the major changes sweeping over science during the Cold War. Something like half of the era's scientists and engineers worked secretively, albeit dutifully, in a variety of applied-science projects connected to the variegated goals of the military-industrial complex from building ICBMs (intercontinental ballistic missiles), to radar dishes to listen to Soviet radio signals bounced off the moon, to using atomic bombs to build harbors, or cloud-seeding experiments to create or guide tropical cyclones over Vietnam,[49] not least, said one, because such "research is the last and only defense against communism."[50] New technology both enmeshed scientists in much sought-after applications and permitted grander experiments.[51] Plenty of biologists worked with, and gained much from, the military-industrial complex, notably new technologies like the sudden and widespread availability of radioisotopes as trace elements as well as mutation agents.[52] To many, the expansion of medical and biological science was understood in no small part as a salve for American science over the wound of their development of atomic weapons.[53]

At the same time, the pursuit of idealized "pure science" (also termed basic or fundamental science) highlighted the gulf between scientists' own values concerning knowledge for its own sake and the demands of their patrons for useful science and applications in exchange for public support. Caltech's president Lee DuBridge succinctly grasped the paradox: "How 'pure' can the research program as a whole be and still command community and public support, or how 'practical' can it be allowed to become without losing the essential spirit of true scholarship—the search for new knowledge?"[54] Counterintuitively, in the early Cold War an apolitical stance often served an overt political purpose for science's patrons, and consequently, although the military-industrial complex garnered substantial and growing criticism in the 1970s stating that it denied openness, stifled cooperation, and hindered international and interdisciplinary exchange, it actually also broadly supported pure science for decades.[55] The reason, as the historian of science Nicolas Rasmussen argued, that molecular biology initially flourished was because it embraced "the mantle of the apolitical scientists' scientists" to ensure government support by explicitly rejecting calls to political action and engaging only in the search for "truth."[56] In other words, molecular biology first prospered in part because of its "political significance," Rasmussen said, as an "offshoot of genetics," the science "notoriously subject to suppression by Stalin," as well as its promise of wondrous medical cures.[57] Went perceptively, albeit privately, noted in his diary that government support for science in the Cold War world stemmed essentially from "the competition with Russia," a cause, he considered upon reflection, that was "hardly mentioned" at the major scientific symposium on the problem of basic research featuring Robert Oppenheimer and even President Eisenhower and at which DuBridge had spoken.[58] Consequently, for two decades after 1945, funding bodies such as the National Science Foundation (NSF) in the United States, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia, and the Centre national de la recherche scientifique (CNRS) in France possessed political support to fund basic science largely because a much-touted science independent of politics could be used as a cudgel against Soviet science and the "monster" of politicized science embodied by the Lysenko affair.[59]

For any postwar plant scientist, no charge was more damaging or inflammatory than that of being labeled a Lysenkoist, a follower of the Soviet agronomist Trofim Lysenko, who ruined Soviet agricultural productivity and encouraged the purge of Russian geneticists in the late 1930s.[60] In effect, genetics became synonymous with anticommunism while plant physiology became suspicious in the McCarthy era, and rumors circulated darkly about plant physiologists and Lysenkoism. As writers, directors, and actors painfully experienced during the House Un-American Activities Committee (HUAC) hearings of the late 1940s, even a loose connection to communists ruined reputations and damned careers. Seeing Reds under every bed, any connection reinforced paranoid suspicions. It may well have been enough, for instance, that a 1948 symposium on vernalization and photoperiodism that contained a frontispiece of a woodcut of Lysenko and a brief description of that "excellent prophet's" prewar work by Eric Ashby, starred many future users of phytotrons including Went, Sterling Hendricks, and Anton Lang, and a foreword by Kenneth Thimann. While neither Went, Hendricks, Lang, nor Thimann went beyond merely mentioning Lysenko's "controversial hypotheses," it seems likely that even such an innocent association cast a long shadow over the reputation of the entire subject of plant physiology.[61] There were whispers, even years later, that some people believed Went to be a Lysenkoist, as the biographers of George Beadle suggest without attribution.[62] Suspicions lingered for decades, and contributed to the lack of recognition for the achievements of plant physiologists.[63]

Was it any wonder then that Went went to such extremes to divorce his controlled-environment laboratories from industrial or political applications? The epitome of effort to label research in phytotrons "basic science" came in 1957 when Went prophesied that the facilities gave no less than a "Theoretical Botany" comparable to a generally accepted "Theoretical Physics."[64] Went advocated that phytotrons aimed to reveal the "universal" factors of growth and flowering and argued that the "general understanding" of the development of a plant had been hindered simply by "inadequate experimental techniques."[65] The message that flowed out to plant scientists the world over was that the experimental control available in phytotrons at last permitted botany and plant physiology to become a basic science akin to physics and free of any association with Lysenko. John Holloway, a forest ecologist in New Zealand, for example, spurred his country's investment in a phytotron because scientists possessed "no real knowledge of the physiology of any New Zealand forest species. All we have are a few deductions based on primitive autecological observations."[66] Only with a phytotron, as Holloway succeeded in arguing to his fellow scientists and his national Department of Scientific and Industrial Research in New Zealand, could biological science claim to know the causes of phenomena. From his ever-expanding phytotron outside Paris, Chouard said, "Phytotronics is the methodological key in plant research, to which phytotrons . . . are the necessary logistics."[67]

This mantle lasted into the 1970s. After that, plant physiologists saw interest in basic science wane, along with their fortunes. By the 1980s, as the president and later historian of the American Society for Plant Physiologists J. B. Hanson noted, support for "fundamental biology [was] a poorer third" behind "medicine, which received the bulk of the funding" and "agriculture a poor second."[68] Eschewing practical applications for dreams of large theoretical breakthroughs, the plant physiologists in their increasingly costly phytotrons struggled, as their best patrons, the NSF and the National Institutes of Health (NIH), shifted from idealistic supporters of basic science to be compelled politically to stipulate practical goals in the 1970s.[69] In just the past two decades, however, support for phytotrons has modestly increased once more because of the urgent commercial and governmental need to understand the biological effects of climate change. At the same time, thanks to scholars like Kärin Nickelsen it is also only now becoming apparent that the history of science in the twentieth century is woefully incomplete without the story of the plant physiologists.[70] Though plants underpin life on this planet my hope is that this book might offer some insight into the continued lowly status of the study of plants among scientists, their historians, and the wider public.

AN IMPORTANT DEVICE NO ONE HAS HEARD OF

The story of phytotrons is little told, and the word itself exotic and unfamiliar.[71] Yet, across at least two dozen institutions in the middle of the twentieth century, a new community of scientists built and used phytotrons. As we shall see, the history of phytotrons replicates many features of the early story of computers, notably about creating "agents of control" as much as couriers of information, as the historian of computing Paul Ceruzzi has argued.[72] Readers will particularly note just how far removed our present conception of computing and biology is from the past: to look at modern computing in the present is to see an information age of personal computing as much as to look at modern biology is to see a genomic age of personal health and wonder how it could ever have been otherwise. These views are now so persuasive that they, in fact, quite readily hide their own early histories, both of biology and computing, and contribute to the general marginalization of plants for historians of science and the public.[73] In other words, the story of phytotrons is little known because the dominant narratives about the discovery of genes are so inescapable they in effect erase the fact that the study of life was also the discovery of controlled environments.

Now forgotten, a scientific community took shape united by a desire to experiment on organisms' environments. The community drew people from a huge range of fields including botany, forestry, horticulture, plant pathology, agronomy, genetics, entomology, and agriculture, but especially plant physiology, brought together often for single research projects though occasionally for whole careers. They sometimes called themselves phytotronists.[74] A comparative history is necessary to tell the story of phytotrons and the phytotronists because science after 1945 was built between disciplines, by multiple instruments, and above all internationally. Globally, a host of phytotrons occupied large portions of research budgets variously in Sweden, New Zealand, Canada, Hungary, Germany, the Netherlands, India, and Japan, while smaller units appeared in Austria, Israel, China, South Africa, Great Britain, and Taiwan.[75] Across all were continual efforts to create a biological science of the whole plant via the construction of increasingly elaborate and expensive technological systems. Many countries agreed with Went in California, Mitchell in New Zealand, and Chouard in Paris, who said "one *big phytotron* at least is necessary for a large country with welcome facilities for those who need such sophisticated equipment."[76] I devote a chapter to one of the largest phytotrons in Australia (chapter 4), but the great phytotron of the Soviet Union and the later Biotron Institute in Japan are the two most significant institutions not addressed in this book. Constrained by language and other barriers, I am in great sympathy with Paul Edwards in dreaming of fully international histories of sciences that work on the planetary scale—I look forward to studies on each of these in the near future.[77] In the meantime, this book dwells primarily on the American experience, not least because Americans built the first and the greatest number of phytotrons, nearly a dozen, variously at Caltech, Duke, Yale, North Carolina State, and Michigan State Universities, along with the related Climatron in Saint Louis and finally the Biotron at the University of Wisconsin-Madison.

The larger arc of the book argues that the story of phytotrons is the complementary half of the story of genetics, namely, the discovery of the biological environment alongside genes. Within that larger narrative are two story arcs. The first, broadly the story of the creation and work of the first phytotron and then the Climatron unites chapters 1 to 3 and ends with a Coda that wraps up the life and career of Frits Went. The second arc describes the creation and work of two, second-generation phytotrons, first in Australia (chapter 4) and then in North Carolina (chapter 5) as comparative examples, and then crescendos with the case of what was supposed to be the apex of phytotronics, the American national Biotron (chapter 6). A second coda briefly discusses the decline of phytotrons in the 1970s and 1980s. My Conclusion offers some thoughts about how the history of phytotrons might aid recent efforts to determine the biological effects of climate change. It highlights that in the Ecotron (1989–2010), a few biologists have constructed whole controlled environments and ecosystems, while even more recent incarnations have been equipped for carbon dioxide (CO_2) measurement, such as those at Michigan State University's Plant Research Laboratory, the Biotron Institute at Kyushu University in Japan, and at the world's newest phytotron at the University of Saskatchewan since 2011.

Throughout, one clue helps reveal the story of phytotrons and phytotronists, namely, the suffix *-tron* itself. Coming after the "physicists' war," plant scientists explicitly appropriated the embodied symbol of the tron from the famous devices of modern physics like cyclotrons and synchrotrons.[78] Of course, many life sciences appropriated metaphors and practices of the physical sciences in the twentieth century.[79] Even so, the phytotronists' usage seems extreme; both Went and the director of *le grand phytotron* outside Paris, Pierre Chouard, swore that "the cyclotron . . . fulfills about the same function in physics as the phytotron does in plant science."[80]

To explain what it meant for a scientist to liken a phytotron to a cyclotron, I follow above all the lead of the historian of science Evelyn Fox Keller, who powerfully noted how "the ways in which [scientists] talk about scientific objects . . . actively influence the kind of evidence [they] seek."[81] The explanation is that in their facilities of environmental control, those biologists became technologists. Moreover, by equating knowledge of the machine with knowledge of the plant, the study of life became an exercise in the technological control over both genes and environments. Phytotrons, then, sit at the intersection of biology and technology, as do many parts of modern life science.[82] Critically, an extensive literature in the history of technology has demonstrated that social processes shape the adoption, understanding, and use of technological systems as much as scientific ideas.[83] Phytotrons, like the computers that regulated them, embodied scientists' and governments' modernist convictions that even the largest social problems could and would be solved by new sciences, new technologies, and new technoscientific infrastructures.[84] In perhaps the most dramatic example, modernism came to Missouri, when the Missouri Botanical Garden not only had the garden's old Palm House demolished but also had the palms themselves left out to die in order to build the Climatron: "The immediate present—and the palms—were sacrificed to the future," declared the garden's *Bulletin*. Trons reflected the optimistic future of modernism where the past needed to be swept aside, echoing the famed exhortation of Ezra Pound—"Make it New!"[85]

PHENOTYPE = GENOTYPE + ENVIRONMENT

The history of biology has been broadly focused on biologists' struggles to specify and then measure the phenomenon in question. Across many approaches to the life sciences, in the twentieth century alone, Linus Pauling notably pursued chemical molecules, others viruses, some cells, still others various animals, and a few ponds.[86] For the plant scientists in phytotrons (among many others), the axiom "GENOTYPE + ENVIRONMENT = PHENOTYPE" spoke to what an organism was.[87] Everyone agreed: from professional ecologists—"an organism without environment is inconceivable"[88]—to gardeners—"plants are the result of their environment," as one indoor gardening book stated, referring its readers back to "the principles of botany."[89] The director of the Duke University phytotron, Paul Kramer, traced this concept back to the German physiologist Georg Klebs who suggested just before the First World War that "hereditary potentials" and "environmental factors" combined to produce a plant's "processes and conditions" that dictated the "quality and quantity of growth."[90] Went championed time and time again that "the ultimate shape and size of a plant depends both on its genetic constitution and on the environmental conditions under which it grew up."[91] Established by the doyens of plant science, the principle flowed down to undergraduates. In one textbook on plants by Went's Caltech colleague Arthur Galston, for instance, students read that "with any given genotype, tremendous control over growth may be exerted by obvious influences in the environment" such as light and temperature.[92] Students read in another undergraduate textbook from 1964 titled *Physics in Botany* that "it is now known that genetical factors are responsible for the time of appearance of flowers, but also, if the environmental conditions are unfavourable, the passage from vegetative to reproductive growth may be retarded or even stopped altogether."[93]

Moreover, the equation suggested a path of research, namely, that the process of measuring the actual characteristics of any whole organism, or "phenotype," required the genotype as well as the environment to be made experimental. Consequently, in the same era that many worked to specify and measure genes, in phytotrons botanists and plant physiologists worked simultaneously to specify and measure environments. Thus to their builders, the phytotron's creation was really the endpoint of a long struggle to control the environment, at least since the famed nineteenth-century physiologist Jacques Loeb, who saw, as the historian of science Philip Pauly noted, "the main prerequisite for success in biological manipulation was command of a wide range of forces active in the organism's environment."[94] Even as innovative breeding techniques for plants and animals had generated a great variety of new crosses and hybrids, early twentieth-century work with early controlled environmental experimentation struggled with and finally conceded that wide deviations in environmental conditions like temperature undermined any conclusions about even basic relationships such as how the length of day affects flowering.[95] Common solutions included agricultural sciences' crop testing which employed active strategies to minimize the variation around the mean yield such as planting trials in several locations across several years, while ecological studies generated intense inquiries into the nature, methods, and successes of statistical sampling of areas and species.[96]

The plant physiologists scoffed at such rustic and inexact measures: as late as 1969, one French plant physiologist noted during a conference of the International Biological Program how "plant physiologists have always had a justified skepticism about field research, particularly on natural ecosystems. Experimental difficulties are severe."[97] Such attitudes underpinned the technological drive to fully replicate and control the environment. Quite simply, the phytotron technologically solved the scientific dilemma presented by the field, namely, being able to exactly repeat climatic conditions, and consequently, when both halves of the

Figure I.5. Twenty-seven-month-old Bourbon trees grown in constant day/night temperatures of, from left to right, 17/12°C, 20/14°C, 30/23°C, 26/20°C, and 23/17°C. From Went, *The Experimental Control of Plant Growth*, plate XIX. Reproduced with permission from John Wiley & Sons, Ltd.

equation were fully reproducible biology would be reproducible. As Went preached in his magnum opus, once biologists accepted that "an organism is the product of its genetic constitution and its environment" it necessarily followed that "no matter how uniform plants are genotypically, they cannot be phenotypically uniform or reproducible, unless they have developed under strictly uniform conditions."[98] Went offered visual evidence that genetically identical trees grown at different temperatures appeared radically different (fig. I.5). For nearly three decades, with the combination of simultaneous advances in both genetics and environments, plant scientists savored their ability to generate reproducible experimental objects for biological study. They called it the Age of Biology.

THE AGE OF BIOLOGY

In 1966 the American National Academy of Sciences (NAS) received a comprehensive report compiled from over a thousand questionnaires sent to a representative third of the estimated number of plant scientists active in teaching and research in the United States. The report, *The Plant Sciences Now and in the Coming Decade,* was a wide-angle snapshot of the biological community concerned with plants. Chaired by Kenneth Thimann who was then at Harvard but had stood by Went's side as the first phytotron opened at Caltech, the panel declared recent discoveries so revolutionary that "the second half of our century" might be called "the beginning of the 'Age of Biology.'"[99] As the panel tellingly concluded, the reality of most plant scientists' working lives was that the advent of "new concepts in biochemistry and genetics" was as important as "the availability of new technological tools such as computers [and] controlled environments."[100] Of course, plant biology was a science of genes and environments, of new concepts and new tools, but the leading figures of American biology saw a far grander vision of their science. By adding a technological mastery of controlled environments to breakthroughs in genetics, they lived and worked at a time when DNA + phytotrons = Age of Biology.

Importantly, the NAS panel's conclusion challenges historians of science to appreciate how the new concepts and the new tools appeared equally significant to, and seemed equally necessary to, the future of the plant sciences. Geneticists, of course, had made great strides in understanding the genotype, including finding new ways to create huge new numbers of crosses, hybrids, and mutants, while plant geneticists soon turned toward evolutionary biology via work on the phenomena of polyploidy, hybridization, and apomixes.[101] Before the Second World War, there was Thomas Hunt Morgan's sweeping genetics work on the fruit fly, and the discovery of molecules that promised to be "magic bullets" such as plant hormones for agriculture, chemicals like DDT, and above all medical cures for the pharmaceutical industry.[102] Postwar, the pursuit of the gene drove the molecularization of the study of heredity, ultimately spurred gene technology and genomics by century's end, and created a culture of heredity. The celebrated moments for the culture of heredity remain the discovery of the structure of DNA in 1953, followed by the technique of recombinant DNA (1972), which permitted manipulation and thus the construction of the Human Genome Project (1991). By being variously informational, traceable, and reductionist, the historian of science Hans-Jörg Rheinberger argued, "the gene" came to be considered "the representative unit of the genotype and the ultimate determiner of the phenotype and, with that, executor of life" over the course of the twentieth century.[103] Indeed, the historian of science Angela Creager described how the conceptualization and manipulation of genes via new techniques, notably radioisotopes, served as "key ingredients of a postwar episteme of understanding life in molecular terms."[104]

The gene's once fellow traveler, however, has been erased in historical memory. Historians of science have noted that it remains one of the great unspoken assumptions of modern biology that many biologists of all stripes considered experimental organisms *identical enough*—not actually identical just sufficiently similar, regardless of the environmental conditions of their development.[105] In addition, it has long been a comfortable and convenient way to simplify the analyses of environment historians, scientists, policymakers, and even social and political theorists. One of the earliest environmental historians, H. H. Lamb, for example, stipulated his "assumption that the climate, the opportunities which it offers and the constraints it places upon man and the environment are effectively constant" for the nineteenth and twentieth centuries.[106] There were also immediately practical reasons for the erasure: in the genetics research program, mutations were the objects sought after by Mendelian genetics, not adaptive changes from environmental conditions,[107] while early molecular biology was undemanding of variable environmental conditions: William Laing from New Zealand's Climate Laboratory remembered that "growth conditions were simple (37°C with shaking)."[108] *E. coli* featured as an ideal reductionist model organism for early molecular biology because, as Evelyn Fox Keller explained, the environment plays no role in the development of the bacterium.[109] In contrast, plant physiologists railed against the "view of an organism as solely active and the environment as solely passive" as "a one-sided picture" as early as the 1920s.[110] All scientists exercised a choice, as the future directors of the Duke phytotron and the Wisconsin Biotron, Paul Kramer and Theodore Kozlowski, respectively, noted in the introduction to their textbook on the physiology of trees in 1960, stressing how "emphasis is placed on the effects of environmental conditions on physiological processes of the organism as a whole, rather than a wholly biochemical one in which emphasis is placed on the details of the processes themselves."[111]

The larger issue is that the erasure of a biological science of the experimental environment has appeared, falsely, as a natural consequence of the triumphant molecular view of life. As the biologist Richard Lewontin and Richard Levins explained, as DNA became a fetish, organisms in modern biology were active and richly described, but the environments in which they grew and developed were considered passive agents, minimally understood, and in any event largely outside biological disciplines.[112] But historians have also helped erase the study of the biological environment: when the historian of science Lily Kay concluded that the discovery of the structure of DNA resolved "what had been defined for decades as the central problem in the life sciences,"[113] she reinforced the erasure of the environment at no less than the very institute (Caltech) and over the same period when the plant physiologists sought to make a biological science of the "environment" alongside the science of the gene in the first phytotron.

Thankfully, Evelyn Fox Keller first stressed the now common view that the history of genetics has overshadowed a larger history of experimental life science.[114] *Engineering the Environment* offers part of what has been overshadowed, namely, the story of a global science of the biological environment at work alongside the science of the biological gene. As every chapter in this book illustrates, the act of both specifying the components of the "environment" and defining the proper measurement of each component preoccupied the plant scientists in phytotrons. Those chapters will serve, as the historian of science Peter Bowler once cautioned, to "try to demythologize the past"[115] by recovering the exotic world of phytotrons. Moreover, they collectively offer some reflection on the topics of what history remembers, what parts of lives and works get retold, what become the famed experiments, and what gets cast into the dustbin of history.[116]

"PAUSE TO THINK WHAT WE ACTUALLY MEAN BY CLIMATE"

Frits Went asked scientists to "pause for a moment to think what we actually mean by climate."[117] Plant physiologists knew that plants grew and developed in complex whole environments from the late nineteenth century onward, and had demanded the ability to claim "with confidence

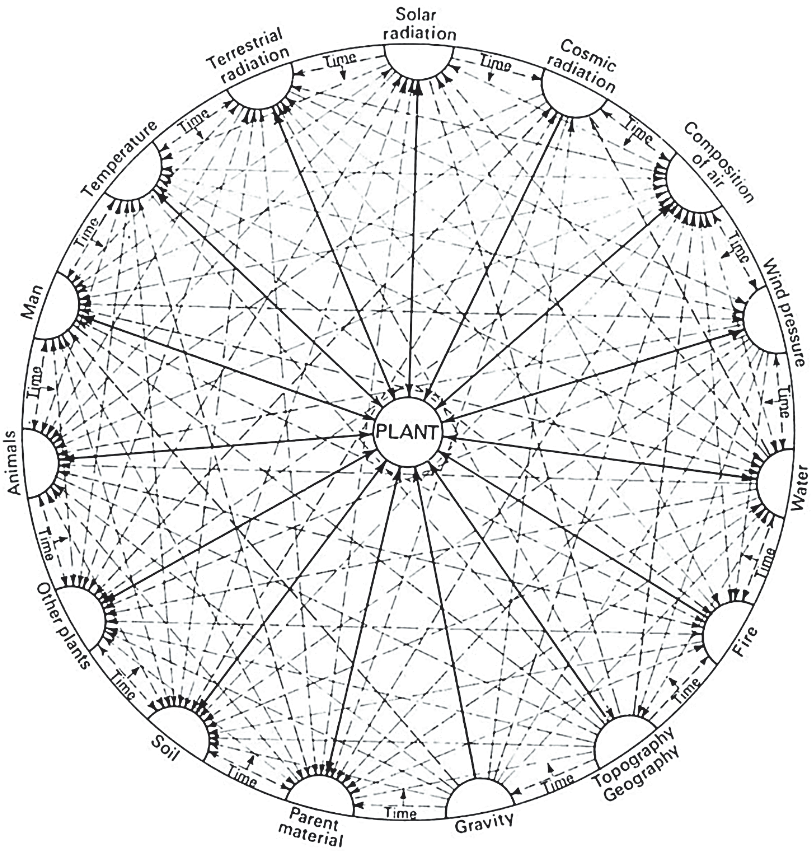

Figure I.6. Dwight Billings's "Holocoenotic" diagram. From Billings, "The Environmental Complex," 256.

that a certain change takes place in the plant when, and only when, accompanied by a *single* change in the environment." Lacking any mechanism for control, Ludwig Jost's 1903 *Lectures on Plant Physiology* resigned plant physiologists to accept the rarity of any "physiological observation" under nature's complex conditions that might confirm "that the special alteration in the surroundings is the cause of the special phenomenon in the plant."[118] But what did they mean by a plant's "environment?" Some plant physiology texts were incredibly broad: one pointed out how, "in the small zone inhabited by living creatures, there is an infinite variety of different types of environment." "The land" possesses soil, which in turn possesses minerals and other organisms, moisture, and atmosphere, a pH, and a temperature; the "atmosphere" possesses the characteristics of humidity, nutrients (like carbon dioxide), respiration, temperature, pressure, wind, and the atmosphere's "optical properties."[119] The text told students that in order to grasp an understanding of the processes governing growth and development required appreciating how all those characteristics exerted feedback effects on "all activities of living things [which] are the expressions of literally thousands of processes being carried out at the same time within the cells."[120]

Others stressed interrelated and interlocking complexity: notably, the ecologist and plant physiologist Dwight Billings at Duke University (later a cosponsor of the Duke phytotron) defined "the environment of a plant as sum of all external forces and substances affecting the growth, structure, and reproduction of that plant," including "heat, light, water, [and] elements." He displayed this complex array of interacting variables in his "holocoenotic environmental complex" diagram (fig. I.6). Importantly, even for Billings as an ecologist, "other plants" were one of only fifteen distinguishable factors defining the environment of a "plant."[121] Phytotronists made each variable into a discrete technology to study the equation of the environment. Their conception of the study of life saw the climate broken into discrete variables, each encased in technological innovations, especially air-conditioning, new forms of lighting, cheap electricity, herbicides, and pesticides. In the creation of both systems of control and controlling systems, plant scientists in phytotrons established a biological measure and meaning for the "environment" that centered on mutually dependent variables. The evocative climax came in the early 1970s from a French phytotronist, who gave the "environment"—*climat*—a mathematical expression:

> Even the notion of climate encompasses a complex of many variables: temperature, light, rain, humidity, winds; which vary according to intensity, length, periodicity, quality, and orientation. If it were possible to write them as an equation, one obtains: Climate = (T + E + P + H + V) × (i + d + p + q + o) or 25 principle components but with a lot of secondary variations. For example, [the product] Eq represents the diverse radiation of the solar spectrum, or of a multiplication of factors: Eq_1 = red, Eq_2 = orange, Eq_3 = yellow, etc.[122]

Scientists' categories reveal much about their intellectual process. "Environment," read the epigraph to one of the last major summaries of phytotrons in 1980, “seems to be the key word in an amazing number of unsolved or partially solved problems in biology.” The summary’s author, Robert Downs, director of the North Carolina State University phytotron and one of the most significant phytotronists in the United States, spoke for many in the by-then declining community as he surveyed not only the international array of phytotrons but their ongoing scientific work. Phytotrons, Downs said, had worked to define what “scientists” considered the great unknown of the science of biology, namely, the proper “measurement of environmental parameters [which] has long been a problem in biology.”[123] In other words, Downs revealed that the biological environment was what some biologists had struggled to specify and then measure. To those ends, “phytotrons provide the means of dissecting the environment,” said Henry Hellmers at the Duke University phytotron, the twin of Downs’s North Carolina State facility.[124]

In contrast, other biologists have described quite different conceptions of what the biological environment is. Evolutionary biologist G. Ledyard Stebbins, for example, highlighted that for many biologists the “environment” was essentially a disciplinary problem. Stebbins rhetorically asked the meaning of the “concept of the environment” in his 1982 book, and he answered that different disciplines viewed the category differently: “naturalists and ecologists” regard the “other organisms” in an ecosystem as the “most significant factors in their environment,” whereas “physicists, chemists, geologists and biologists . . . think of the environment chiefly in terms of its physical features—climate, temperature, moisture, soil, and atmosphere.”[125] In contrast, thirty years earlier Billings’s diagram defined “other organisms” as an equivalent component to any particular climatic feature.

To understand those divergent views, I build on the historian of biology Garland Allen’s classic narrative of twentieth-century biology that saw “naturalist” biologists emphasize the phenotype while “experimentalist” biologists focused on the genotype.[126] The emergence of an experimental science of the environment suggests that there was a third group, the “technologist” biologists who emphasized control over the environment. This third way reshaped the meanings of those core concepts of biology, namely, “phenotype,” “genotype,” and “environment,” because whereas botanists of earlier generations had concluded that a plant existed as only an individual expression of a range of possible expressions for their type, the phytotronists regarded an environment as integral to the plant itself, not just noise in the phenotype.[127]

Not coincidentally, the founder of the first phytotron highlighted these issues. All biologists accepted "phenotypic variability . . . as a basic property of living matter," Went said, in that any single set of genes presented a range of expressions in nature. Plant breeders and horticulturalists had worked to reduce variability, but the assumption that "atomistic reactions" controlled variability had driven them, Went claimed, toward "statistical analysis." To Went, this had been a distraction: instead, "if phenotypic variability had been considered as being largely due to environment, more serious efforts would have been made to control the external environment of growing plants." Writing in no less than the American *Proceedings of the National Academy of Sciences,* Went announced in 1953 that his experience "show[ed] that environment rather than the atomistic nature of biological reactions is responsible for phenotypic variability."[128] Went remained convinced until his death that the underlying problem with the creation of biological knowledge was the absence of controlled environments, and that only through such environments could science study variability and ascertain actual causes. In short, embracing technology and reductionism, as much at the genetic scale as at the environmental, technologist biologists sought the laws of growth via their ability to control the environment added to the geneticists' established control over the genotype. Control over environmental variability offered control over organism variability and thus gave experimental certainty.

Consequently, the story of the creation of phytotrons was at its heart a modernist project in the Age of Biology. The phytotronists built their facilities and began their research convinced that knowledge of the technological systems would bring knowledge of living systems. The first phytotron certainly began as a reductionist, imperial project to establish which climatic condition governed growth, or flowering, or fruit set; at the same moment the geneticists saw great success via reductionism. And like the geneticists, plant scientists had also been trained to consider genes and environments separately: Otto Frankel's concluding remarks at the opening of the Australian phytotron mentioned how "our minds are conditioned to regard 'genetic' and 'environmental' pathways as distinct and, in a mechanistic sense, unrelated."[129] In one's new phytotron, of course, a scientist could keep a set of genes or series of environments constant so that the other could be the subject of experiment. Yet it is also clear from Frankel's remarks that a leader in plant science was already dissatisfied with this simple reductionism. The experimental production of environments was unexpectedly complex.

In fact, this book concludes that what the technologist biologists learned was that their conception of the environment demanded interlocking assemblages of feedback-laden technological systems to replicate and control interrelated variables. Struggling with their array of devices to maintain conditions at preset levels, they came to appreciate how feedback was constitutive of the environment, the plant, and life itself. Environments and organisms, and even nature itself, were differential equations not linear functions. Consequently, toward the end of the century, conceptions of the "environment" became more explicitly cybernetic, notably as ecology and climatology developed an array of computer models.[130] In plant physiology, however, the cybernetic meaning of the "environment" always remained tied to the physiologist's pursuit of experiment control over climates. As recently as 2007, Henry Hellmers explained how the "effects of environmental factors are more often synergistic or antithetic than additive because plant growth is capable of adapting, within limits, to environmental changes."[131] At the same time, the conception of the plant itself became more cybernetic: Chouard's colleague in France, N. de Bilderling, noted, "as a matter of fact, certain environmental factors provoke reactions from the plant which, by interacting with others, can conceal direct actions and thereby complicate our understanding of phenomena and our explanation of the way factors act."[132]

Alongside new cybernetic conceptions of nature and organisms, came a new cybernetic understanding of plant science itself. By the late 1960s, it appeared that disciplinary and epistemological systems of biology were predicated on feedback, in a situation similar to the historian Paul Edwards's analysis of the vast infrastructure machine at work to collect, process, and evaluate climate data.[133] In the most overt exemplar, a trio from the botanical institute of the University of Würzburg at a meeting of physiologists during the International Biological Program (unfortunately timed to take place only a year after the Soviet suppression of Czechoslovakia in 1968) diagrammed the evolving place of phytotrons within experimental biology for their audience (fig. I.7). For O. L. Lange, E. D. Schulze, and W. Koch, experiments in phytotrons

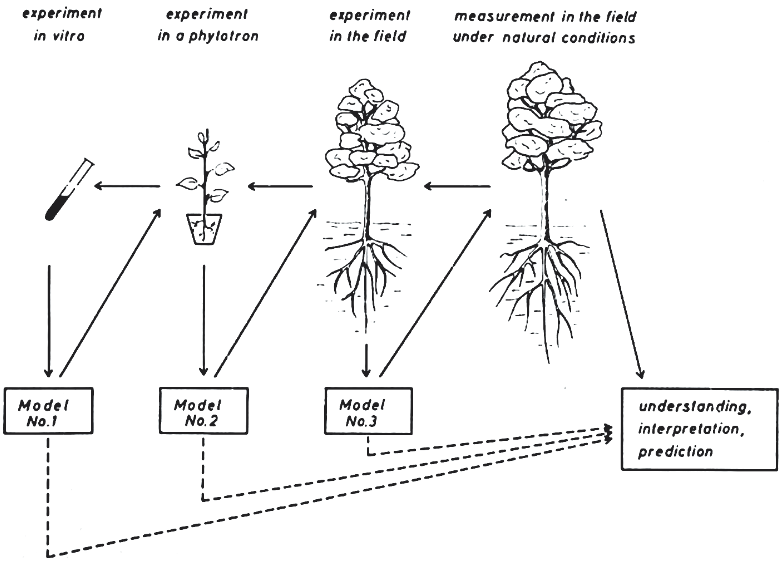

Fig. 1. Diagram for the necessary investigations to explain photosynthetic productivity of plants in the field.

Figure I.7. Diagram for the necessary investigations to explain photosynthetic productivity of plants in the field. From O.L. Lange, E.D. Schulze, and W. Koch, "Evaluation of Photosynthesis Measurements Taken in the Field," in *Prediction and Measurement of Photosynthetic Productivity: Proceedings of the IBP/PP Technical Meeting*, Trebon, 14–21 September 1969 (Wageningen: Centre for Agricultural Publishing and Documentation, 1970), 339–352, 340. Reproduced courtesy of Wageningen UR.

occurred in between in vitro or test-tube experiments and isolated fields trials. Moreover, they specified the relationship between in vitro experimentation, experiments in phytotrons, experiments in the field, and finally measurements under natural conditions as a network of feedback arrows. It was via integrating several levels of control, linked via feedback loops, that "understanding, interpretation, and prediction" would emerge in biological science. Those loops involved experiments in vitro, in phytotron, and in field.[134] Twenty years later, Thomas Yuill offered the University of Wisconsin-Madison Biotron to his "colleagues" in exactly the same way, highlighting that the Biotron provided "facilities that will fit between the laboratory and the field."[135]

The director of the Hungarian phytotron at Martonvásár Sándor Rajki called phytotrons "the grand experiment" of modern biology.[136] In short, plant scientists saw that no one discipline held a monopoly

Figure I.8. "What can a Phytotron do for Australia?" From "What Is Needed for an Australian Phytotron?" March 28, 1958. NAA, Series A4940, file C2060. Reproduced courtesy of the National Archives of Australia.

on life science because the way to grasp an understanding of life's processes was as a series of cybernetic feedback loops between test tubes, phytotrons, and field experiments. Although the first phytotrons were built as universal facilities, what they demonstrated to their creators in practice over the Age of Biology was that no one style of experimentation was independently sufficient, the science of the plant required them all.

AN AIR-CONDITIONED EDEN

In the sunshine of the 1950s, the hand of man finally took hold of capricious nature through controlled environments—at least that was the provocative image in the booklet promoting an Australian phytotron (fig. I.8). The computer-like square product symbolized a conviction that through modernist technological science, nature would be made regular, controlled, and predictable. "What can a Phytotron do for Australia?" the text accompanying the image asked. Building on Steven Shapin and Simon Schaffer's fundamental observation that solutions to problems of knowledge are embedded in practical solution of the problem of social order, the icon conveys that the technological control over the environment assured the social goal of control in the Cold War era.[137] In the case of phytotrons, control meant to grip the randomness of the prescientific glasshouse or field and forge a future through human hands where regular, consistent heads of wheat would stabilize humanity. And that, Andy Weir's astronaut might conclude, makes the story of the experimental control of the biological environment one of truly "extreme botany."