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The Universe, the Evolution of the Perverse, and a Rice Problem

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About the author

John Sheehy did his BSc in physics, his MSc in electronics, and his PhD in agricultural botany and physics at the University College of Wales. He was a Nuffield Foundation Fellow in the Developmental Genetics Department.

His interests in weather-crop interactions and instrumentation led him to co-author with Prof. Ian Woodward the textbook *Principles and Measurements in Environmental Biology*. On sabbatical at the University of California-Davis, he took over Professor Bob Loomis' teaching load and conducted research on the relationship between biological nitrogen fixation and photosynthesis with Professor Don Philipps. On returning to the UK, the pioneering research of John's group at GRI Hurley uncovered a major error in the technique widely used for measuring nitrogen fixation. This was followed by the discovery of a mechanism controlling diffusion in legume root nodules. He built a theoretical model of a nodule with Dr. Fraser Bergersen in the Commonwealth Scientific and Industrial Research Organisation (CSIRO) while on a sabbatical in Australia.

John left the research service and set up his own consultancy business, Creative Scientific Solutions. He also became a part-time lecturer in systems analysis in the Business School of the Wycombe College of Brunel University. This work led him to interact vicariously with the private sector, but he kept an interest in research and wrote several models for research groups in Europe and the UK. Being in business and teaching business people for five years gave him a very different perspective on life from the one he had held as a researcher.

The opportunity to solve important problems relevant to poor people brought him to IRRI, where he is systems modeler/crop ecologist and head of the Climate Unit in IRRI's Agronomy, Plant Physiology, and Agroecology Division.

The author's unofficial CV

John's family has had a long connection with agriculture. His Cro-Magnon ancestors ran a small cave-painting business specializing in charcoal outlines of primitive cows. When the discovery of wooden hut construction destroyed the business, the family emigrated to the west of Ireland, where they concentrated on improving their DNA combinations. The result, after twenty thousand years of tingling gene mingling, is the author of this publication.

The universe, the evolution of the perverse, and a rice problem

John E. Sheehy

This publication is rather unusual. I want to discuss science, the scientist as part of an organization, and, finally, using some of my own work, illustrate some of the challenges and uncertainties faced by a scientist working in international agricultural research. I believe that a change in perspective is an important aide to understanding and problem solving and I hope to convince you of its value.

As a preamble, I compare a definition of science (Maddox 1988) with that of history (Fernández-Armesto 1995). You can see that there is a substantial difference between the two.

***Science*[1] is the collective and cumulative attempt to understand the natural universe.**

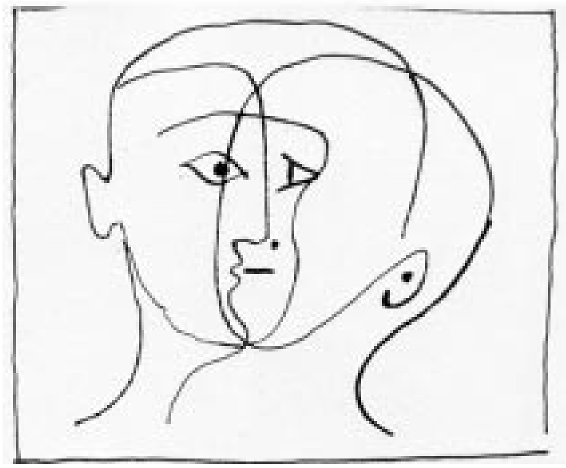
***History*[2] is a creative art, best produced with an imagination disciplined by knowledge and respect for the sources.**

The two definitions would definitely answer the problem often posed in school: explain the difference between science and history. But the definition of history begs the question, What is art? It reveals a remarkable view that history is produced and without historians there would be no history. I would have added to the definition of science the fact that science is creative. In my opinion, science is a highly creative discipline. It requires imagination disciplined by knowledge with respect to the published literature. The two definitions would then resemble each other. Therefore, to differentiate them, I would add that science is about discovery and invention, whereas history is about rediscovery and the interpretation of past events in human affairs.

In this short publication, I cover a span of only (!) 15,000 million years. I want to illustrate the increasing pace in the evolution of invention and its implications for scientists. I want to capture the different perspectives of a scientific organization. IRRI's scientific community has a view of what it considers the organization to be about and I present that view. The other important views are the administration and human resources view and the finance office's view. The people in these different disciplines have different jobs and perspectives on the manner in which the organization functions. So there is a perspectives issue to be explored.

When I first came here and gave a seminar on modeling as part of my interview, I said it was important to change our perspective, that, for too long, crop physiology had been dominated by models led by carbon supply through photosynthesis. I said that approach was stale and we needed a fresh start. By considering a nitrogen-led approach to crop physiology, we obtain a different perspective on growth and development. Novel questions such as those concerning carbon limitations to growth, feedback effects from nonstructural carbohydrates, and what controls carbon allocation within plants arise (Sheehy et al 1996).

Pablo Picasso used the technique of superimposing images from different vantage points. Here we have two views of a person, a front view and side view. The result produces something novel; it is not just a sterile operation. Picasso's second image takes the same basic idea, but superimposes more detailed images. Again we have a change in perspective, produc-



ing something that is both fascinating and informative. I hope this demonstrates the potential benefits to be gained from a change in perspective. I want to use this technique to challenge some of the ideas held at IRRI in a somewhat dogmatic manner.

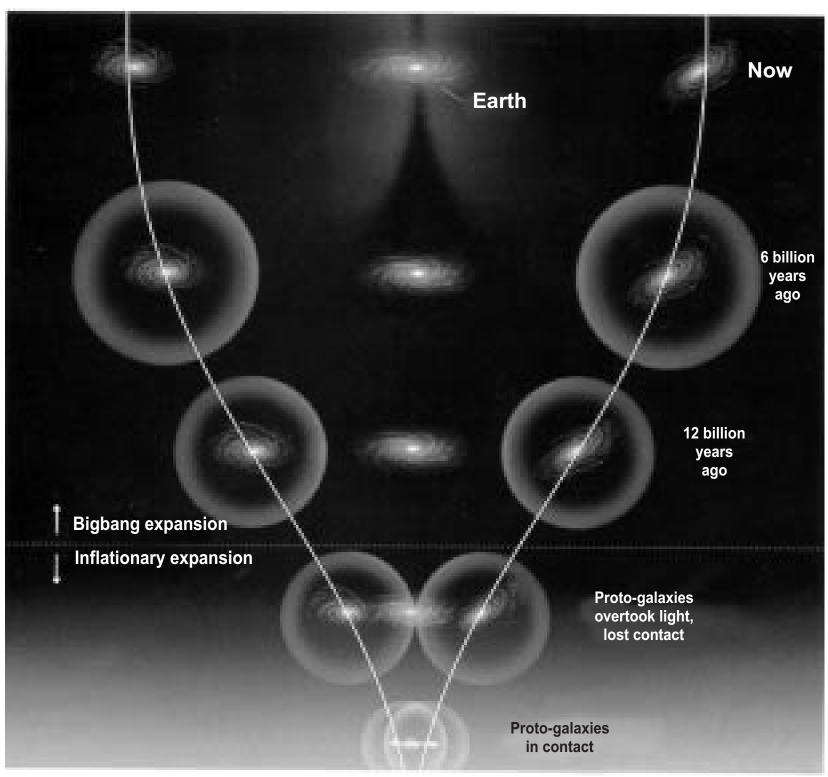
Evolution of science and invention

It is not easy to decide where and when to begin this paper, which has a temporal and spatial context, so I will start at the very beginning.

We can't go back farther than 15,000 million years to the Big Bang (Hawking 1988), which, if physical theories are correct, was the instant in which the universe began. Ultimately, life as we know it stems from the peculiarities of that moment, in which the physics of relationships between matter and energy were shaped.

Our planet Earth aggregated under the influence of gravity and subsequent meteor impacts some 4,000 million years ago. About 3,996 million years later, following three massive extinction of life forms (the last claiming the dinosaurs), our remote ancestors evolved (Fortey 1997).

Stone tools emerged a few million years later, but the style of those tools remained in a state of technical arrest, showing little or no signs of innovation for a million years. The



chronology, in years, of invention is interesting: from simple stone tools 2,000,000 years ago to the transistor 50 years ago (Table 1).

Science began at about the time of the Iron/Writing Age; a mere 3,000 to 4,000 years ago. Science was predated by invention. Modern science was founded by the Greeks (600 BC), who used philosophical principles rather than gods to rationalize the world. After the ancient Greeks, little or no progress was made in science for a thousand years. We may not fully realize it, but the human race seems to have lived in states of arrested progress in science and technology throughout most of its history (Fernández-Armesto 1995). Progress in inventiveness has occurred in discontinuous bursts, but, except for the period following the collapse of the Roman Empire, the pace of change has increased. The interval between major inventions is diminishing, perhaps in part as a result of the increase in the number of scientists. This has created the impression that all problems can be readily solved; as a consequence, the pressure on scientists to achieve breakthroughs has increased alarmingly.

Table 1. The chronology of invention (years ago).

Simple stone tools	2,000,000
Bifaced tools	750,000
Fire	500,000
Burials	100,000
Polished stone tools	50,000
Cave paintings	30,000
Metal (Cu) work	7,000
The wheel	5,000
Iron tools	3,000
Writing	3,000
Science	2,500
Telescope (A.)	400
Electric light	120
Gasoline engine	114
Airplane	96
Transistor	50

The changes resulting from scientific advances have not occurred uniformly. There are still places in the world where people live in a state close to that of our Stone Age ancestors. It is salutary to remind ourselves that ancient crop yields may not have been too dissimilar to those in today's developing world. Wheat yields in 2400 BC in the Tigris valley averaged 1.8 t ha^{-1}, with the maximum values in Babylon estimated at 12 t ha^{-1}. The low yield of many ancient crops probably resulted from the high demand for straw (Sinclair 1998) rather than a poor understanding of how to select high-yielding cultivars, particularly in the Roman Empire. It may also be the case that progress in agriculture has been more discontinuous and much slower.

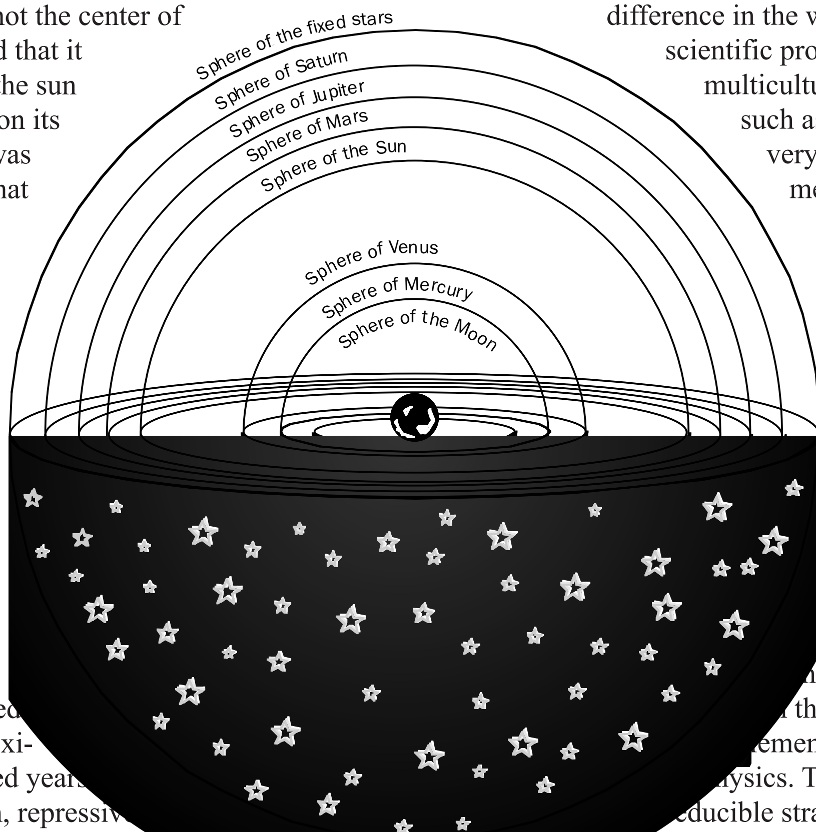
Origins of scientific conflicts between empiricists and rationalists

The collapse of the Roman Empire arrested scientific and technological development in Europe for nearly a thousand years. The flowering of creativity is fostered by economic wealth and historically has occurred simultaneously in the arts, craftsmanship, and science. Significant progress in these fields of human endeavor began again in about AD 1500. The salt cellar (1540), made by Benvenuto Cellini, an Italian from Florence, shows Neptune and Ceres who represent the water and earth. Their legs are intertwined, showing that when you have these two elements coming together salt is formed. The portrait of the French Ambassador to England and his friend, the Bishop of Lavaur, was painted in 1533, at 10:30 a.m. on 11 April. The scientific instruments give the date and time, the books and musical instruments add to the impression of learning associated with power in the Middle Ages. During the Renaissance, an explosion in the arts was accompanied by the freeing of some minds from superstition.

The Greeks had several astronomical theories concerning Earth's position in the heavens with respect to the planets and stars. Ptolemy's theory that Earth was the center of the

universe gained universal acceptance, becoming part of religious belief in the Catholic Church, the religion of medieval Europe. The theory suggested that Earth is the center of the universe and that the planets were suspended on spheres that rotated around Earth. The outer sphere carried all of the stars; beyond that sphere was heaven and beneath the earth was hell.

Copernicus in 1543 concluded that Earth was not the center of the universe and that it rotated around the sun while spinning on its axis. The idea was so outrageous that the Church banned his book. For publicizing the concept, Giordano Bruno (Manchester 1992) was condemned by the Church as a heretic and burned at the stake. Galileo narrowly avoided the same fate approximately a hundred years later. This harsh, repressive climate effectively ended the development of scientific ideas in Italy. The initiative passed to England, where, at the time Galileo was imprisoned, Newton was explaining the mechanism controlling the movement of the planets in terms of a force called gravity. He predicted that the planets moved around the sun on elliptical pathways. The intellectual contribution of Newton is immense and, even though his theory was subsumed into Einstein's theory of general relativity, his equations are still used for most calculations of terrestrial motion.



Newton, the towering scientific genius of his age, believed in empiricism, that is, that one goes from observation to scientific theory. That view was not shared elsewhere in Europe, where Europeans believed that intellectual intuition was the true source of all knowledge. Consequently, a schism developed between British and Continental science, the echoes of which exist even today. The United States inherited the empirical tradition and with hybrid vigor added to the tradition of doing "being seen to do!"

Cultural background can make a big difference in the way we approach scientific problems. In a multicultural organization such as IRRI, this is a very important message.

Physics in the 20th century has moved away from the grasp of the nonspecialist. Since the middle of the century, it has been impossible to be both an experimentalist and a theoretician in the field of elementary particle physics. There is an irreducible strangeness in quantum mechanics, the theory used to describe matter at the subatomic scale. A particle is described as a wave function and its behavior requires a statistical interpretation. There appears to be a duality in nature; in some circumstances, particles behave as waves. There is even an "uncertainty principle" that relates to the fact that the position and momentum of a particle cannot be predicted precisely. The complexity of modern physics has made it remote from public understanding and has probably contributed to a decline in funding for physics toward the end of this century (Weinberg 1988).

Conjectures and refutation—Karl Popper

> **"Erroneous beliefs have an astonishing power to survive, for thousands of years, in defiance of experience, with or without the aid of any conspiracy".**
>
> K. Popper. *Conjectures and refutations: the growth of scientific knowlege.* Routledge, 1989

Karl Popper (1989), the eminent scientific philosopher, analyzed the difference between empiricism and rationalism and suggested that neither view was entirely correct and that all approaches in science are welcome, but must be examined critically. One of the most disturbing statements made during the course of his analysis is worth quoting: "Erroneous beliefs have an astonishing power to survive, for thousands of years, in defiance of experience, with or without the aid of any conspiracy." This is a chilling reminder of our collective responsibilities in ensuring that we do not encourage such erroneous beliefs by promulgating bad science!

Popper states that the belief that we progress in science from observation to theory is wrong. He suggests that we continually try to impose regularities on the world and we try to interpret the world in terms of laws invented by ourselves. In other words, we jump to conclusions and only discard them later if observations show they are wrong. We do not proceed from observation to theory! We progress by making conjectures and refutations, by trial and error. Furthermore, all laws and all theories remain conjectural or hypothetical even when we believe we can doubt them no longer. Data collection is not by itself science nor does it give the collector any special status. We only become a scientist when we translate data into new information. The accumulation of unused databases, "a legacy for others," is a sure sign that the erroneous belief that we progress from data to scientific theory is believed zealously.

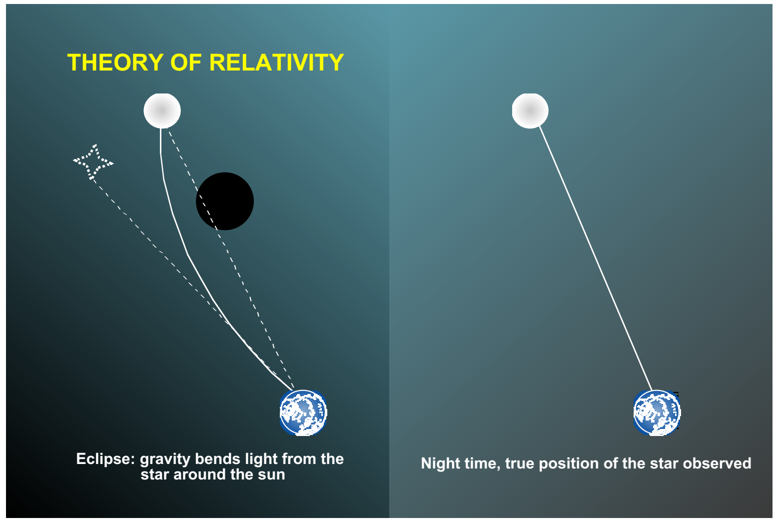
Science and pseudoscience

How do we tell the difference between science and pseudoscience? After all, pseudoscience sometimes gets it right and real science sometimes gets it wrong. The astrologer may predict correctly that you will win a lottery. We know scientists often get it wrong, enough said! Popper says that it is easy to look for verification for every theory if we look for confirmations and he has outlined the guidelines for a genuine test of the difference:

1. Confirmations only count when there is a risk of the theory failing.
2. Good theories prohibit things.
3. A genuine test of a theory is an attempt to falsify it!

You will note that attempts to verify or validate are impermissible as tests.

Popper goes on to say that some genuinely testable theories, when found to be false, are reinterpreted by introducing some ad hoc assumptions. This either destroys or lowers the status of the theory. One of the great experiments in physics confirmed Einstein's theory of relativity. Einstein had predicted that light would be bent by gravitational attraction, a quite astonishing prediction because light does not have any mass. Sir Arthur Stanley Eddington (1882-1944) decided to test the theory, so, during the night, he took a photograph of a star and took another during an eclipse of the sun. The position of the star had apparently moved because the light from the star was being bent by the gravitational attraction of the sun. This confirmed the validity of the theory. If the experiment had failed, physicists would not have said, "Let's recalibrate our model," they would have abandoned the theory.



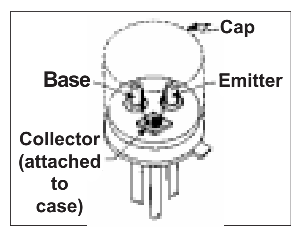
You will note that by definition calibration of models renders them unscientific! The use of tools, which are unscientific, confers on their predictions the reliability of horoscope forecasts based on astrology.

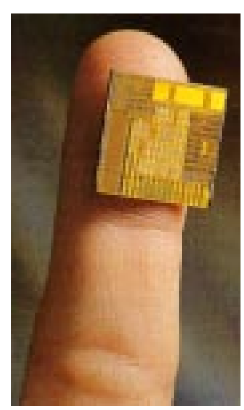
The scientist is therefore a professional doubter who attempts to falsify the theories of others. The almost unconscious forces shaping the perverse nature of scientists begin to reveal themselves. Scientists are doubters; they should doubt everything and accept nothing at face value. (We thus have the making of an individual who is difficult to manage in conventional terms.)

Fabrication of measuring technology

Before 1449, there were approximately 30,000 books in Europe. In 1450, Gutenberg invented moveable metal type and by 1500 there were some nine million books. The information revolution had begun. The growth of native languages was stimulated and the use of Latin as a lingua franca in Europe ended. Five hundred years later (1948), William Schockley invented a device, the transistor, which ranks with the wheel in its impact on human affairs. It has revolutionized not only communications but also almost every machine made in the modern world. Transistors are even implanted in human beings to sustain life (pacemakers) or enhance the ability of people with brain damage to communicate.

When I was a student, in the 1960s, building a portable miniature electrocardiogram, I could get two transistors on the end of my little finger. Today, a wafer-thin silicon chip with an area of 1 cm^2 contains seven million transistors. This astonishing feat of miniaturization has enabled the communication era to take place. The PCs on our desks, the calculators, the mobile phones, and other paraphernalia of modern life use small amounts of power to execute complex tasks.

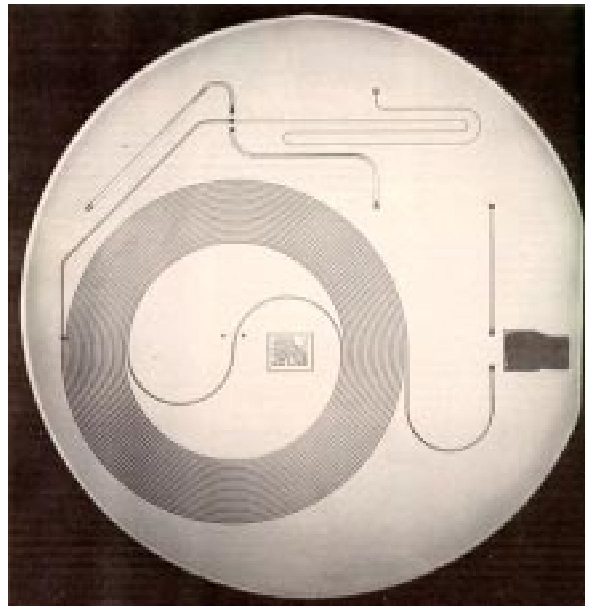




Unlike the printing press, the transistor has emphasized global communications through its role in computer communications (Internet) and emphasized the use of English as a global language.

In 1983, a gas chromatograph with a coil 1.5 m long was built on a 25-cm^2 silicon chip. I think that is an absolutely stunning demonstration of the power of miniaturization techniques applicable to silicon.

I think it is interesting to ask the question, Why do we not have an instruments group at IRRI housing electronics and electromechanical skills? Our inability to fabricate novel apparatuses must say something about the nature of our science. It is vital that we remember that we must not make the measurable important, but rather the important measurable!

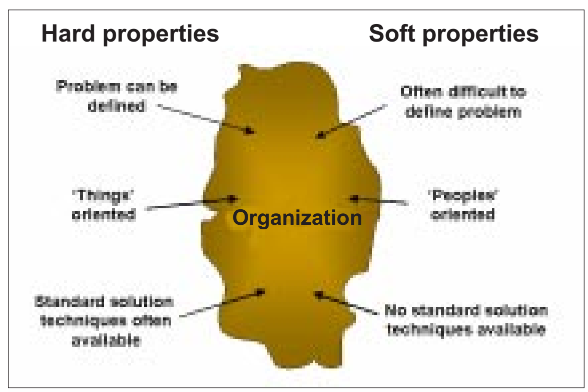


The scientist and the organization

Next, I'm going to consider the scientist as part of an organization. I spent some time outside of publicly funded research, and it is a very, very different world. Perhaps, as a result, I think about the IRRI organization in a somewhat different way than do my fellow scientists. First, let me give you another definition.

An organization is an orderly structure in which people cooperate for a common purpose. The organization has properties (hard and soft), a structure (mechanistic or organic), a mission statement, objectives, plans, and policies.

Scientists in the 20th century are embedded in organizational structures that create microclimates conducive to fostering or limiting their creativity. Usually, they inhabit projects that demand resources. The management system that controls the resource flow has to be sufficiently responsive to enable unexpected peaks in demand to be met. This is best achieved through some significant devolution of power over expenditure. Clearly, it is in this area that individual aspirations and policies often conflict.



If I were a scientist who had never worked in a business school and somebody asked me to draw a diagram of a scientific organization, I would have drawn something like Figure 1. I would put the administration at the top, above the scientific habitat, following the pre-Copernican idea that paradise is upward and hell is

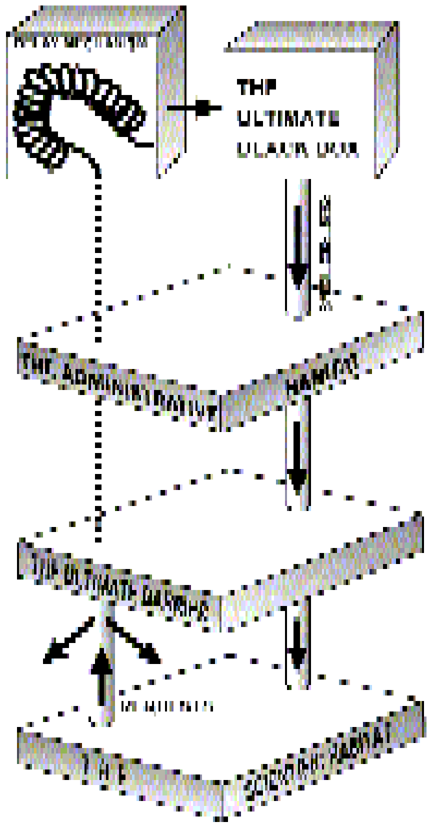
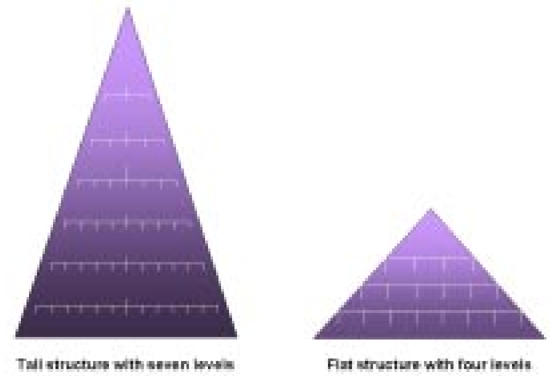
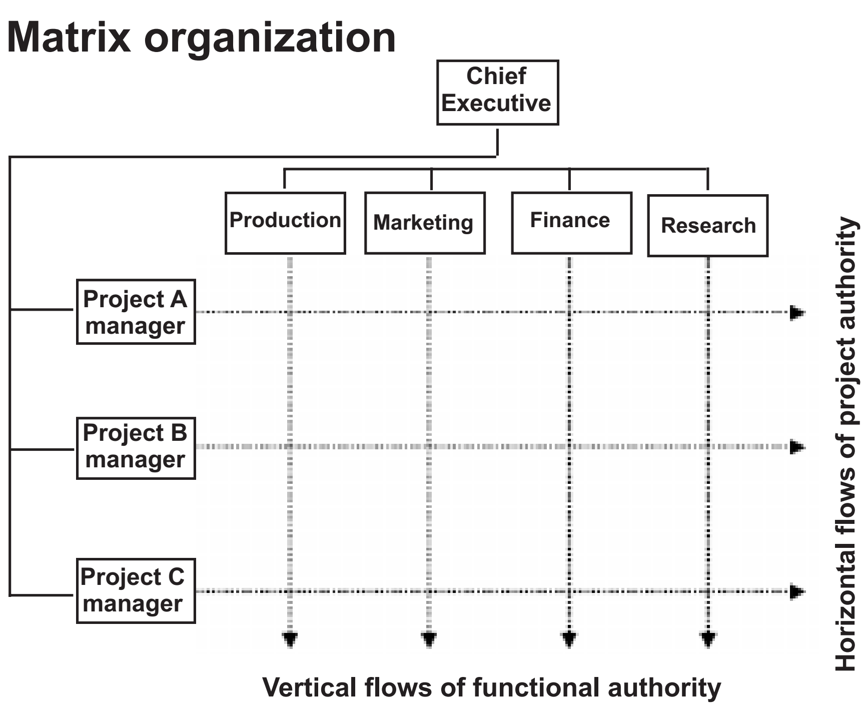


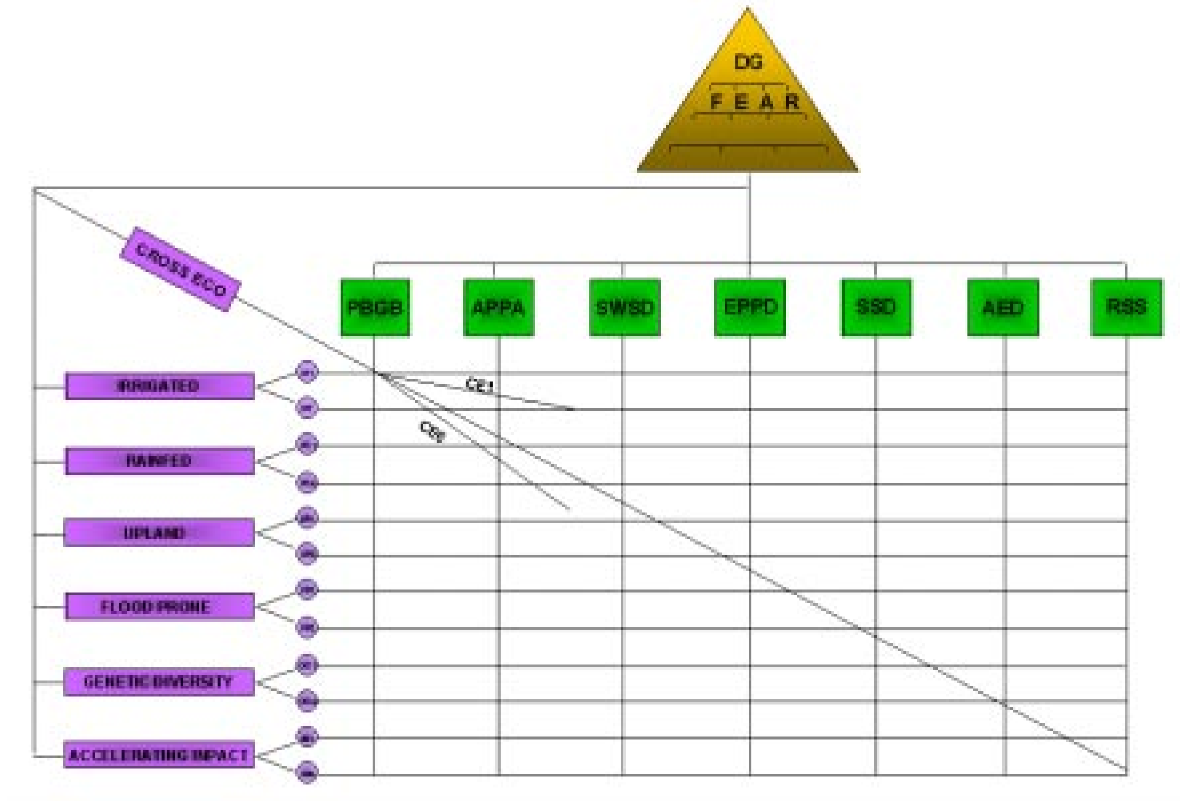
Fig. 1. The administrative habitat.



There are tall organizational structures with many levels contained within them so that the top management is extremely remote from the workers. Other structures are flat, having fewer levels in them. Another not uncommon structure is the matrix, often found in hi-tech organizations. The matrix is really very simple: on top sits the chief executive, along one axis of the structure are the divisions, and along the other are the projects. It is well recognized that conflicts do occur between project managers and division heads. Nonetheless, this interdisciplinary approach increases productivity and helps

below. In this scheme, requests are sent upward, but of course there is a barrier between paradise and Earth, so most requests don't seem to ever get through. The peculiar thing is that, if they do penetrate the barrier, they seem to take a long time to get responded to and the response often emerges as a restriction. Anyway, I happen to believe that's a misguided view of an organization.



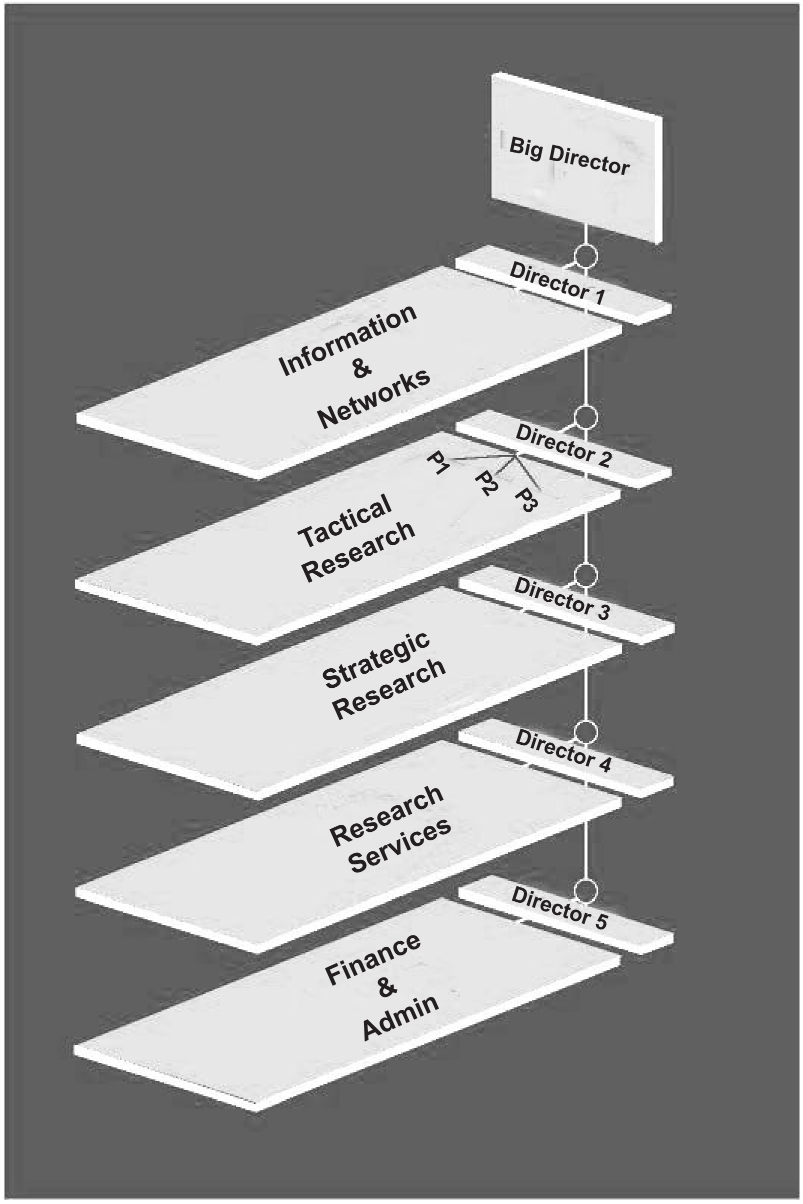


Note: FEAR = finance, external relations, administration, and research, PBGB = plant breeding, genetics, and biochemistry, APPA = agronomy, plant physiology, and agroecology, SWSD = soil and water sciences division, EPPD = entomology and plant pathology division, SSD = social sciences division, AED = agricultural engineering division, RSS = research support services.

solve difficult problems. In a simple matrix, the chief executive has a direct line of communication with the project managers as well as the division heads.

In contrast, the IRRI matrix is some sort of structure with the director general at the apex; below him is FEAR: finance, external relations, administration, and research. The divisions are along the top axis and the programs along the vertical axis. The cross-ecosystems program does not fit in the matrix structure. It crosses both the divisions and the programs and another dimension would be needed to contain it. Furthermore, IRRI has imposed another layer of management—program leaders to manage the project leaders. But even more peculiar than that is the mode of operation. A project leader runs a multi-disciplinary project under the overall guidance of the program leader. But the program leader can be in a project. So, the project leader who used to have the program leader as a boss has now become his boss in the project! A further complication is that the project leader has a division head as another boss, but when the division head joins the project, the project leader becomes his boss. All this change in who is boss when and where does cause confusion and administrative constipation. But I'm sure that it was well intentioned when it was constructed. I think it is unfair for me to be critical without putting forward some other organizational option, which I will do later.

In my opinion, individual creativity is not continuous, it occurs in bursts, often in response to the stimulus of a problem, an economic pressure, or perhaps even vanity. Science is a passion and like all passions sometimes it burns intensely and at other times the flame goes out. The time engaged varies with the intensity of the passion and, for that reason, and others, I do not favor rigid definitions of the work week. I favor flexibility, but I also favor clear, clean, well-

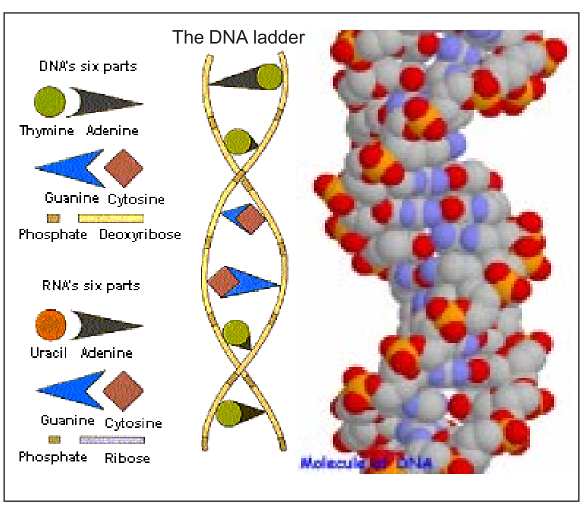


structured guidelines. I recognize the fundamental conflict between the concepts. It is the role of senior management to resolve such conflicts in a pragmatic manner. Nonetheless, there is a dichotomy in attempting to create an environment that fosters creativity through its flexibility and at the same time has a well-defined management structure.

Administrators need to understand that the innate cause of perversity in scientists is linked with good scientific training. Success in science is often the result of serendipity and so is unpredictable. The pace of scientific change means that scientists operate in a highly pressured and competitive environment. In my opinion, the administrative organization needs to be supportive, flexible, responsive, and flat. The IRRI structure, like a modern transistor, should have about five distinct layers: the first containing management and financial services, the second research support services, the third strategic research, the fourth tactical research programs, and the fifth information and networks. Each layer would be headed by a director. We would then have the BD (big director) as the chairperson on a committee of five layer directors.

The difference between repeatable and nonrepeatable science

At the beginning of the 20th century, physics, chemistry, and biology were distinct and different sciences. The ultimate unity of all the sciences at the molecular level has now been recognized. The discovery of the structure of DNA has been as revolutionary as the discovery of planetary motion by Copernicus. The age of the gene, genetic modification, life spans of centuries, and human cloning raise issues every bit as disturbing as the questions raised during the Renaissance. Nevertheless, the significant differences between the sciences at higher levels of integration remain. Experiments in physics, chemistry, and laboratory biology are quantitatively repeatable, those in field agriculture are not. The weather, variable soil resources, and unpredictable variation in pest and disease profiles all ensure that distinguishing between erroneous and valid conclusions is not easy. Nonetheless, we believe that crops behave in a mechanistic manner so that a superior plant character in one crop is likely to be a superior character in another (such as erect leaves) (Fig. 2). High yields necessarily involve harvests of large amounts of nitrogen (Sinclair and Sheehy 1999). My Japanese collaborator Professor Takeshi Horie and others (1997) showed that the number of spikelets per unit ground area is related to plant nitrogen concentration (Horie et al 1997) (Fig. 3). The demand for this nitrogen cannot be met by the roots and so high yields must be funded out of stored nitrogen. This requires a higher leaf area for storage and more erect leaves. Therefore, erect leaves are a necessary adaptation to allow a high leaf area for nitrogen storage.



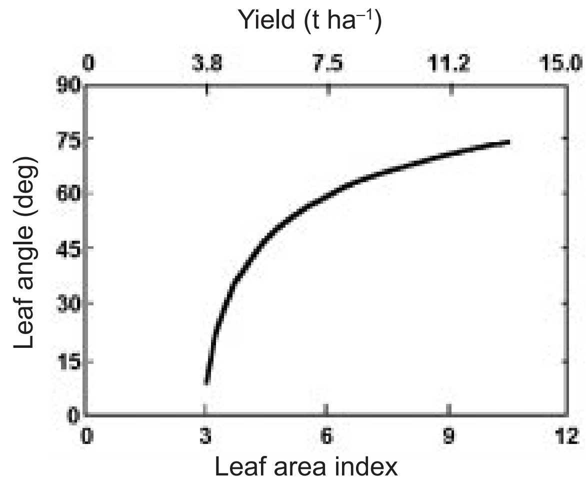


Fig. 2. Relationship between leaf angle and leaf area index in rice.

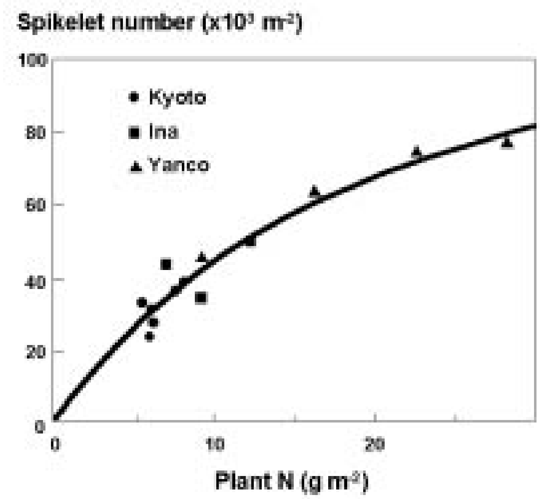
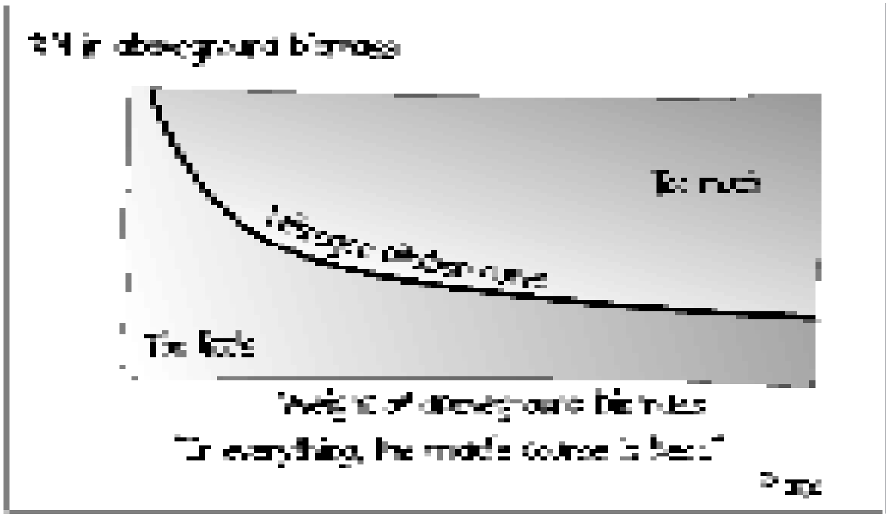


Fig. 3. Number of spikelets per unit area of ground as a function of crop nitrogen content.

A rice problem: a peculiar growth pattern on route to high yields



To meet the demand for food from Asia's rising population, a 40% increase in rice yield is required by 2020. For 30 years in the tropics, however, 10 t ha^{-1} has remained the maximum value, regarded as a thermodynamic yield barrier. Here we show that the yield barrier can be surpassed, given sufficient nitrogen to maintain the critical concentration for metabolic activity, and that these productive crops showed an unusual growth pattern.

At IRRI, Philippines, in the dry season of 1997, crops of the elite indica-type rice cultivar IR72 and current lines of the new plant type (NPT) were transplanted and irrigated in the standard way (Rice Almanac 1997) with weekly applications of nitrogen fertilizer totaling 420 kg ha^{-1}, and with strings across some plots to prevent lodging in IR72. The yields of both IR72 and the NPT were 11.6 t ha^{-1} (at 14% moisture content), a year without tropical storms and consequent lodging. The NPT, which does not lodge, suffered damage from the striped stem borer (moth larva, *Chila suppressalis* (Walker)) during grain filling. The harvest index (grain dry matter as a fraction of aboveground dry matter) was 0.55 for IR72 and 0.40 for the NPT.

Yield is influenced by the time-course of growth, through accumulation, storage, and remobilization of carbohydrate and nitrogen, and by final biomass, through harvest index. In contrast to the usual pattern of a logistic curve exhibited by annual crops, we found an apparent plateau around the time of flowering (Fig. 4, a and b). From the start of flowering, harvests were every two days and it was this frequency of sampling that revealed the plateau. The growth anomaly could be the slowing of growth during flowering, deviation from expected curve A, or very rapid growth afterward, deviation from curve B (Fig. 4a). It is interesting to note that if harvests had been every one or two weeks, as is common, a standard logistic-type curve would have appeared acceptable.

Table 2. Comparison of the actual performance of IR72 and the new plant type, 1997 dry-season experiment.

Cultivar	GY[a] (t ha^{-1})	Straw wt. (t ha^{-1})	Harvest index	Spikelet no. m^{-2}			% filled grain no.	Productive tillers (no. m^{-2})
				Filled	Unfilled	Total		
NPT	11.62 (0.54)	15.51 (0.88)	40 (1)	50,340 (3,280)	28,762 (1,171)	79,102 (4,021)	63.4 (1.4)	305 (12)
IR72	11.63 (0.67)	8.4 (0.33)	55 (1)	44,030 (2,219)	12,949 (1,240)	56,970 (2,984)	77.38 (1.5)	540 (31)

[a]GY = grain yield at 14% moisture content.

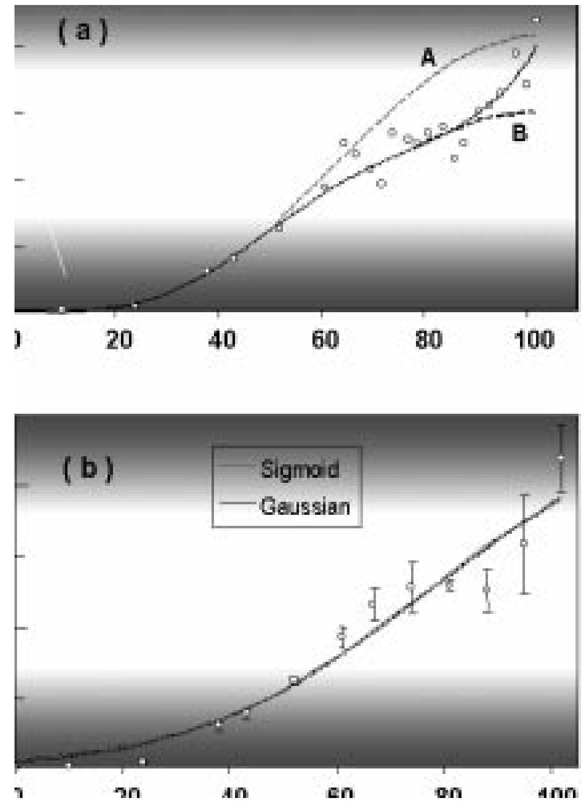


Fig. 4. The growth of aboveground biomass (points) of a rice crop (cultivar IR72) grown in the dry season at IRRI, Philippines: (a) the solid line is the growth curve backtransformed from a cubic polynomial, chosen for parsimony and interpretability of the coefficients, fitted to the natural logarithm of biomass to make variances more homogeneous. The broken lines A and B are logistic curves; (b) logistic curves fitted to the same basic data set as in (a), selecting one data point at weekly intervals.

Several doubts arise:

1. Is there an artifact in the yield vs time data?
2. Does the artifact result from an unusual form of sampling error?
3. Is there a genuine slowing down of growth?
4. Is that slowing due to photosynthesis or respiration, or both?
5. Are diseases and pests exerting a strong downward pressure during flowering?
6. Are the primary rate processes big enough to power growth rates observed?
7. Should we fit the simplest curve or the best within reason?

I can think of no reason why a sampling error should occur only during flowering or why the same pattern is observed in two cultivars. I think we can dismiss (1) and (2). The curve-fitting procedure, however performed, indicates that there are changes in growth rate; in response to (3), the data suggest a genuine slowing down of growth. I find it astonishing that we do not have the data required to answer the question posed in (4). Measurements have been made, but they are patchy and many have systematic errors. A gap in knowledge exists. The issue of pests and diseases raised in (5) is difficult to quantify; the damage we observed continued until harvest. There did not appear to be a spontaneous recovery in any damaged materials and issues of compensation do not arise at this late stage of growth. The answer to the question raised in (6) is "probably," but we need measurements to confirm that the rates are sufficiently large and sustainable until maturity. There is no simple answer to (7). The best fit that passes through all points is nonsense and so the curve chosen can become a matter of judgment unless we choose the simplest plausible curve, in this case a cubic.

Changes in incident solar radiation and the fraction intercepted by the crops from the start of flowering were too small and inconsistent to account for the slowing of growth.

Other possible explanations for slow growth (movement of dry matter between roots and shoots, loss of weight as shed pollen, loss of weight from decay of dead plant matter) do not seem able to account for the size of the phenomenon. Increased respiration or decreased photosynthesis, or both, could cause the slowing of growth. Extra respiratory costs may be associated with transferring stored carbohydrate and nitrogen from leaves and stems to the filling grain. Photosynthesis may be decreased by an abundance of soluble carbohydrate when vegetative growth has ceased and grains to be filled are becoming available only gradually. If the results are interpreted as a marked upswing in growth after flowering, an alternative explanation is required.

The critical nitrogen management imposed enabled these crops to sustain two or three live leaves per tiller through to final harvest, a time when most leaves are usually dead. Consequently, during grain filling, we calculate (using the model Oryza1) that photosynthesis declines by only about 50%, whereas it is reported that respiration decreases ninefold over the same period. The difference between the rates of the two processes would provide the resources for the late surge in growth. Further experiments are required to establish whether such unusual patterns of growth are commonplace in high-nitrogen conditions. However, given the variability of weather and pests from year to year, further ambiguity may be expected.

We can be optimistic about raising rice yields now that the 10 t ha^{-1} yield barrier has been breached. Our inability to explain the anomalous growth pattern suggests that we do not yet have a complete understanding of the physiology of high-yielding crops and that further progress will be aided by that better understanding.

Finale

It is curious to reflect on the fact that much of our science is based on trying to explain in a rational way what we see or sense around us, yet our evolution seems to be rooted firmly in chance. Furthermore, scientific progress has been intermittent and society can lose interest in technical progress. Nonetheless, the pace of change has increased and, because of that, we live in an uncomfortable world, using value sets derived before the era of biotechnology. Moral dilemmas abound. To prosper, we have to make sure that our science is always relevant, explicable, and appealing to ordinary people if funding, one measure of acceptability, is to continue. We should be confident that the pursuit of higher yields, through environmentally sustainable methods, by multidisciplinary teams is both a valid and noble goal.

I would like to end by quoting a few lines concerning the 21st century from the book *Millennium* by Felipe Fernández Armesto (1995). "Our descendents will see population increase level off to a point where it can be handled by advances in agronomy which—under the pressure of population growth and the need to exploit new and previously under-used environments—will replace medicine in the next century as the life-saving wonder science of the world."

Illustrations

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Glossary

Data are facts, events, transactions, measured quantities and so forth.

Information is data that have been processed in such a way as to be meaningful to the person who receives the information.

Science is the collective and cumulative attempt to understand the natural universe.

History is a creative art, best produced with an imagination disciplined by knowledge and respect for the sources.

Theory is a model containing a set of rules used to explain observations.

Organization is an orderly structure in which people cooperate for a common purpose.

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