Setting innovation free in agriculture

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1.1 Introduction

Since the late 19th century, the earth has been transformed by the applications of science through technology and modern medicine. There have also been great increases in food production through intensive agriculture and factory farming. Over the same period, capitalism has created international systems of trade, investment, and global corporations, whose job is to increase profits. Everyone is affected. Almost all agricultural systems now operate within this scientific, technological, and capitalist environment. In most parts of the world traditional agricultural methods have been replaced by modern “scientific” practices, including mechanization and the use of factory-made fertilizers, herbicides, fungicides, and pesticides. Irrigation has been extended widely, often at the expense of nonrenewable aquifers, and in some areas irrigation has degraded the soil through salinization. Large-scale deforestation to create more agricultural land has contributed to a startling loss of biodiversity. The increase in population from 1 billion in 1800 to 2 billion in 1927 to 7.7 billion in 2019 has created a much greater demand for food, as has the increase in meat consumption, which creates the need to feed billions of animals in factory farms on cereals, soya beans, and other crops.

Science and economics are not theory-neutral. They are expressions of worldviews, and we need to be aware of the prevailing worldview, or else we will follow it through blind faith.

In his influential book The Structure of Scientific Revolutions (1962), the historian of science Thomas Kuhn argued that, at any given time, the sciences are shaped by a particular model of reality that he called a paradigm. The paradigm defines valid ways of doing research. Most of the time, “normal science” goes on within the prevailing orthodoxy, but from time to time there is a shift in the fundamental model of reality through a scientific revolution, when a new, more inclusive paradigm supersedes the old one. Factors that help precipitate paradigm changes include anomalies, which are awkward phenomena that do not fit into the prevailing paradigm. They are usually dismissed, denied, or explained away until there is a shift in paradigm, giving a broader view of reality that enables these anomalies to be included.

Contemporary science and economics are based on a materialist philosophy of nature, which asserts that all reality is material or physical. There is no reality but material reality. Matter is nonconscious. Human consciousness is a functionless by-product
of the physical activity of the brain. God exists only as an idea in human minds, and hence in human heads. There are no purposes in nature, and evolution is purposeless.

One major anomaly for this materialist paradigm is consciousness itself, the very existence of which is called “the hard problem” in the philosophy of mind. Another is purpose. Obviously, humans have purposes, and so do nonhuman animals. So, where do consciousness and purposes come from if nature is fundamentally nonconscious and purposeless? Some philosophers wrestle with these questions, but most people simply ignore them.

These materialist beliefs are powerful not because most people think about them critically, but because they don’t. The facts of science are real enough, and so are the techniques that scientists use, and so are the technologies based on them. But the belief system that governs conventional scientific thinking is an act of faith, grounded in a 19th century ideology. The same materialist assumptions underlie our economic systems. And underlying these systems of thought is a vision of science as a world-transforming activity, led by a new priesthood, a vision dating from the 17th century, when mechanistic science was first established. The enormous successes of science and technology have indeed been world transforming and seem to have proved this vision true. But they have also led to an uncritical scientific dogmatism, which is now inhibiting free enquiry, threatening the survival of countless species, and endangering human survival.

1.2 The scientific priesthood

Francis Bacon (1561–1626), a politician and lawyer who became Lord Chancellor of England, foresaw the power of organized science more than anyone else. To clear the way, he needed to show that there was nothing sinister about acquiring power over nature. When he was writing, there was a widespread fear of witchcraft and black magic, which he tried to counteract by claiming that the knowledge of nature was God given, not inspired by the devil. Science was a return to the innocence of the first man, Adam, in the Garden of Eden before the Fall.

Bacon argued that the first book of the Bible, Genesis, justified scientific knowledge. He equated man’s knowledge of nature with Adam’s naming of the animals. God “brought them unto Adam to see what he would call them, and what Adam called every living creature, that was the name thereof” (Genesis 2: 19–20). This was literally man’s knowledge, because Eve was not created until two verses later. Bacon argued that man’s technological mastery of nature was the recovery of a God-given power, rather than something new. He confidently assumed that people would use their new knowledge wisely and well: “Only let the human race recover that right over nature which belongs to it by divine bequest; the exercise thereof will be governed by sound reason and true religion.”

The key to this new power over nature was organized, institutional research. In New Atlantis (1624), Bacon described a technocratic utopia in which a scientific priesthood

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*a* Bacon (1951), p. 50.
made decisions for the good of the state as a whole. The Fellows of this scientific “Order or Society” wore long robes and were treated with a respect that their power and dignity required. The head of the order traveled in a rich chariot, under a radiant golden image of the sun. As he rode in procession, “he held up his bare hand, as he went, as blessing the people.”

The general purpose of this foundation was “the knowledge of causes and secret motions of things; and the enlarging of human empire, to the effecting of all things possible.” The Society was equipped with machinery and facilities for testing out explosives and armaments, experimental furnaces, gardens for plant breeding, and dispensaries.

This visionary scientific institution foreshadowed many features of institutional research, and was a direct inspiration for the founding of the Royal Society in London in 1660, and for many other national academies of science and research institutes. But although the members of these academies were often held in high esteem, none achieved the grandeur and political power of Bacon’s imaginary prototypes.

In England in Bacon’s time (and still today) the Church of England was linked to the state as the established church. Bacon envisaged that the scientific priesthood would also be linked to the state through state patronage, forming a kind of established church of science. And here again he was prophetic. In nations both capitalist and communist, the official academies of science remain the centers of power of the scientific establishment. There is no separation of science and state. Scientists play the role of an established priesthood, influencing government policies on the arts of warfare, industry, agriculture, medicine, education, and research.

Bacon coined the ideal slogan for soliciting financial support from governments and investors: “knowledge is power.” But the success of scientists in eliciting funding from governments varied from country to country. The systematic state funding of science began much earlier in France and Germany than in Britain and the United States, where until the latter half of the 19th century most research was privately funded or carried out by wealthy amateurs like Charles Darwin (Kealey, 1996).

In France, Louis Pasteur (1822–95) was an influential proponent of science as a truth-finding religion, with laboratories like temples through which mankind would be elevated to its highest potential:

> Take interest, I beseech you, in those sacred institutions which we designate under the expressive name of laboratories. Demand that they be multiplied and adorned; they are the temples of wealth and of the future. There it is that humanity grows, becomes stronger and better.

By the beginning of the 20th century, science was almost entirely institutionalized and professionalized, and after the Second World War expanded enormously under government patronage, as well as through corporate investment. The highest level of

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c Fara (2009), p. 132.
e Kealey (1996).
funding is in the United States, where in 2015 the total expenditure on research and development was $495 billion, of which $121 billion came from the government. But governments and corporations do not usually pay scientists to do research because they want innocent knowledge like that of Adam before the Fall. Naming animals, as in classifying endangered species of beetles in tropical rainforests, is a low priority. Most funding is a response to Bacon’s persuasive slogan “knowledge is power.” By the 1950s, when institutional science had reached an unprecedented level of power and prestige, the historian of science George Sarton approvingly described the situation in a way that sounds like the Roman Catholic Church before the Reformation:

Truth can be determined only by the judgement of experts…

Everything is decided by very small groups of men, in fact, by single experts whose results are carefully checked, however, by a few others. The people have nothing to say but simply to accept the decisions handed out to them. Scientific activities are controlled by universities, academies and scientific societies, but such control is as far removed from popular control as it possibly could be.

Thomas Kuhn helped focus attention on the social aspect of science and reminded us that science is a collective activity. Scientists are subject to all the usual constraints of human social life, including peer-group pressure and the need to conform to the norms of the group. Kuhn’s arguments were largely based on the history of science, but sociologists of science have taken his insights further by studying science as it is actually practiced, looking at the ways that scientists build up networks of support, use resources and results to increase their power and influence, and compete for funding, prestige, and recognition. Bruno Latour’s Science in Action: How to Follow Scientists and Engineers Through Society (1987) is one of the most influential studies in this tradition. Latour observed that scientists routinely make a distinction between knowledge and beliefs. Scientists within their professional group know about the phenomena covered by their field of science, while those outside the network have only distorted beliefs. When scientists think about people outside their groups, they often wonder how they can still be so irrational:

[T]he picture of non-scientists drawn by scientists becomes bleak: a few minds discover what reality is, while the vast majority of people have irrational ideas or at least are prisoners of many social, cultural and psychological factors that make them stick obstinately to obsolete prejudices. The only redeeming aspect of this picture is that if it were only possible to eliminate all these factors that hold people prisoners of their prejudices, they would all, immediately and at no cost, become as sound-minded as the scientists, grasping the phenomena without further ado. In every one of us there is a scientist who is asleep, and who will not wake up until social and cultural conditions are pushed aside.

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For believers in the “scientific worldview,” all that is needed is to increase the public understanding of science through education and the media.

Since the 19th century, a belief in materialism has indeed been propagated with remarkable success; millions of people have been converted to this “scientific” view, even though they know very little about science itself. They are, as it were, devotees of the Church of Science, or of scientism, of which scientists are the priests. This is how a prominent atheist layman, Ricky Gervais, expressed these attitudes in the Wall Street Journal in 2010, the same year that he was on the Time magazine list of the 100 most influential people in the world. Gervais is an entertainer, not a scientist or an original thinker, but he borrows the authority of science to support his worldview:

*Science seeks the truth. And it does not discriminate. For better or worse it finds things out. Science is humble. It knows what it knows and it knows what it doesn’t know. It bases its conclusions and beliefs on hard evidence --- evidence that is constantly updated and upgraded. It doesn’t get offended when new facts come along. It embraces the body of knowledge. It doesn’t hold on to medieval practices because they are tradition.*

Gervais’ idealized view of science is hopelessly naïve in the context of the history and sociology of science. It portrays scientists as open-minded seekers of truth, not ordinary people competing for funds and prestige, constrained by peer-group pressures and hemmed in by prejudices and taboos.

Bacon’s vision of a scientific priesthood has now been realized on a global scale. But his confidence that man’s power over nature would be guided by “sound reason and true religion” was misplaced.

### 1.3 The fantasy of omniscience

The fantasy of omniscience is a recurrent theme in the history of science, as scientists aspire to a total god-like knowledge. At the beginning of the 19th century, the French physicist Pierre Simon Laplace imagined a scientific mind capable of knowing and predicting everything. These ideas were not confined to physicists. Thomas Henry Huxley, who did so much to propagate Darwin’s theory of evolution, extended mechanical determinism to cover the entire evolutionary process:

*If the fundamental proposition of evolution is true, that the entire world, living and not living, is the result of the mutual interaction, according to definite laws, of the forces possessed by the molecules of which the primitive nebulous of the universe was composed, it is no less certain the existing world lay, potentially, in the cosmic vapour, and that a sufficient intellect could, from a knowledge of the properties of the molecules of that vapour, have predicted, say, the state of the fauna of Great Britain in 1869.*

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1 Laplace (1819), p. 4.
When the belief in determinism was applied to the activity of the human brain, it resulted in a denial of free will, on the grounds that everything about the molecular and physical activities of the brain was in principle predictable. Yet this conviction rested not on scientific evidence, but simply on the assumption that everything was fully determined by mathematical laws. Even today, many scientists assume that free will is an illusion. Not only is the activity of the brain determined by machine-like processes, but there is no nonmechanical self capable of making choices (Chivers, 2010).

In 1927, with the recognition of the uncertainty principle in quantum physics, it became clear that indeterminism was an essential feature of the physical world, and physical predictions could be made only in terms of probabilities. The fundamental reason is that quantum phenomena are wavelike, and a wave is by its very nature spread out in space and time; it cannot be localized at a single point at a particular instant, or, more technically, its position and momentum cannot both be known precisely. Quantum theory deals in statistical probabilities, not certainties. The fact that one possibility is realized in a quantum event rather than another is a matter of chance.

In neo-Darwinian evolutionary theory, randomness plays a central role through the chance mutations of genes, which are quantum events. With different chance events, evolution would happen differently. T. H. Huxley was wrong in believing that the course of evolution was predictable. “Replay the tape of life,” said the evolutionary biologist Stephen Jay Gould, “and a different set of survivors would grace our planet today” (Gould, 1989).

In the 20th century it became clear that not just quantum processes but almost all natural phenomena are probabilistic, including the turbulent flow of liquids, the breaking of waves on the seashore, and the weather; they show a spontaneity and indeterminism that eludes exact prediction. Weather forecasters still get it wrong in spite of having powerful computers and a continuous stream of data from satellites. This is not because they are bad scientists but because weather is intrinsically unpredictable in detail. It is chaotic, not in the everyday sense that there is no order at all, but in the sense that it is not precisely predictable. To some extent, the weather can be modeled mathematically in terms of chaotic dynamics, sometimes called “chaos theory,” but these models do not make exact predictions (Gleik, 1988). Certainty is as unachievable in the everyday world as it is in quantum physics. Even the orbits of the planets around the sun, long considered the centerpiece of mechanistic science, turn out to be chaotic over long time scales.¹

The belief in determinism, strongly held by many 19th- and early 20th-century scientists, turned out to be a delusion. The freeing of scientists from this dogma led to a new appreciation of the indeterminism of nature in general, and of evolution in particular. The sciences have not come to an end by abandoning the belief in determinism. Likewise, they will survive the loss of the dogmas that still bind them; they will be regenerated by new possibilities.

By the end of the 19th century, the fantasy of scientific omniscience went far beyond a belief in determinism. In 1888, the Canadian-American astronomer Simon

¹ Munowitz (2005), chap. 7.
² Horgan (1997).
Newcomb wrote, “We are probably nearing the limit of all we can know about astronomy.” In 1894, Albert Michelson, later to win the Nobel Prize for Physics, declared, “The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. . . . Our future discoveries must be looked for in the sixth place of decimals.” And in 1900, William Thomson, Lord Kelvin, the physicist and inventor of intercontinental telegraphy, expressed this supreme confidence in an often-quoted (although perhaps apocryphal) claim: “There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.”

These convictions were shattered in the 20th century through quantum physics, relativity theory, nuclear fission and fusion (as in atom and hydrogen bombs), the discovery of galaxies beyond our own, and the Big Bang theory—the idea that the universe began very small and very hot some 14 billion years ago and has been growing, cooling, and evolving ever since. Nevertheless, by the end of the 20th century, the fantasy of omniscience was back again, this time fueled by the triumphs of 20th-century physics and by the discoveries of neurobiology and molecular biology. In 1997, John Horgan, a senior science writer at Scientific American, published a book called The End of Science: Facing the Limits of Knowledge in the Twilight of the Scientific Age. After interviewing many leading scientists, he advanced a provocative thesis:

> If one believes in science, one must accept the possibility – even the probability – that the great era of scientific discovery is over. By science I mean not applied science, but science at its purest and greatest, the primordial human quest to understand the universe and our place in it. Further research may yield no more great revelations or revolutions, but only incremental, diminishing returns.  

Horgan is surely right that once something has been discovered—like the structure of DNA—it cannot go on being discovered. But he took it for granted that the tenets of conventional science are true. He assumed that the most fundamental answers are already known. They are not, and every one of them can be replaced by more interesting and fruitful questions, as I show in my book The Science Delusion (called Science Set Free in the United States).

### 1.4 The credibility crunch for materialism

Within biology, an extreme form of materialism took hold in the 1970s and 1980s in the form of molecular biology, which soon became the dominant approach. More holistic forms of biology were marginalized. This molecular biological paradigm had enormous effects both on medicine and also on agriculture, shifting the focus of research to the molecular level. Hundreds of billions of dollars of public and private

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60 Quoted in Horgan (1997).
funds have poured into genome projects, genetic modifications of animals and plants, gene editing techniques, and other ingenious biotechnologies. There have been impressive successes, like the technical triumph of sequencing the human genome and the genomes of many other species, as well as some specialized applications, such as the identification of the genetic basis for rare hereditary human diseases. There are several examples of the commercially successful genetic engineering of crops. Billions of dollars in profits have flowed to corporations that own the patents on these genetically modified varieties. But this one-sided molecular approach has shifted attention away from many other possibilities in medicine and agriculture.

For more than 200 years, materialists have promised that science will eventually explain everything in terms of physics and chemistry. Science will prove that living organisms are complex machines, minds are nothing but brain activity, and nature is purposeless. Believers are sustained by the faith that scientific discoveries will justify their beliefs. The philosopher of science Karl Popper called this stance “promissory materialism” because it depends on issuing promissory notes for discoveries not yet made. Despite all the achievements of science and technology, materialism is now facing a credibility crunch that was unimaginable in the 20th century.

In 1963, when I was studying biochemistry at Cambridge University, I was invited to a series of private meetings with Francis Crick and Sydney Brenner in Brenner’s rooms in King’s College, along with a few of my classmates. Crick and Brenner had recently helped to “crack” the genetic code. Both were ardent materialists and Crick was also a militant atheist. They explained that there were two major unsolved problems in biology: development and consciousness. They had not been solved because the people who worked on them were not molecular biologists—not very bright. Crick and Brenner were going to find the answers within 10 years, or maybe 20. Brenner would take developmental biology, and Crick consciousness. They invited us to join them.

Both tried their best. Brenner was awarded the Nobel Prize in 2002 for his work on the development of a tiny worm, *Caenorhabditis elegans*. Crick corrected the manuscript of his final paper on the brain the day before he died in 2004. At his funeral, his son Michael said that what made him tick was not the desire to be famous, wealthy, or popular, but “to knock the final nail into the coffin of vitalism” (Ridley, 2011). (Vitalism is the theory that living organisms are not fully explicable in terms of physics and chemistry alone.)

Crick and Brenner failed. The problems of development and consciousness remain unsolved. Many details have been discovered, dozens of genomes have been sequenced, and brain scans are ever more precise. But there is still no proof that life and minds can be explained by physics and chemistry alone.

The fundamental proposition of materialism is that matter is the only reality. Therefore consciousness is nothing but brain activity. It is either like a shadow, an “epiphenomenon,” that does nothing, or it is just another way of *talking* about brain activity. However, among contemporary researchers in neuroscience and consciousness studies there is no consensus about the nature of minds. Leading journals such as *Behavioural and Brain Sciences* and the *Journal of Consciousness Studies* publish many articles that

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*In Popper and Eccles (1977).*
reveal deep problems with the materialist doctrine. The philosopher David Chalmers has called the very existence of subjective experience the “hard problem.” It is hard because it defies explanation in terms of mechanisms. Even if we understand how eyes and brains respond to red light, the experience of redness is not accounted for.

In biology and psychology the credibility rating of materialism is falling. Can physics ride to the rescue? Some materialists prefer to call themselves physicalists, to emphasize that their hopes depend on modern physics, not 19th-century theories of matter. But physicalism’s own credibility rating has been reduced by physics itself, for four reasons:

First, some physicists insist that quantum mechanics cannot be formulated without taking into account the minds of observers. They argue that minds cannot be reduced to physics because physics presupposes the minds of physicists (D’Espagnat, 1976).

Second, the most ambitious unified theories of physical reality, string and M-theories, with 10 and 11 dimensions, respectively, take science into a completely new territory. String theories and M-theories are currently untestable, so they can only be judged by reference to other models, rather than by experiment. These theories also apply to countless other universes, none of which has ever been observed. Some physicists are deeply skeptical about this entire approach, as the theoretical physicist Lee Smolin shows in his book *The Trouble With Physics: The Rise of String Theory, the Fall of a Science and What Comes Next* (2006). String theories, M-theories, and “model-dependent realism,” which tests models against other models, rather than by empirical evidence, are a shaky foundation for materialism or physicalism or any other belief system.

Third, since the beginning of the 21st century, it has become apparent that the known kinds of matter and energy make up only about 5% of the universe. The rest consists of “dark matter” and “dark energy.” The nature of 95% of physical reality is literally obscure.

Fourth, the Cosmological Anthropic Principle asserts that if the laws and constants of nature had been slightly different at the moment of the Big Bang, biological life could never have emerged, and hence we would not be here to think about it. So, did a divine mind fine-tune the laws and constants in the beginning? To avoid a creator God emerging in a new guise, most leading cosmologists prefer to believe that our universe is one of a vast, and perhaps infinite, number of parallel universes, all with different laws and constants, as M-theory also suggests. We just happen to exist in the one that has the right conditions for us.\(^p\)

This multiverse theory is the ultimate violation of Ockham’s razor, the philosophical principle that “entities must not be multiplied beyond necessity,” or in other words that we should make as few assumptions as possible. It also has the major disadvantage of being untestable.\(^q\) And it does not even succeed in getting rid of God. An infinite God could be the God of an infinite number of universes.\(^r\)

Materialism provided a seemingly simple, straightforward worldview in the late 19th century, but 21st-century science has left it far behind. Its promises have not been fulfilled, and its promissory notes have been devalued by hyperinflation.

I am convinced that the sciences in general and agricultural science in particular are being held back by assumptions that have hardened into dogmas, maintained by

\(^p\) Carr (ed.) (2007).
\(^q\) Ellis (2011).
powerful taboos. These beliefs protect the citadel of established science, but act as barriers against open-minded thinking.

### 1.5 The unfulfilled promises of molecular biology

It is hard to recall the atmosphere of exhilaration in the 1980s as new techniques enabled genes to be cloned and the sequence of “letters” in their genetic code to be discovered. This seemed like biology’s crowning moment; the genetic instructions of life itself were finally laid bare, opening up the possibility for biologists to modify plants and animals genetically, and grow richer than they could ever have imagined. Almost every week newspaper headlines reported a new breakthrough: “Scientists find genes to combat cancer,” “Gene therapy offers hope to victims of arthritis,” “Scientists find secret of aging,” and so on.

The new genetics seemed so promising that soon the entire spectrum of biological researchers was busy applying its techniques to their specialties. Their remarkable progress led to a vast, ambitious vision: to spell out the full complement of genes in the human genome. As Walter Gilbert of Harvard University put it, “The search for this ‘Holy Grail’ of who we are has now reached its culminating phase. The ultimate goal is the acquisition of all the details of our genome.” The Human Genome Project was formally launched in 1990 with a projected budget of $3 billion.

The Human Genome Project was a deliberate attempt to bring “Big Science” to biology. Physicists were used to huge budgets, partly as a result of the Cold War; there was enormous expenditure on missiles and hydrogen bombs, Star Wars, multibillion-dollar particle accelerators, the space program and the Hubble Space Telescope. Ambitious biologists suffered from physics envy. They dreamed of the days when biology would have high profile, high prestige, and multibillion-dollar international projects. The Human Genome Project was the answer.

At the same time, a tide of market speculation in the 1990s led to a boom in biotechnology, reaching a peak in 2000. In addition to the official Human Genome Project, Celera Genomics carried out a private genome project, headed by Craig Venter. The company planned to patent hundreds of human genes and own the commercial rights to them. Celera Genomics’ market value, like that of many other biotechnology companies, rocketed to dizzy heights in the early months of 2000.

Ironically, the rivalry between the public and private genome projects led to a bursting of the bubble before the sequencing of the genome had even been completed. In March 2000, the leaders of the public genome project publicized the fact that all their information would be freely available to everyone. This led to a statement by US President Clinton on March 14, 2000: “Our genome, the book in which all human life is written, belongs to every member of the human race…We must ensure that the profits of the human genome research are measured not in dollars, but in the betterment of human life.” The press reported that the president planned to restrict genomic patents. The stock markets reacted dramatically. In Venter’s words, there was a “sickening

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slump.” Within 2 days, Celera’s valuation lost $6 billion, and the wider market in biotechnology shares collapsed by $500 billion.¹

On June 26, 2000, President Clinton and the British prime minister, Tony Blair, with Craig Venter and Francis Collins, the head of the official project, announced the publication of the first draft of the human genome. At the press conference in the White House, President Clinton said, “We are here today to celebrate the completion of the first survey of the entire human genome. Without a doubt this is the most important, most wondrous map ever produced by mankind. It will revolutionise the diagnosis, prevention and treatment of most, if not all, human diseases…Humankind is on the verge of gaining immense, new power to heal.” The British science minister, Lord Sainsbury, said, “We now have the possibility of achieving all we ever hoped for from medicine.”⁶ One of the editors of Nature proclaimed that by the end of the 21st century, “genomics will allow us to alter entire organisms out of recognition, to suit our needs and tastes . . . [and] will allow us to fashion the human form into any conceivable shape. We will have extra limbs, if we want them, and maybe even wings to fly.”¹⁰

This astonishing achievement of sequencing the human genome has indeed transformed our view of ourselves, but not as anticipated. The first surprise was that there were so few genes. Rather than the predicted 100,000 or more, the final tally of about 23,000 was very puzzling, and all the more so when compared with the genomes of other animals much simpler than ourselves. There are about 17,000 genes in a fruit fly, and about 26,000 in a sea urchin. Many species of plants have far more genes than us—rice has about 38,000, for example.

In the wake of the Human Genome Project, the mood changed dramatically. The optimism that life would be understood if molecular biologists knew the “programs” of an organism gave way to the realization that there is a huge gap between gene sequences and actual human beings. In practice, the predictive value of human genomes turned out to be small. For example, in the case of height, genomes predict less than that achieved with a measuring tape. Tall parents tend to have tall children, and short parents short children. By measuring the height of parents, their children’s heights can be predicted with about 80% accuracy. In other words, height is about 80% heritable. By the year 2008, “genome-wide association studies” compared the genomes of 30,000 people and identified about 50 genes associated with tallness or shortness. To everyone’s surprise, taken together, these genes accounted for only about 5% of the inheritance of height. In other words, the “height” genes did not account for 75% of the heritability of height. Most of the heritability was missing. Many other examples of missing heritability are now known, including the heritability of many diseases, making “personal genomics” of very questionable value. Since 2008, in the scientific literature this phenomenon has been called the “missing heritability problem.”

In a study published in 2011, the percentage of heritability of height that could be predicted on the basis of the genome of unrelated individuals was 15%, ⁷ an

⁴ Makowsky et al. (2011).
improvement on earlier methods, but still far short of the heritability predictable by measuring the heights of relatives without sequencing any genes at all. And measuring people’s heights with a tape measure is billions of dollars cheaper than the genomic approach.

The optimism of stock-market investors who hoped for big returns from molecular technologies has suffered recurring blows. After the biotech bubble burst in 2000, many biotech companies either went out of business or were taken over by pharmaceutical or chemical corporations. An article in the Wall Street Journal in 2004 entitled “Biotech’s Dismal Bottom Line: More than $40 billion in Losses” went on to say, “Biotechnology . . . may yet turn into an engine for economic growth and cure deadly diseases. But it’s hard to argue that it’s a good investment. Not only has the biotech industry yielded negative financial returns for decades, it generally digs its hole deeper every year.” In 2006, Harvard Business School published a detailed analysis of the industry. They found that “only a very tiny fraction” of biotechnology companies had ever made a profit, and that promises of breakthroughs had failed over and over again. Defenders of the industry argued that more time was needed, but the Harvard Business School analysis pointed to the opposite conclusion: “[G]iven the extremely poor long-term performance of the biotechnology industry in general, and specific firms in particular, capital has been, if anything, too patient.”

Nevertheless, new biotechnology companies are continually being launched. Many of them burn through hundreds of millions of dollars with nothing to show for it. Most promise new and highly profitable medical advances, while others are directed at producing new genetically engineered varieties of agricultural crops or farm animals.

Since around 2015, a new gene-editing technique called CRISPR-Cas9 has become a popular basis for a new wave of biotech start-up companies. These techniques may well lead to some specialized medical applications, particularly for rare genetic disorders, and some niche applications in plant breeding (Jaganathan, Ramasamy, Sellamuthu, Jayabalan, & Venkataraman, 2018). A newer gene editing technique called “prime editing” allows even more precise manipulation of DNA sequences (Cohen, 2019). But precision gene editing is of very limited use because so many traits are polygenic. They are affected by large numbers of genes with very small effects, rather than one or two master genes that can be edited precisely.

Despite its underwhelming business record, this vast investment in molecular biology and biotechnology has had wide-ranging effects on the practice of biology, if only by creating so many jobs. The demand for graduates in molecular biology has transformed the teaching of biology. The molecular approach now predominates in most universities and it has strongly influenced science teaching in secondary schools.

Precisely because there has been such a strong emphasis on molecular biology, its limitations are becoming increasingly apparent. The sequencing of the genomes of ever more species of animals and plants, together with the determination of the structures

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of thousands of proteins, is causing molecular biologists to drown in their own data. There is practically no limit to how many more genomes they can sequence or proteins they can analyze. Molecular biologists now rely on computer specialists in the rapidly growing field of bioinformatics to store and try to make sense of this unprecedented quantity of information, sometimes called the “data avalanche” (Howe & Rhee, 2008).

1.6 Toward a more holistic approach

These historical developments and philosophical movements have had an enormous impact on agriculture, along with the growth of capitalism and in particular its globalized neoliberal form. By becoming aware of these assumptions it becomes easier to see how research in agriculture could move in a more holistic direction.

The paradigm of mechanistic materialism is now being challenged by a view of nature as organic and alive, a more holistic paradigm. Some philosophers of mind and neuroscientists are now adopting a panpsychist worldview instead, according to which all self-organizing systems, including atoms, have an element of mind or subjective experience (Goff, 2019). The Gaia hypothesis, the idea of the earth as a living organism, is one example of this change. But even for those who have no interest in these theoretical arguments, for practical reasons alone we need to change the way we think and act.

1. The cult of the scientific priesthood privileges knowledge of scientists from universities, and in particular scientists from universities in developed countries, over that of local farmers and agronomic practices. Traditional systems of knowledge are dismissed as superstitious or ignorant in favor of the currently fashionable views of technical experts. A more holistic approach to agriculture would not ignore traditional knowledge, locally adapted crop varieties, practices, and experience, but try to find out more about them and integrate them in agricultural development policies where appropriate.

2. The fantasy of omniscience leads to an obsession with quantitative precision, which ignores the complex ecological systems and patterns of interconnection that exist in the natural world. This reflects itself in the monopoly of monoculture, and the idea that improved varieties can be rolled out over large geographical areas because they represent the new improved scientific version of a crop as opposed the thousands of locally adapted varieties that were grown by farmers beforehand. Within plant breeding it leads to a focus on small numbers of genes that can be genetically modified, and with CRISPR-Cas9 and prime editing to a focus on single genes and small parts of single genes. Where symbiosis is recognized, as in the case of rhizobial bacteria that fix nitrogen in the root nodules of legumes, inoculants of a single defined strain are used despite the fact that in the soil there are complex mixtures of rhizobia and symbiotic mycorrhizal fungi. Moving beyond this obsession with quantitative precision would lead to a recognition of the importance of mixed cropping, soil microbiomes, the importance of many different genes, and also epigenetic effects in inheritance.

3. In economics and government planning, an obsession with quantitative results, like profits or growth in national products, leads to a tunnel vision that ignores the social and cultural life of farmers, ethical questions of land ownership and labor, animal welfare, the health of the ecosystem, effects of pollution, and long-term damage caused by soil erosion and degradation. A more holistic approach would take these factors into account instead of ignoring them.
4. Economic measurements are usually made on a short-term basis, like the annual growth in gross national product, annual profits of corporations, and annual crop yield figures. Corporations and shareholders also think in terms of annual profits, while in democracies politicians think in terms of electoral cycles of a few years. But the ecology of the earth, the health of the soil, and the sustainability of farming practices require much longer-term thinking.

5. With the increasing globalization of business, enormously powerful companies are able to influence consumer demand through advertising and government policies through lobbying. Their motives are not human welfare and health, nor long-term sustainability of the ecosystem, nor healthy populations, but short-term profits. The results include soil degradation, extinction of many species, toxic wastes, runoffs from farms, and an epidemic of obesity. A more holistic approach would inevitably take a longer-term and more sustainable perspective.

In the light of these principles, I discuss several new possibilities for agricultural research and development. Business as usual is unsustainable in the context of soil degradation, environmental pollution, deforestation, loss of biodiversity, increasing human population, climate change, limited water resources, and the obesity pandemic. New initiatives on large and small scales are needed. Here are several possibilities. Some, such as enhancing the microbiome of the soil, pragmatic plant breeding, and epigenetic inheritance, depend on a change in worldview; others make sense within both materialist and nonmaterialist frameworks of thought.

1.6.1 Rediscovering and testing traditional practices

All over the world, farmers have traditional practices that developed long before the advent of mechanistic science. Some of these practices are relatively uncontroversial from an ideological point of view, like mixed cropping (including intercropping). Increasingly though, traditional practices such as mixed cropping have given way to monocultures, mainly as a result of mechanization. However, even in more industrialized countries, mixed cropping still takes place in pastures, with mixtures of grass and clover, where nitrogen fixation by the root nodules in the clover reduces the need for nitrogen fertilization. The same principles apply to traditional mixed cropping and intercropping systems in which leguminous crops are combined with cereals, as in the “three sisters” system in Mexico, with maize, climbing beans, and squash grown in clusters. Intercropping systems are more systemized in that they are planted in rows, for example, with alternate rows of cereals and legumes, such as sorghum and pigeon peas in India. In this system, the pigeon peas not only enrich the soil with nitrogen and benefit subsequent crops through their root residues and fallen leaves, but also continue growing after the harvest of the earlier-maturing sorghum, using the vacated space, and after the end of the monsoon extracting residual soil moisture through their deep roots (Sheldrake, 1984). Such intercropping systems are more efficient in terms of utilization of land and resources, show higher yields under a wide range of environmental conditions, and also reduce the risk of crop failure (Rao & Willey, 1980).

By testing traditional cropping systems and other practices, useful lessons can be learned, as in the investigation of sorghum/pigeon pea intercropping systems already
discussed. There may be much scope for new mixed cropping systems that can use land and water more efficiently and also reduce dangers from pests and diseases. The first place to look for suitable systems would be in traditional practices by small-scale farmers in different parts of the world. Researchers could explore how these systems could be used in modern contexts. New possibilities will be opened up by precision agricultural equipment.

Unfortunately, agricultural researchers, aid agencies, and governments have often assumed that modern science knows best, and that traditional practices need to be replaced by modern farming methods, including the use of new cultivars grown in mechanized monocultures with chemical inputs of fertilizers, herbicides, and insecticides. The opposite approach is to find out what practices farmers have used traditionally, and why. This is one of the areas of research in agricultural anthropology (Rhoades & Rhoades, 2008), but this is still a neglected field of enquiry that could make an important contribution to sustainable agriculture (Sarkar, 2017).

1.6.2 Enhancing the microbiome of the soil

It has been known for many years that soil microbes can help enhance the fertility of soils both through nitrogen fixation by free-living microbes and in root nodules of legumes. At the same time, mycorrhizal fungi help plants to mobilize phosphorus and nitrogen from the soil, and also increase their ability to take up water. The activities of mycorrhizae and of nitrogen-fixing microbes are suppressed when chemical fertilizers are added to the soil. The richness of the microbiome and diversity of mycorrhizae are generally highest under organic farming systems (Manoharan, Rosenstock, Williams, & Hedlund, 2017). In recent decades the emphasis has been on the use of chemical fertilizers, and relatively little attention has been paid to the ecology of soil microorganisms (Hart & Trevors, 2005).

As it becomes more imperative to farm sustainably and preserve the fertility and structure of the soil, a new wave of research on the ecology of soil microbes would be very helpful. The effects of different soil management practices, cropping systems, and rotations have a major effect on the microbial ecology (Bender, Wagg, & van der Heijden, 2016). The ecosystem of the soil is severely disrupted by plowing, and one of the selling points for Conservation Agriculture is that it avoids this form of disturbance. However, insofar as conventional systems, both tillage- and nontillage based, depend on chemical herbicides, like glyphosate, they can also have adverse effects on soil ecology. Glyphosate is toxic to mycorrhizae and reduces the viability of mycorrhizal fungal spores and the colonization of roots by mycorrhizal fungi (Druille, Cabello, Omacini, & Golluscio, 2013). Organic and biodynamic farming systems avoid this problem, but still disrupt the soil microbial ecology through tillage.

Conservation Agriculture generally uses less glyphosate per hectare compared to conventional tillage agriculture, and many smallholders do not use glyphosate in their Conservation Agriculture systems. A global review by Goss, Carvalho, and Brito (2017) found no evidence of negative effects of glyphosate application on mycorrhizae diversity, colonization, and function in Conservation Agriculture systems for a number of reasons, including healthy soils, no or minimal soil disturbance, maintenance of a
protective soil mulch cover, and crop and root system diversification, all of which have been shown to promote mycorrhizae. On the other hand, inversion tillage was found to have an adverse effect on mycorrhizae in the soil and their ability to inoculate subsequent crops because of the degradation of mycorrhizal habitat and soil health (Goss et al., 2017).

It is tempting to think that inoculating crops with mycorrhizal fungi will solve these problems, and many companies now sell “bioinoculant” products designed to do this. However, adding exogenous mycorrhizae to the soil often has little or no effect on the growth and yield of the crop, and may even be harmful, because the added organisms are in competition with mycorrhizae that are already present in the soil, and which have evolved in those specific ecological conditions (Hart, Antunes, Chaudhary, & Abbott, 2017). The same applies to inoculation of legume crops with strains of the nitrogen-fixing bacterium *Rhizobium*. In laboratory experiments with plants grown in sterile soil, such inoculations can produce dramatic improvements in growth, but in the field the soil is not sterile and already contains a complex microbial ecosystem. We need sustainable agricultural practices, including crop rotations that enhance the health and effectiveness of the ecology of the soil, rather than practices that harm this ecology. Much more research is needed on the effects of crop rotations, organic and inorganic nutrient additions, and tillage or no-tillage practices on the soil microbiome and on the dynamics of mycorrhizae (Goss et al., 2017).

### 1.6.3 Automated equipment with artificial intelligence could help small farmers

In Europe, North America, Australia, and other parts of the world, the need to cut labor costs has led to continual increases in the sizes of fields and farms, and also the size of machines. One man operating a very large machine incurs lower labor costs than several men operating smaller machines. But although the cost of labor is reduced, the capital costs rise to a level that is unaffordable for most farmers. For example, in 2018 in the United Kingdom, combine harvesters ranged in price from around £140,000 to £550,000 (about $180,000 to $720,000), depending on make and size. Together with large tractors and other equipment, farming involves huge capital investments or equipment leasing costs, which drive the economics of farming toward ever-larger units. Farms of 1000 acres or more are increasingly common. With the price of arable land around £8000 ($10,000) per acre, the land alone for such a farm costs around £8 million ($10.5 million). No young person could possibly become a farmer under these conditions without enormous inherited wealth or heavy financial backing.

But we may be on the threshold of a major change. Rapidly improving technologies for self-driving cars and self-driving agricultural machinery, using GPS navigation systems, will enable driverless tractors and harvesters to become normal pieces of machinery. In addition, artificial intelligence (AI) allows for precision sowing, drilling, and harvesting methods. Instead of a one-size-fits-all approach, modern equip-

ment can respond to differences in soil condition and apply fertilizers appropriately in parts of fields where they are needed, recognize weeds and physically remove them, apply insecticides where plants are being attacked, and harvest fruit and vegetables selectively when they are ripe. Just as driverless cars can be large or small, so can automated farm machinery. Soon it may no longer be necessary to have vast farms with gigantic machines to reduce labor costs. Small farms with smaller and cheaper intelligent machines could become financially viable. Field sizes and farm sizes could be reduced, and cropping systems become more diverse.

Sophisticated computerized equipment could also make it easier to use mixed cropping systems, some of which are at present unfeasible because they cannot be mechanized; without mechanization, labor costs are too high. New, sophisticated technologies using AI could enable efficient, productive, and diverse mixed cropping systems to flourish in place of monocultures.

1.6.4 Urban gardens and part-time farming

In some parts of the world, significant amounts of food are grown by people who are not professional farmers, as in allotments in the United Kingdom (Acton, 2011), and community gardens, as in the United States and Canada. In many other parts of the world, including Cuba and parts of Africa, urban gardens are important sites of local food production. Altogether, an estimated 800 million people worldwide currently practice some form of urban agriculture (Edmondson, Davies, Gaston, & Leake, 2014).

In terms of productivity per unit area, these gardens are often better than agricultural monocultures. In the United Kingdom, during the Second World War, in the “Dig for Victory” campaign, allotments and gardens provided around 10% of the food consumed, despite covering less than 1% of the area of arable cultivation. Recent research has shown that gardens and allotments can produce yields of fruit and vegetables 4–11 times greater than the same area under conventional agricultural crops (Thompson, 2014). Moreover, a study comparing the soil in allotments and in conventional arable fields in Britain showed that the allotments had on average 32% more organic carbon and 25% more total nitrogen. They were also less compacted. Unlike most arable farmers, 95% of the allotment gardeners composted biomass on site and many also added organic-based fertilizers and commercial composts. They were farming more sustainably than most farmers, and maintaining a higher soil quality (Edmondson et al., 2014).

In some parts of the world, through an inheritance system whereby children share the family land, there is a continual splitting up of family farms, with the result that some people living in cities have small farms nearby that they look after on a part-time basis, combining weekend farm work with urban jobs, as in the neighborhood of Freiburg-in-Breisgau, Germany.

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*There are many YouTube videos online that show these systems in action, for example, [https://www.youtube.com/watch?v=Rl77FVebxVI](https://www.youtube.com/watch?v=Rl77FVebxVI) (Retrieved 5 June 2019).

*https://www.allotment-garden.org/allotment-information/allotment-history/ (Retrieved 11 June 2019).*
There is a large potential for an increase in this kind of food production through making small farms, gardens, or orchards more available to people living in towns. In some parts of the world, there is an unsatisfied demand for opportunities to grow food in and around cities as a hobby, or as a part-time occupation. In Britain, for example, there are long waiting lists for allotments, and a chronic shortage of supply. Thus more food could be produced in a healthy and diversified way by making more areas for gardening or small-scale farming available in or near urban areas. But where will the land come from?

Landowners near towns would be unlikely to want to sell land and thus potentially lose out on huge capital gains if the land were developed for building, but they could be willing to lease land on 5- or 10-year leases. For example, I have calculated that if landowners in Britain rented out land for family orchards and gardens in small units, say a fifth of an acre, or 800 m², they could receive at least 20–30 times more annual rent per acre than renting it to a farmer for arable monoculture (Sheldrake, 2013). There would also probably be an improvement in the physical and mental health of the families looking after these orchards and gardens.

### 1.6.5 Using human wastes

When I was doing research at ICRISAT in India, some of my field studies on chickpeas took place in a Himalayan village in the Lahaul Valley, near the border with Tibet. I was staying with a farming family in a traditional farmhouse. The toilet arrangement consisted of a room with an elevated floor on which there was a hole, through which all the wastes dropped down into straw, forming a rich manure. This was put back onto the family’s land each year, and thus the nutrients were directly recycled. I did not realize at the time that I was seeing, and taking part in, a traditional practice that had predominated for millennia throughout large parts of eastern Asia. As F.H. King showed in his classic book *Farmers of Forty Centuries, Or, Permanent Agriculture in China, Korea and Japan* (1911), nothing was wasted. Human excreta in the form of “night soil” were a valuable commodity. Public toilets were a means of collecting useful resources. As King saw for himself on a journey he made from Yokohama to Tokyo, “In such places as railway stations, provision is made for saving, not for wasting, and even along the country roads screens invite the traveller to stop, primarily for profit to the owner more than for personal convenience” (King, 1911, p. 9).

By contrast, most of us have grown used to a system in which our own wastes are literally wasted, flushed away in plumbing systems that require enormous quantities of water. Meanwhile urea and other fertilizers are made in factories or mined from the earth, and then applied to the soil in excessive quantities, with the runoff causing large-scale pollution of rivers, lakes, and seas.

One starting point for the recycling of human wastes would be to collect urine separately. It is easier to process and rich in nutrients, particularly urea. Humans generally excrete between 12 and 20 g of urea a day or up to 7 kg a year. If we take a moderate

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figure of 5 kg per year per person, with the world’s population around 7.5 billion, about 38 billion kg or 38 million tons of urea are excreted. In 2016, world urea production in factories was about 170 million tons a year,\(^a\) about five times more than the amount produced by humans. So, urine alone cannot supply all the urea that is used. Nevertheless, urea from urine could make a significant contribution. The easiest way to start would be to collect urine from male urinals, storing it in tanks, and transporting it in tankers to enhance the composting of nitrogen-poor biological wastes, like straw, or to add to anaerobic biomass digesters, facilitating the growth of microbes that do the digesting, producing methane for generating electricity.

Until recently, in Europe, as in other parts of the world, toilet facilities were in out-houses with earth closets, or simply outdoors. The human wastes went into the earth. Modern composting toilets make this process more efficient, but most people today live in cities rather than in the countryside, and often in apartment blocks. In these conditions, how can human excretions be recycled rather than literally wasted? One solution would be to have a separate plumbing system for toilets instead of combining their effluents with other aqueous wastes, such as those from kitchen sinks, baths, and showers. Nontiolet fluid waste can be treated separately and can more easily be regenerated into usable water. The toilet effluents from an urban neighborhood, or a large apartment building, could be piped directly to a local biogas digester. Food wastes could also be collected and added into it. Local biogas plants would both generate electricity and produce heat, which would be used in local heating systems.

Animal wastes are already used in this way. In the Indian subcontinent there are about 2 million domestic gobar biogas digesters, which provide cooking gas for a family through the digestion of cow dung and provide valuable fertilizer from the residues. In China there are even more. In Europe, there are now many large-scale urban biogas digesters primarily using food wastes. On some farms, the slurry from cow barns is fed into these digesters and mixed with grass and other sources of biomass. These technologies could relatively easily be adapted to use human wastes, and indeed some sewage plants already include anaerobic digesters.

The liquid residues from anaerobic digesters are a good organic fertilizer, rich in nitrogen and other plant nutrients, and can be applied to the land as liquid fertilizer, after suitable dilution.

### 1.6.6 Using weeds

Weeds are by definition plants that are growing in the wrong place. They are unwanted because they compete with crops and reduce their yields. But many weeds are weeds precisely because they are hardy and grow vigorously. These could be advantages when the desired harvest is biomass. Although most weed species are useless for human consumption, or as animal feed, some might be useful crops for producing biomass for digesters. The feasibility of using weeds in biogas digesters has already been established with water hyacinth (Almoustapha, Kenfack, & Millogo-Rasolodimby, \(^a\)https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2018/fertilizer-industry-handbook-2018-with-notes.pdf/ (Retrieved 11 June 2019).
which is a highly invasive water weed in many tropical and subtropical regions, and is one of the fastest growing plant species on earth.

1.6.7 **Phase out the use of food crops for biofuels**

Partly driven by concerns about climate change, in some parts of the world food crops are used not for food but for the production of liquid fuel, mainly ethanol. In the United States, for example, about 40% of the total maize production is used for ethanol, and 36% for animal feed. Most of the rest is exported. Only a small fraction of the total maize is used as food for Americans, and much of it is in the form of high-fructose corn syrup. The energy balance of ethanol production from maize is very modest—there is only about twice as much energy in the ethanol as in the fossil fuels required to grow the maize and to produce the ethanol, compared with eight times more energy with alcohol produced from sugar cane in Brazil. The production of all this maize is heavily subsidized by the US government—in 2012, by about $20 billion. And much of this government money benefits the giant food companies that dominate the US market: Archer Daniels Midland and Cargill, the biggest privately owned corporations in the world. These companies in turn invest heavily in lobbying the US government and in shaping the system of subsidies that brings them so much profit (Pollan, 2006).

These subsidies could be used very differently—for example, to help reduce run-off and erosion, to improve soil quality, and to promote more diverse and sustainable cropping systems. This is largely a political problem, but there is great scope for research in developing agricultural alternatives to the present system. In terms of energy production, there are already alternatives to liquid fuels, as in solar and wind power, which will become increasingly important as the shift to electric vehicles accelerates.

1.6.8 **Reducing demand through human dietary changes**

According to an analysis in 2011, about 75% of all agricultural land, including pastureland, is dedicated to animal production. The proportion of cereal grains, soya beans, and other crops for feeding to intensively farmed animals amounts to about 24% of total crop production by mass, and about 36% by calorie content. In addition, livestock production is responsible for about 18% of total greenhouse gas emissions (Cassidy, West, Gerber, & Foley, 2013).

The conversion efficiency of all this food into meat is very low. In terms of calories, only about 10%–12% of the calories fed to animals ultimately contribute to human diets through meat and other animal products (Foley, 2013). If plant foods were eaten directly by humans, far more food would be available for the world’s growing population. As one recent analysis showed, “Growing food exclusively for direct human consumption could, in principle, increase available food calories by as much as 70%, which could feed an additional 4 billion people.” Even small shifts in the allocation of

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crops from animal feed could significantly increase the availability of food globally (Cassidy et al., 2013). Raising animals for meat also uses large quantities of water. Excessive meat consumption also increases the risk of several kinds of cancer, particularly colon and rectal cancer (Larsson & Wolk, 2006).

In some Western countries there is already a rise in the proportion of people eating vegan, vegetarian, and “flexitarian” diets, reducing the consumption of meat, and for the European Union as a whole the consumption of meat, especially beef, is expected to decline by 2030. There are also a number of innovations for producing meat substitutes from fungal protein, insect proteins, and cultured animal cells, which could further help to reduce the demand for feed grains, soya beans, and oilseeds for animals in factory farms.

Other dietary changes that could have large effects on overall food supply would be an increased use of drought-tolerant crops like sorghum and millet. In many parts of India, for example, where water is in short supply, much of the available water is used to grow a relatively small acreage of rice, the most water-demanding crop. But if the same water were spread more thinly, especially using sorghum or millet, crop yields would increase, overall food production would go up, and the food supply would also be more nutritious (Davis et al., 2018). Through a combination of government policies, changes in subsidy systems, marketing, and working with food industries, preferences could change, and the overall agricultural system could become more efficient through reducing the production of rice in favor of more water-efficient crops.

Thus some of the most important factors shaping agriculture in the decades to come will be changes in dietary habits. These are outside the sphere of farming itself but no discussion on the future of agriculture can ignore them. And the economic forces that affect agricultures are not simply a result of humans’ dietary desires and disposable incomes; they are affected by the economic interest and lobbying power of agricultural and food businesses, food advertising, and by government policies, including taxation and subsidies. Although imposing a tax on meat or rice consumption would probably be politically difficult in most countries, governments can make major changes by altering the system of subsidies. In the United States, for example, large subsidies encourage the production of feed grains, especially maize, soya beans, and other crops used in factory farming, and thus indirectly subsidize the intensive production of meat, making it much cheaper than it would otherwise be. In India, government subsidies have favored the production of irrigated wheat and rice over other cereals, thus distorting the market in favor of the wasteful use of water.

### 1.6.9 Pragmatic plant breeding

Long before the time of Charles Darwin and Gregor Mendel, people were breeding plants and animals by breeding from variants that appeared spontaneously, or by making crosses between promising parents and selecting among the offspring. Many of

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breeds of dog, including Pekinese, Afghan hounds, and sheepdogs, long predate the era of genetics. So do the many kinds of cabbage, including kale, broccoli, and Brussels sprouts, all members of the same species *Brassica oleracea*. Indeed, it was precisely such examples of pragmatic animal and plant breeding that provided Charles Darwin with much of the raw material for his thinking about the power of selection. His book *The Origin of Species* (1859) contains many examples, and he goes into more detail in *The Variation of Animals and Plants Under Domestication* (1868). Likewise, Mendel was able to work out some of the principles of inheritance because different varieties of peas already existed, thanks to the activities of plant breeders. The successes of plant breeding came first. Genetics followed.

For most of the 20th century, governments funded the breeding of agricultural crops in agricultural institutes and universities. Their aim was to produce new varieties suitable for use by farmers, and the farmers only had to buy their seed supplies once; they could use their own seed thereafter. In Britain, for example, the Plant Breeding Institute at Trumpington, near Cambridge, funded by the UK government through the Agricultural Research Council, produced many new varieties, some still grown commercially, like Maris Piper potatoes and Maris Otter barley, used in brewing. But since the 1980s, agricultural research has been largely privatized. The Plant Breeding Institute itself was privatized in 1987 and sold to Unilever, who sold it on to Monsanto in 1998. The amount of research work declined. The buildings were demolished in 2009, and Monsanto sold the land to developers for housing.\(^1\)

The concept of plant breeding and agricultural research in the spirit of public service had been replaced by the goal of maximizing corporate profits. Profits are greatest if farmers have to buy seed afresh each year, rather than saving their own from previous years. Under the older system of Plant Breeders’ Rights, farmers are allowed to use their own seed in subsequent years. But, corporations favor a system whereby they can patent seeds, and then force farmers to buy them over and over again. Monsanto successfully sued hundreds of farmers in the United States for using their own seeds on the grounds that they were infringing Monsanto’s patents, and won more than $23 million from the farmers (Harris, 2013).

In 2018, the German-based Bayer Corporation acquired Monsanto. Three multinational corporations, Bayer/Monsanto, Syngenta, and DuPont, now control the majority of the world’s seed market.

Coinciding with the wave of privatization in the 1980s was a rising optimism about the prospect of exploiting genes through genetic engineering. In traditional plant breeding, the selection of desirable characteristics came first, and genetic analysis followed. In genetic engineering, a gene has to be identified first and then engineered into a plant through biotechnology. Thus a gene from *Bacillus thuringiensis* coding for an insecticidal protein was transferred to cotton and maize, rendering them poisonous to insects. Likewise, a gene from a bacterium that can metabolize the herbicide glyphosate (marketed as Roundup by Monsanto, and now Bayer) has been transferred to a wide range of crops, most notably soya beans. By

\(^1\)http://www.trumpingtonlocalhistorygroup.org/subjects_PBIhistory.html (Retrieved 11 June 2019).
making these crops “Roundup Ready” a whole field can be sprayed with Roundup to kill all plants except the Roundup Ready crops, which have enzymes that can destroy this poison. The majority of soya beans planted in the United States are now genetically modified (GM) so that they can break down Roundup. This system promotes the sales of Roundup, and creates extreme monocultures, but it does not necessarily lead to higher yields. In 1999, in an analysis of more than 8000 field trials in the United States, the Roundup Ready soya beans yielded on average 6.7% less than conventional varieties (Benbrook, 1999). This “yield drag” is probably a by-product of the technical process of genetic modification, which involves collateral damage to other genes. Monsanto claims that a new version of Roundup Ready overcomes this problem. However, the company’s own data show that its GM variety yields less than the conventional variety the trait is inserted into.

Despite the many promises made about the transformation of agriculture by genetic engineering, the practical applications are limited by the fact that most characteristics of crops are not controlled by single genes that can be engineered into the crop. In fact genome-wide association studies in both plants and animals have shown that for most complex hereditary traits, dozens or even hundreds of genes are involved, most of which have small effects. These characteristics are “polygenic” and cannot be controlled by inserting or deleting a single gene, or even two or three genes, by genetic engineering (Sheldrake, 2020).

For similar reasons, the recent technique of gene editing through the CRISPR-Cas9 system may have some limited uses in specialist situations, but, as in the case of genetic engineering, its highly focused approach on single genes, or even single base-pairs within single genes, cannot address important characteristics in crop plants that depend on large numbers of genes.

One aspect of a new pragmatism could be to breed crops as mixtures. Planting mixed varieties of a particular crop, like wheat, could reduce susceptibility to disease compared with a monoculture of a pure line. Genetically mixed crops could have survival and yield advantages, because instead of all the plants reacting in the same way to pests, diseases, and adverse climatic conditions, some respond differently and more effectively than others. For example, in a large-scale test in China, a mixture of rice varieties was sown on thousands of farms. The ravages of rice blast, the most significant fungal disease of rice, were reduced to acceptable levels without the use of any fungicide. As a report in Nature put it, “This approach is a calculated reversal of the extreme monoculture that is spreading throughout agriculture, pushed by new developments in plant genetics” (Wolfe, 2000).

In summary, a combination of the molecular paradigm, biotechnology patents, and corporate empire building has distorted the field of plant breeding. Pragmatic plant breeding, aided by molecular genetic technologies where appropriate, is more likely to result in the breeding of better crops than the single gene approach. Breeding crops that can be grown as mixtures may confer further benefits in insect, disease, and drought resistance, giving greater stability of yield.

1.6.10 Epigenetic inheritance and its possible applications

In the 20th century, the inheritance of acquired characteristics, or “Lamarckian inheritance,” was treated as heretical in Western biology. It contravened the neo-Darwinian theory of evolution, which explicitly denied that such inheritance was possible, and focused on the natural selection of gene frequencies within interbreeding populations and on random mutations of genes. This scientific question was also heavily politicized during the period of the Cold War. In the Soviet Union, the orthodox school of biology, under the leadership of Trofim Lysenko, strongly favored the inheritance of acquired characteristics. Mendelian geneticists were persecuted.

Yet, since the turn of the millennium, the inheritance of acquired characteristics has been rebranded as “epigenetic inheritance” and has become mainstream. This is an area of very active research in biology. There is now no doubt that plants sometimes inherit characteristics acquired by their parents or more remote ancestors in response to the conditions under which they were grown. In the 1960s and 1970s this was clearly demonstrated by a pioneer of what we now call epigenetic research, Alan Durrant, whose research on flax showed striking and enduring changes caused by soil fertility. For example, flax plants grown with high levels of nitrogen fertilizer became taller and less branched, and this feature appeared in subsequent generations, even without elevated levels of nitrogen in the soil (Durrant, 1962). Durrant was swimming against the neo-Darwinian tide, but recent research has revealed many other examples of epigenetic inheritance. Similar epigenetic effects occur in animals (Miska & Ferguson-Smith, 2016).

Yet in agriculture, it is still generally assumed that seeds of a given variety are simply carriers of the DNA of that variety and are not influenced by the conditions under which they were grown. In the light of research on epigenetics this seems unlikely. There may well be epigenetic effects in crop plants; the conditions under which the seeds or vegetative propagules are grown may have an unsuspected influence.

Indeed, recent research on epigenetic inheritance in plants points to possible useful applications (Hauser, Aufsatz, Jonak, & Luschnig, 2011). In many plant species there are inducible defense systems, whereby after an initial attack the plant produces substances that enhance its ability to withstand further attacks. One defense signaling system depends on the production and movement within the plant of jasmonic acid and related metabolites. In experiments with Arabidopsis and with tomatoes, plants were exposed to caterpillars that ate their leaves, and their descendants, grown from seed, were assessed for resistance to caterpillar attack. The growth of the caterpillars was reduced by about 40% relative to controls. This resistance carried over to the second generation, even when the first generation descended from attacked plants were not exposed to caterpillars. The resistance faded out in the third generation when there were no further attacks (Rassman et al., 2012). This epigenetically inherited resistance depended on the ability of plants to mobilize the jasmonate signaling system and to produce small interfering RNAs, which are known to play a part in the epigenetic modulation of gene expression (Henderson & Jacobsen, 2019).

In other studies with Arabidopsis, the exposure of plants to drought also had epigenetically heritable effects (Zhang, Fischer, Colot, & Bossdorf, 2013). So did exposure
to high temperatures. In one study with *Arabidopsis*, plants were exposed to mild heat (30°C) in the parental and F1 generation, and then grown at normal temperatures in the F2 generation. They were again exposed to heat in the F3 generation. In this third generation, the plants grown at 30°C produced six times more seeds when their ancestors had been exposed to heat than control plants whose ancestors had been grown at a normal temperature (Whittle, Otto, Johnston, & Krochko, 2009).

In this context, it would be well worth reexamining the archives of Soviet biology, where what we now call epigenetic phenomena were widely investigated in the context of agriculture from the 1930s to the 1950s. In the West it was generally assumed that all these results must be fraudulent or pseudoscientific because the inheritance of acquired characteristics was believed to be impossible. Now that epigenetic inheritance is known to be real, it seems likely that biological and agricultural journals from the Soviet era could contain much useful information. People with a good knowledge of genetics, epigenetics, and Russian could be employed to carry out an extensive review of this literature and compile a series of review articles that might well provide starting points for new investigations.

Heritable epigenetic effects often fade out over time, so the biggest effect would be in the generation following the exposure of their parents to environmental conditions that induce an adaptive response. If these effects were to be implemented practically, then this system would be rather like the production of hybrid maize or other hybrid crops. To use epigenetically improved seeds, then seed material for the next generation would be produced afresh each year, just like an F1 hybrid. Such a system might even enable organic farmers whose crops suffer from severe insect damage to recoup some of their losses. If the farmers have low seed yields from insect-damaged crops, they may be able to obtain a premium price for these seeds if they confer a greater resistance to insect attack on the next generation.

### 1.7 Setting innovation free

Most of current agricultural research is not determined by questions from farmers or gardeners, but by developments within academic and corporate science, and above all by the prospects of patenting genetic modifications or edited genes or promoting agrochemicals. A complementary approach would be to ask farmers and gardeners what problems they face and what kinds of solutions they are hoping for. Several years ago, on a BBC radio news program, there was a discussion of science funding. An interviewer asked a woman who had an allotment what kind of question she would ask to researchers, if she had a chance to do so. She replied that she was growing carrots organically, and they suffered from carrot root fly attacks. Someone had told her that if you put grass clippings on the soil it could reduce these attacks. She wanted to know whether this was true and how she could do it most effectively. The interviewer then spoke to the head of the UK Biotechnology and Biological Sciences Research Council, a government body that channels taxpayers’ money into biological research, asking if this was the kind of question they were addressing, or could address. He
replied that they were dealing with much more fundamental and important issues like the potential for the genetic modification of crops and the sequencing of genomes.

There are probably hundreds of such questions that could be answered by research. Some may already have been answered. If there was a system whereby farmers and gardeners could submit questions, receive answers if they already exist, and open up new lines of research if answers do not already exist and if the question seems worthwhile, these practical problems could be a fruitful stimulus for new research.

Another approach would be to reward creativity. Many millions of people throughout the world grow food plants in gardens, allotments, or farms. Many of them have had years of experience. Some are creative and experimental. But at present, if a farmer or gardener comes up with an innovation, it is unlikely to be of interest to academics in universities or to global corporations. And there is little or no possibility for an ordinary person to communicate with academics and researchers.

If systems were set up whereby innovations could be submitted as entries for prizes that rewarded the development of new crops, new cropping systems, or new horticultural or agricultural practices, then there would be an incentive for independent creativity by people who are not professional researchers. As well as innovations flowing from top down, as in the case of new crop varieties, GM plants, agrochemicals, and new machinery, innovations could flow from the bottom up, from people who are literally on the ground and who have carried out their own investigations and experiments.

One of the problems with Thomas Kuhn’s analysis of paradigm change in science is that it seems to validate dictatorships. When a new paradigm comes into force, the old model is rejected or discredited. A new orthodoxy replaces the old one. This is a model of revolutions akin to political revolutions in which one authoritarian regime is replaced by another. Perhaps the next kind of scientific revolution could be different, and instead of ushering in a new orthodoxy, it could open the way to a tolerant pluralism.

This is what I hope for. Innovation will be most free when no particular orthodoxy achieves a monopoly of power, or of funding, and when scientific research in general, and agricultural research in particular, are carried out pragmatically, liberated from the dogmas of materialism, molecular triumphalism, and neoliberal capitalism, and placing a major emphasis on the building up of the quality of the soil and on sustainability.

References


