4 System thinking in agriculture: an overview

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Chapter 4 in: System Thinking in Agriculture an overview. Chapter 4 in Emerging Challenges for farming systems - lessons from Australian and Dutch agriculture; edited by Ken Rickert. Rural Industries Research and Development Corporation. P.O.Box 4776, Kingston Act 2604.

A sufficiently vast and considerable intellect, knowing the complete laws of microscopic physics and the physical state of the universe at any moment, could calculate the state of the universe at all subsequent times; all prior ones, too, if the laws are reversible. (Laplace, Essai philosophique sur les probabilités, 1814)

Step by step, there lies waiting, quite perfect, what is needed for that step (Indian wisdom, quoted by Auerbach, 1999);

A reference to Aristotle and Leibniz has long ceased to be required in serious books. But […] several basic ideas of fractals might be viewed as mathematical and scientific implementations of loose but potent notions that date back to Aristotle and Leibniz, permeate our culture, and affect even those who think they are not subject to philosophical influences. (Mandelbrot, 2000).

The road emerges as we are walking (a line from a Spanish poem by Antonio Machado)

'Maturity is the ability to hold on to different world views, preferably conflicting, at the same time.' (C. West Churchman quoted by Richard Bawden)

'Newton separated light into parts [different colours] while Goethe was interested to see what happened when parts [different colours] were joined together' (Brian Goodwin, pers. comm., 2000).

Abstract

Agricultural developments in the 20th century are characterised by impressive yield increases. In spite of its successes, however, agriculture's image has also become marred by issues such as unequal distribution of food and income, large-scale social change and concerns about pollution and/or exhaustion of natural resources. Can agriculture continue to feed the world, and if so, in which way? All these issues relate to similar developments and concerns in other sectors of society and in our opinion system thinking provides concepts and tools for the analysis and design of such developments. System thinking is considered here as an informal kind of system theory that can also use emerging and as yet immature concepts to explore the behaviour of the world in which we live. System thinking may take many different forms and can help to explore questions regarding the future of farming, to the extent that agricultural systems represent a special case of systems in general. Much can also be learned by combining insights from agriculture with those from other disciplines, such as mathematics, physics and psychology. Such combinations should even allow for the bridging of traditional – but man-made – divisions. Therefore, this chapter outlines different forms of system thinking. It discusses aspects of reductionist and holistic approaches, static and dynamic thought, as well as the so-called control versus

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participation paradigm. We think that these extremes span 'reality', and we therefore opt for a combination of approaches rather than for one or the other. This is the central issue of this chapter, i.e. the need to integrate insights from different disciplines, from thinking focussed on matter to thinking focussed on mind, from arts to sciences. By doing so, it aims to show that concepts from psychology, ecology and physics, such as perception, coping strategies, predator-prey relations and thermodynamic theory, can clarify discussions about agricultural development. It also aims to show that man is part of nature, that 'he' is a participant that has to make choices rather than a neutral observer who can control nature for a single-minded anthropocentric goal. The last part of this chapter is therefore dedicated to the discussion of generalised forms of system behaviour and their application in daily life, based on thermodynamic theory.

Introduction

Agricultural development of the past century tends to be characterised by impressive production increases through increased use of land, fossil resources, labour, and technological innovations or farmers' ingenuity (Chapters 1 and 2). The achievements, however, are marred by negative trade-offs that seem to be intimately linked to so-called progress. Examples of emerging concerns in this respect are unequal distribution of food and income at local, regional and global levels, declining bio-diversity, dwindling water reserves, and side-effects from using biotechnology etc. Some authors maintain a rosy or cornucopian view of the options for agriculture, others are more conservationist, while an intermediate group takes a balanced but necessarily ambiguous view. The divergence of opinion is confusing in itself, but matters are made even more complex due to the fact that changes in agriculture cannot be understood in isolation, they are inextricably linked to other developments in society.

System theory provides concepts and tools to better understand complex developments in agriculture and society, because farming systems are just one type of system in general. The terms *'system theory'* and *'system thinking'* both refer to an activity that is as old as mankind and that knows many traditions. We mostly use the term 'thinking' because it permits the use of valuable ideas that are not (yet) formalised. Understanding the different traditions in system thinking can clarify the origin of present practices and policies in agriculture; it can even have therapeutic value in showing the roots of 'hang-ups' in modern thought, and it can help to establish choices for the future. This chapter, therefore, outlines a few major traditions in western system thinking and ventures into their significance for the 21st century. In doing so we address three major issues:

- *Uncertainty and changing conditions.* Three key concepts in this respect are *context, relations and non-linearity*. Context is a general term for the management environment outlined in Chapter 1. It implies that what is 'good' or true in one place may be 'bad' or untrue elsewhere. For example, fossil fuels or agro-chemicals may be useful in one place but counterproductive in other systems. The existence of relations implies that an action in one place may trigger unexpected effects elsewhere. For example, the introduction of pesticides can result in trade-offs that cause consumers to switch to other products. Non-linearity refers to the phenomenon that trends cannot be extrapolated linearly, and that too little as well as too much of any given intervention or activity may not be good (Odum, 1975).
- *The link between matter and mind.* Bridging traditional divides, such as exist between thinking in terms of *matter* and *mind*, is in our view essential for a future that is worth living. Much thinking about agriculture focuses on biophysical entities (matter) that can be quantified, thus leaving qualitative, intangible and psychological (mind) effects exclusively to considerations of society and politics. At the same time, many socially oriented disciplines have difficulty in understanding and/or accepting the importance of physical laws. In this chapter we continue to use the distinction between matter and mind to make sure that both aspects are considered; not to imply that they are separable in some strict sense.

- *Enabling discussion.* Concepts pertaining to system behaviour provide a basis for discussing the future of agriculture, exploring uncertainty and variation in systems, linking cornucopian and conservationist thought, and for reassessing basic notions in our thinking.

This chapter first reviews ancient traditions in system thinking. It subsequently distinguishes modern schools of system thought, here categorised as hard-, soft- and complex system thinking, respectively HSM, SSM and CSM. (the 'M' in this acronym stands for 'methodology'). It also makes a distinction between approaches, thinking, and methodology, because thinking about approaches necessarily precedes choice of method. Brief reference is made to farming systems research across the globe. We discuss the relation between complexity, inevitable trade-offs and the strange mixture of uncertainty and repetition of form. Finally, a discussion of system dynamics contrasts rather static thinking about farming systems with evolutionary approaches. It thus connects major themes of modern and ancient system thinking by relating several forms of system behaviour, like co-evolution, lock-in and predator-prey relations to aspects of agricultural development. Whilst a few of these behaviours are known in one way or another, the section on ancient system thinking shows that new concepts tend to be initially accepted for their instrumental value, and only later lead to a paradigmatic shift in thinking if at all. Useful background reading is found in Bertalanffy (1968), Stakman *et al.* (1967), Prigogine & Stengers (1985), Gleick (1987), Cohen & Stewart (1994), Klir (1991), Ison & Russell (1999), Conway (1987) Capra (1997), Röling (1996), Checkland (1999), Jackson (2000) and Collinson (2000).

Ancient system thinking and uncertainty

Western system thinking can trace its origins to the days before the ancient Greeks and today still tends to repeat arguments resembling those of millennia ago. For example, a major rift in modern thought occurs between traditions that think in terms of steady states (equilibrium, *ceteris paribus*), clockwork notions and 'hard' facts on the one hand, and traditions that assume 'fluidity' and uncertainty (non-equilibrium, *ceteris imparibus*) on the other. The first tradition sets fixed targets and tends to aim for 'final' solutions. In this school of thought, an irrigation scheme, a new cultivar or biotechnology will, once and for all, solve the world food problem: *'the war against hunger must be won'* (Stakman *et al.*, 1967). The latter tradition thinks in fluid terms of change, combining several perceptions of reality, and it accepts change by adaptive management. This approach reflects the notion of the ancient Greek philosopher Heraclitus who said *'nothing is permanent'*. This view contrasted with that of the Pythagoreans, who attempted to perceive everything in terms of geometry. Much to their dismay the latter discovered that the value of π ('pi') could not be calculated numerically, a shock that resembles the difficulty of today's paradigm-shift: away from clockwork-certainty towards uncertainty; from control to participation[5]. Some centuries later, the early church 'controlled' uncertainty for at least a millennium by proposing dogmas as a form of 'unquestioned authority'. This approach was challenged during the Renaissance by people who valued empirical observation over church authority, a challenge reminiscent of the one today by postmodernists to traditional science (Funtowitz and Ravets, 1994). It was a time when Galileo and Copernicus proposed a heliocentric model of the solar system, an idea already expressed by early Greeks such as Aristarchus. It allowed for the use of much simpler methods to understand planetary behaviour. But at that time this was a notion that ran counter to established dogma. Furthermore, Kepler's suggestion to use ellipses challenged the religious 'certainty' that planets represented some kind of deity, which by virtue of this nature should follow circles as indicative of their perfect form. It was one thing to 'instrumentally' use these formulas to more easily explain the motion of the planets, it was something else altogether to suggest that they implied a paradigm shift, i.e. that they should affect our thinking about the nature of the universe.

A major contribution of Descartes to the intellectual discourse concerning 'reality' and uncertainty was to revive ancient notions of reason as a complement to the inadequacy of observation alone. As a father

[5] The terms "control" or "participation" is taken from Brian Goodwin (pers. comm., 1999)

of modern reductionism he also rekindled a hard duality: the unequivocal separation of matter (*res extans*) and mind (*res cogitans*). This distinction helped to cope with uncertainty, thus providing a useful conceptual tool in a time of much mysticism and little critical observation. Unfortunately, this separation of mind and matter has almost become an article of faith that is hard to shed. Today there may be too much emphasis on matter and too little on mind in thought on agriculture, although some biophysical thinkers tend to attribute to their socio-economic counterparts an excessive preoccupation with mind.

Descartes was followed by Newton, who developed formulas that explained what Leibniz described as the 'clockwork' universe, in which everything is predictable i.e. where 'certainty' rules, where 'control' is possible, and where one knows 'what happens in one place if one presses a lever in another place'. However, Newton was more proud to have discovered similarity between the microcosm of the falling apple and the macrocosms of planets. He was not primarily interested in the 'clockwork' aspect of the universe. Perhaps his interest in this respect was more incidental, and more in the repetition of form sense that is called fractal behaviour and discussed later in this chapter (Box 4.1.). Newton's writings became the prototype for scientific reasoning and his axioms nourished Laplace's fantasy about the omniscient scientist: *a 'daemon' knowing the laws of nature and the position and velocity of every particle in the universe at an instant, could predict and retrodict the detailed character of the world at any moment of time.* The 18th century astronomer's mind is an approximation of Laplace's daemon, and much of today's 'mechanistic' analysis and design of farming systems reflects that thought. Translated into today's reality it means, for example, that knowledge about DNA can secure 'food for all', or that diseases can be prevented by knowing a causative germ. Importantly, however, Newton could only calculate the orbits of two bodies, and not of three or more interacting bodies where complex 'relations' confused the regularity of the clockwork universe. Uncertainty was not overcome by Newton: he 'shelved' it, and his deliberate simplification of nature was forgotten by his followers.

Indeed, Newton's followers took the 'two body' simplification as an article of faith, just as the dispute about uncertainty between Einstein and Bohr, some two centuries later, was essentially an argument about faith. Bohr accepted uncertainty as a physical phenomenon, while Einstein tried to further understand the 'logic' of God's thinking. He could not accept that God worked with chance, 'that God played dice', even though he accepted the uncertainty-relationship established by Heisenberg[6] for its instrumental value. These arguments reflect the difficulty of the church with Galileo's heliocentric world-view and Kepler's ellipses. Cardinal Bellerminy could accept the formulas of Kepler and Galileo as 'instruments', as long as they were not meant to define a world-view, or to affect the existing paradigm. Does it also perhaps reflect today's difficulty on the part of mechanistic thinkers in current 'science' to accept that simple predator-prey models have more than merely instrumental value for agricultural development. Do they have a 'religious' difficulty in accepting that 'man' is part of nature rather than 'in charge' of nature? Where does modern thinking on agricultural development position itself, and how does our choice of method and paradigm affect the outcome of our analysis and prediction? Do we continue to look for certainty of measurement, or do we accept uncertainty and the need for participation?

Since the 1960s the notion of uncertainty has acquired a much more prominent place in system thinking (Klir, 1991). A further breakthrough in thought involving uncertainty of physical systems came with the advent of computers and new insights from thermodynamic theory. And it was also recognised by the founders of SSM in organisations, companies and communities, i.e., situations where humans play a central role (Prigogine and Stengers, 1985; Gleick, 1987; Checkland, 1999). The existence of uncertainty in both social and physical systems is hardly surprising if one remembers that the mind-matter distinction is man-made, and that it has led to a situation where so-called 'sciences' and 'arts' seem to have lost the capacity to communicate. For some one hundred years now, the time span covered by this book with respect to agricultural developments, the concepts of relativity and quantum physics

[6] It states that one cannot know both the place and the velocity of an electron simultaneously.

have exerted their influence on the science of the very big and the very small. Now complexity has started to influence modern system thinking in and around agriculture, but the debate on uncertainty and on the validity of former distinctions is yet to show its full impact. Concerns about climate change, recent outbreaks of BSE, foot-and-mouth disease, SARS, Avian influenza, political change and the threat of war, computer viruses, scepticism with regard to globalisation, etc. demonstrate only too well that 'one can expect unexpected things to happen', and that values and paradigms can undergo sudden and dramatic change. We appear to have returned to the days of Heraclites, who stressed fluidity in systems, in the days of Plato who talked of reflections of a real truth, and in the days of Aristotle, who looked for patterns and drives behind systems. The challenge is to use these concepts beyond their instrumental value alone, and to let them have an impact on our global view of agricultural development in the 21st century.

Modern system thinking in agriculture

Modern system thinking concerning agriculture exists in different forms, which we here classify into hard-, soft- and complex methodologies (HSM, SSM and CSM)[7]. Together they span the space between *systematic* approaches on the one hand and *systemic* approaches on the other. A *systematic* approach emphasises objective measurements, quantification, reductionist thinking and mechanistic synthesis. In other words, and metaphorically speaking, the observer does not affect the 'clockwork', but 'he' knows what happens anywhere if one part of the system is changed. In this approach, parts can be studied in isolation and they can be engineered to 'control' the future. The work on DNA to understand the maize plant's effect on a farmer's income is a case of mechanistic thought that resembles the simplification of Newton's two-body problem. Basically, nothing is wrong with such thinking unless it pretends to explain everything. A *systemic* approach assumes that the observer is part of the system through the choice of parameters and methods made. It stresses change in and around a system, as well as the need to include qualitative aspects of the mind in addition to 'hard facts' about matter. Indeed, systemic approaches stress that, for example, the direction of agricultural development depends on whether the researcher chooses to include non-physical aspects of farming and/or different perceptions about reality, e.g. those of agro-industry, politicians or organic farmers. To state that choices about method affect the outcome sounds like self-evident common sense, but it was precisely the notion that Einstein refused to accept in Bohr's theories, other than for instrumental value.

One form of research on agricultural development is called farming systems research (FSR). It originated in the late 1960s and early 1970s from work on the so-called Green Revolution, because results from laboratory settings and experimental fields were manifestly not applicable in variable contexts, unless the field conditions could be 'controlled' in terms of availability of water, new seeds, chemicals and standard farming methods. Another reason for the emergence of FSR was that many technologies were showing unexpected trade-offs due to operative relations both within and among systems: a reflection of the three-body problem. The investment in FSR is impressive. It uses aspects of HSM, SSM and CSM, and encompasses approaches applicable to both tropical and temperate conditions (Conway & Barbier, 1990; Collinson, 2000). For the purposes of this book, however, we only elaborate on the characterisation of thought and paradigms in HSM, SSM and CSM while staying away from the more practical and very useful procedures of FSR.

Hard system methodology (HSM)

The initial HSM work in agriculture followed upon experiences from engineering and was characterised by an approach expressed by De Wit in his inaugural address as:

[7] Like other classifications, this distinction between HSM, SSM and CSM is man-made and of limited value, but is deemed useful for the discussions contained in this book. Many other classifications are possible; the International Society of System Science has some 30 special interest groups, each representing a different orientation in system thinking.

'...the development of models of agricultural systems (or of biological systems in general) has to follow a heuristic approach that requires testing at two levels, i.e. the explanatory level, where relations should be in accordance with observed phenomena at process level, and at the explainable level, where model results should be in accordance with observed phenomena at system level' (De Wit, 1968).
This mechanistic approach was especially useful in Western agriculture where farmers operated highly controlled production systems and where uncertainty was externalised through the use of external inputs. The approach also appeared useful in identifying technical constraints in the agriculture of the developing world, but the focus of much agricultural research was on the relative certainty of issues concerning matter. As said by pioneers of the green revolution in Mexico: *'we are concerned about and aware of the complexities of social evolution, but [...] we have restricted our discussions to subjects [of matter] that we have studied intensively for many years'*. (Stakman *et al*., 1967). Much valuable work in this field was done in Europe, the US and Australia by scientists like C.T. de Wit, C.R.W. Spedding, L.T. Evans and R.S. Loomis (see Rabbinge *et al.*, 1990; Spedding, 1990; Evans, 1998 and Loomis *et al*., 1976).

Almost from the start, criticism was voiced concerning the 'technocratic' basis of this HSM and its neglect of the 'human factor'. Indeed, in different parts of the world, and in many different disciplines, the need for a 'different' approach became increasingly clear (cf. Checkland, 1981; Chambers *et al.*, 1989). In spite of these criticisms, however, it is to the credit of HSM that the world has seen two- to three-fold increases in yields per unit area or per animal, in both tropical and temperate climates. The sense of achievement and 'control' by HSM workers was expressed at the 75th anniversary of the American Society of Agronomy by one of its former presidents:
'The foundation for much of the progress in agriculture [...] has been laid by crop and soil scientists. [...] The cultural practices, farming systems, fertilisers and other chemical inputs used in modern agriculture are creations of your hands' (Brady, 1983).

The HSM thinking behind these yield increases was based on reductionism, emphasis on aspects of matter and visions of a mechanistic clockwork universe. They define a system rather statically as being:
a unit with well defined boundaries and a well-defined goal that consists of interdependent parts that transforms inputs into outputs (Figure 4.1).

By implicitly focussing on 'useful' and measurable outputs, the HSM tends to ignore the 'mind' aspects and the effects of 'waste'. Also, by 'freezing' a system into well-defined boundaries, it tends to overlook variability and changes in time and space. It ignores a definition whereby a system is:
a way of doing things, an established procedure (Longman, 1985).

Hereafter, the 'static' definition refers to the structure of a system (we use the term 'form' throughout this book). The static approach is also used by HSM to consider other typical "system" notions like hierarchy, parts and boundaries (Box 4.1). Those notions are valid in all forms of system thinking, but they are only applied in a rigid way in HSM. The 'dynamic' definitions refer to dynamic aspects of system behaviour over time (called 'processes' in this book). We often refer to the forms and processes of systems, and also to their combination that we refer to as the *mode*. Both form and process are inseparable aspects of system behaviour, but a terminological distinction is retained in order to ensure that neither aspect is forgotten, similar to the distinction between mind and matter mentioned previously. Mode changes occur when form and/or process experience inordinate stress.

The static view of systems deliberately reduces interactions between the system and its context (surroundings) while focusing on measurable 'matter' entities, often embracing only the short term. It echoes Galileo's emphasis on the need to 'measure', from the time that mysticism and dogma's ruled. In its extreme form, the system's description and boundary definition by HSM occurs in such a way as to construe the system as being affected by its context while the system itself does not affect the context. In doing so, HSM marginalizes uncertainty, an approach that is known in classical economics as *ceteris paribus* (everything else remains the same), and in Newtonian physics as the *'two body'* simplification. This approach may be convenient and at times useful, but it erroneously assumes that a small effect is no effect, an assumption challenged by the 'butterfly' effect described in the section on CSM. Thus, HSM tends to conceive of a system as a temporary frame taken out of a sequence of events. It might, for example, state that 1 kg of nitrogen from an external source yields 20-30 kg of grain, without paying attention to the long term side-effects of that nitrogen in terms of matter (groundwater enrichment) and/or mind (farmer's income and social position). Typically, HSM does not specialise in the prediction of trade-offs, such as emerging and inherent inequity between wealthy and less well-to-do farmers, increased risk associated with continuous mono-cropping, environmental impacts of using large quantities of chemical inputs, or decreasing efficiency of input use at high input levels.

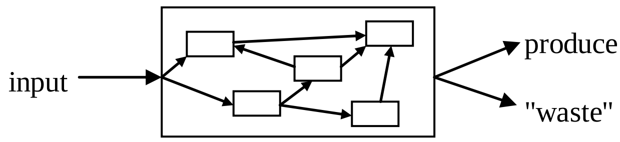


Figure 4.1.A system as a unit, in this case an animal with input in the form of feed, fertiliser, etc., with output in the form of 'produce' such as milk, meat, eggs, draught, and with 'waste' such as dung, urine and heat. Particularly the long-term effects of waste were for a long time neglected in the reductionist tradition of HSM.

Eventually HSM developed tools to address its own deficiencies, such as the analysis of system behaviour at different spatial scales from farm household level upward (Box 4.1), and the effects of different objectives and their trade-offs. Interactive Multiple Goal Linear Programming models are typical examples of a HSM approach, which attempts to introduce the effects of bio-physical factors and economic considerations in terms of technical relationships (Table 4.1). They explore trade-offs and the scope for development at farm and regional level, but any conflict between different optimal solutions, such as in Table 4.1, is left for society at large to resolve (Van de Ven, 1996; De Wit *et al.*, 1988; Vereijken, 1997; Rabbinge and Van Diepen, 2000; Van Ittersum *et al.*, 1998). Thus the usefulness of these approaches is continually criticised. Uncertainty about the perceptions of various stakeholders and policy changes undermine the validity of the HSM emphasis on 'objective' measurement and mechanistic relations. Both, SSM and CSM offer opportunities to understand system behaviour beyond quantities, mechanistic relations, and aspects of matter alone.

Soft system methodology (SSM)

The variety existing in the perceptions and 'goals' of stakeholders in different sectors and at different levels of modern agriculture was basically sidelined in HSM, just as Newton's followers shelved the three-body problem. However, this variation was encountered elsewhere at the start of the Green Revolution, and also workers like Checkland (1981) found that existing assumptions of objectivity and certainty in system analysis and in the design of commercial companies simply did not hold. They coined the term 'soft system', a somewhat unfortunate choice because it might be interpreted as suggesting that soft interpretations are to be taken less seriously than those of HSM. SSM stressed the point that employees or farmers have different perceptions of their own situation relative to those of directors or policy makers. Moreover, the perceptions of both groups may change over time, for example due to the effect of observers that come with questionnaires designed for policy makers, or due to changing policies, prices and even jealous neighbours. Climate change, outbreaks of disease in animals and humans, or events like those of the twin tower attack in September 2001 are only a few of the many other 'incidents' that have changed public opinion and personal goals in the past few years.

Table 4.1. The best extreme values of six goals optimised (bold) in the columns and the associated values of other goal variables in the rows, all per hectare per year, for the experimental dairy farm 'De Marke' in the Netherlands (Van De Ven, 1996). Note that the optimum for one criterion does not tend to coincide with the optimum for another criterion, a notion elaborated among others in Box 4.1.

Goal	Milk prod. (≥ 12000 kg)	Lab. inc. Dfl	NO_3 (kg N; ≤ 34)	NH_3 (kg N; ≤ 30)	P surplus (kg P; ≤ 0.5)	N surplus kg N
Milk prod.	**17660**	3700	34	30	0.5	225
Labour income	15350	**4380**	34	30	0.5	269
$NO_{3\ \text{leaching}}$	12000	1650	**13**	22	0.5	165
$NH_{3\ \text{volatilisation}}$	12000	2145	34	**17**	0.5	160
Total P surplus	15180	4210	34	30	**0.0**	269
Total N surplus	12000	1120	24	20	0.5	**94**

Box 4.1. Hierarchy, common versus individual interest, and fractals

Individual systems do not exist in isolation from each other. They interact and together form larger systems in a hierarchy where boundaries are hard to define or even non-existent. For example, several cells (made up of organelles) make one organ (root system, kidney, brains). The organs together make a larger system (plant, animal, man), they together make farms, village communities, regions, etc. Each of these levels can be considered as a 'separate' system, i.e. it is always important to state at which level one is working (organelle level, organ level, and so on to national level and beyond). Cells themselves are infinitely complex, but their complexity simplifies itself as one moves one level higher in the hierarchy where one considers a cell without 'losing the wood for the trees' in the details of interaction at individual cell level. This also implies that for a larger system to function, one needs to accept that the lower level systems adjust themselves towards the larger whole, but that the reverse is also true! Farmers tend to be interested in plot, herd and whole farm yield, not so much in the specific individual yield of a plant, animal or other component. Governments tend to be interested in the 'common' well-being or gross national product of a region, if necessary at the expense of certain individuals.

Not only does the complexity of systems at lower levels simplify itself at higher (and lower!) levels. Systems also tend to repeat behaviour at different levels of space and time. This aspect of repetition is reflected in the notion of fractals. For example, measuring the length of a coastline appears to be easy if one has a given 'yardstick' that overlooks irregularities like rocks. However, with a finer 'yardstick' one encounters new complexities, such as how to factor cracks and irregularities in rocks into the measuring process. This metaphor was developed by the mathematician Richardson in the early 20th century. It was revived by Mandelbrot in his 'discovery' of fractals, mathematical reflections of real life phenomena where systems at several levels of space and time repeat similar behaviours. For example, irregular feed intake in animals over the day is matched by irregular feed intake over weeks, seasons, years, countries; irregular energy fluxes and nutrient supply in plants, or farms and regions show similar patterns. In the same way, one can better understand the principles of mixed farming by learning from similar processes at cell level, plot level or international level. A paradigm shift is implied by the realisation that system behaviours tend to repeat themselves whether 'we' are cell, 'man' or rabbit and fox populations. All of a sudden we are part of nature, not above it, in spite of the special responsibilities and choices that we may have (Cohen and Stewart, 1994; Schiere *et al.*, 1999; Mandelbrot, 2000).

It can indeed be said that the uncertainty factor likewise exists in agriculture, people, animals, and crops, and also that, crucially, farming systems are learning systems. Indeed, many consumers and farmers have started to question the control attitude of modern approaches to agriculture, which in their view results in the exploitation and/or destruction of natural resources, or in unequal access to resources. Sceptics have begun to question how long we can continue to use fossil reserves at current rates, or why most of the land should be in the hands of a proportionate minority. Some farmers turn to organic farming while others hesitate to make investments necessary to remain apace with recent trends in farming. In other words, 'attitude' and perceptions are questioned, while previously accepted linear 'hard' facts and traditional paradigms are reassessed. Consequently HSM struggles to follow, whereas SSM takes changes of mind and 'ethical' considerations as an integral part of life. SSM internalises the concept that the observer's choice of measurement (paradigm) affects the outcome of the research. The Einstein-Bohr argument about uncertainty in physics becomes apparent here in decision-making about farming as demonstrated by the differences between HSM and SSM. In addition, SSM stresses that a cow or a field, for example, is not just a physical entity. The cow or the field also has emotional value (meanings, goals) for farmers and consumers, a notion that is captured in the term 'second order information' (Ison & Russell, 1999). Thus the distinction between matter and mind becomes less clear or even counterproductive; it is a man-made distinction after all. The concept of 'learning systems' from SSM has more than merely an instrumental value. It is a departure from the HSM notion that systems have an explicitly defined goal, rather than continuously changing goals. It also requires a paradigm shift in terms of the method used for choosing policy in agriculture and in daily life, towards a new balance between control (HSM) and participation (SSM), as expressed in the Spanish and Indian quotes at the beginning of this chapter.

The inherent participation (interaction) of the observer in the act of observation is illustrated in the fishnet-metaphor by Addington (quoted by Ashby, 1958):
'An empirical scientist who threw a net into the sea examined the catch, and then announced the empirical law that "all sea creatures are more than two inches long." '
This metaphor re-introduces ethics and choice into system analysis by stressing the now familiar point that method chosen determines the outcome of research, since no combination of measurements can ever give the full picture of reality. The fishnet metaphor is paralleled by the coastline metaphor mentioned in Box 4.1. Essentially it states that the length of the coastline increases as the scale of measurement decreases. Eventually such measurement takes into account also the shape of sand grains and cracks in rocks. Ultimately one ends up 'measuring' the circumference of the rocks and grains, or even molecules or intercellular cavities. This effort of obtaining exact measurements makes one lose sight of the original question, a well-known experience in much objectivist and reductionist science. To measure is 'to know only very partially', full control is an illusion, choice is inevitable, and the learning process forces the observer to continuously adjust the monitoring approach. In addition, the measurement intervention itself determines the outcome, a possibility that is marginalised in HSM, but stressed in SSM whose followers are well aware that their method of measuring affects the answer. Ultimately SSM challenges the partly Aristotelian notion of a 'goal'. As stated by Checkland and Scholes (1990):
A system does not have a goal but it is given one according to its context (and by implication: changing contexts result in changing goals; added by JBS).
Furthermore, SSM is not focused on precise definition of system boundaries; Röling (1994) says:
A system is a construct with arbitrary boundaries for discourse about complex phenomena to emphasise wholeness, interrelationships and emergent properties.

The idea of changing goals and vague system boundaries bewilders some HSM practitioners. It does justice, however, to uncertainty and the existence of unstructured situations in 'real life' that is full of change and contradictory perceptions. For example, a boundary for a cow is not a boundary for a nitrogen molecule. And a boundary for 'matter' may not be a boundary for 'mind', just like the time scale for a farmer tends to differ from that of a distant policy-maker who studies macro-economics. Use of SSM implies that the observer accepts the existence of different world-views. It is a paradigm shift that goes beyond instrumental value: SSM explicitly restores the uncertainty as well as the active role of the observer (stakeholder) within the process of enquiry and in coping with problems. Participation and adaptive management, defined as continuous (learning) response to feedback becomes necessary in a worldview where systems change with the context (Chapter 10). The Landcare program in Australia and environmental co-operatives provide examples of what participatory approaches can do if policy permits: rural communities address local problems according to local priorities (Chapter 6).

Complex system methodology

Issues of system dynamics and continuous learning are sidelined and shelved in HSM, whereas they are part and parcel of SSM, and they occupy a central position in CSM. For HSM workers the hardest part of the paradigm shift required to adopt CSM is that they have to start dealing with the uncertainty associated with changing and multiple perceptions, a notion already present in SSM. One might say, however that SSM workers on their part find it hard to adopt CSM because they tend to distrust the mathematical and physical origins of CSM. The SSM tradition is perhaps just as stuck in the 'mind' mode as the HSM tradition is stuck in the 'matter' mode. One 'novelty' of CSM is that it extends uncertainty accruing from human systems into physical systems and vice versa, thus bridging the man-made gap between matter and mind (Capra, 1997). It goes beyond the dynamic models used, for example, by Meadows *et al*., (1972). It stresses the emergence of real mode changes and completely new systems, not extensions of previous ones (Chapter 5).

Any precise definition of complexity would be an oxymoron, but a characterisation of a [complex] system from a CSM point of view could be:
A complex system has innumerable emergent properties, hard or even impossible to define boundaries, and relations and characteristics that are open to an infinite number of different interpretations.

Characterisation rather than precise definition is inherent in the notion of uncertainty. It has the advantage of providing flexibility but, conversely the disadvantage that one loses control. Another implication of this characterisation is that results cannot be traced back to single causes. In terms of the discussion on biotechnology, DNA modification only results in higher yields and/or farm income (these two are not necessarily related) if 'allowed' by a context consisting of climate, farmers, soil type and pest/disease pressure. Basically, this is Newton's simplification of the three body problem revisited. Control methods to trace the 'real' cause can be powerful, but they eventually fail due to administrative detail and high costs, subjective choice of boundaries, or by overlooking relations between a system and its surroundings. Systems do indeed affect their context in a way that eventually leads to unexpected dynamics. Typical examples of such unexpected effects are the social costs associated with the outbreak of foot-and-mouth disease in Western Europe in 2001, the political consequences of the SARS outbreak, or the social change associated with the plant breeding programme underlying the Green Revolution. Both higher yields and disease affect the *mind* as much as the *matter* of the farming community.

A landmark contribution to the theory behind CSM was the chance discovery of the 'butterfly effect', by Lorenz in the 1960s (Gleick 1987). He found that predicted complex (weather) patterns changed dramatically, with (even minute) changes in the initial values of the model. Butterfly effects may get dampened and cancelled out by other effects (boundaries!) They may also combine with other processes to become stronger, a typical case of interaction between systems and their context. One example was the introduction of rabbits in Australia (a whim in somebody's mind) that combined with an absence of natural predators to cause environmental disaster in biophysical and socio-economic terms. Other examples are the chance emergence of a prion that causes BSE in a world with cheap transport and the recycling of animal products: the beef scare is a 'result' *and* a cause with yet unforeseen consequences! Lorenz's butterfly effect led to the uncertainty factor entering the domain of matter, i.e., in mathematics and physics. Uncertainty could no longer be confined exclusively in the mind domain, because nothing can be measured more accurately than the small deviation that is large enough to cause unexpected behaviour. Basically, it has to do with the notion contained in Gödel's statement that:

'if you fix the rules of inference, and any finite number of axioms, there are meaningful statements that can neither be proved nor disproved' (Ruelle, 1991).
The CSM tradition starts by recognising that important factors underlying unexpected system behaviour include notions such as::

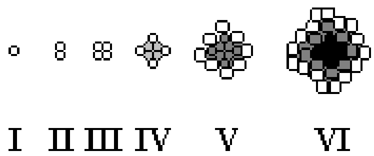
- The butterfly effect: uncertainty about the initial conditions (see the assumptions by Laplace in the quote at the start of this chapter).
- The 'lock-in', i.e. positive feedback and the delay between action and reaction. This occurs, for example, when a society is stuck with its infrastructure, or when a business is stuck with an investment or attitude that prevents adaptation to changing contexts (Box 4.7).
- Non-linear system behaviour as a consequence of the fact that a given system's rate of growth depends on the context and condition of that system at the preceding moment. For example, the growth of an industry, or plant or animal population, depends on its size at a preceding moment and on the past, present and expected resource flows (Box 4.6). The 'learning' of a system depends on its previous experiences; relations exist between past and present contexts and systems.
- Relations between sub-systems as well as between systems and their contexts (Box 4.2). A change in one part affects other parts, that is the holistic aspect of complex system thinking going beyond Newton's 'two-body' simplification. For example, the decision of one farmer to plant wheat may depend on others deciding to do the same. And new varieties or cropping patterns eventually affect ground water levels, social organisation, and so on, well into uncertainty.

The relevance of such notions for policy-making is that rigidity and emphasis on administrative measures for system control are unlikely to be effective in the long term. Beyond certain (threshold) values, systems start to respond by behaving differently. They yield less, or they diversify into different modes as implied in Box 4.2 and Box 4.3. Complex problems that have no easy solution tend to result in different coping strategies, the combination of which results in the next phase. More refined measurements and extrapolations may be counter-productive if they obscure other avenues. They may even 'waste' resources that could better be used for more relevant and/or emerging phenomena elsewhere if they keep us locked in tradition ('lock-in'). For example, the post-World War II emphasis on high yields in Australia and the Netherlands ignored the emerging problems of salinisation and eutrophication. And the recent outbreak of foot-and-mouth disease in Europe illustrated two other potential difficulties with the linear measurement and control approach. First, a centralised rigid and large bureaucracy can aggravate an emerging problem. Second, one sided emphasis, ostensible control of 'accidents', may actually lead to higher social and physical costs, rather than to more efficient overall production.

The 'emergence' of a combination of several coping strategies, rather than one or a few isolated solutions is central to CSM and it is a major characteristic of non-linear system behaviour (Box 4.3) . One of the coping strategies is the decay or 'death' of an existing system, a 'solution' that is politically often hard to accept. However, it tends to allow for the emergence of new forms. Schumpeter calls this 'creative destruction' (Holling, 1995). It is a notion remarkably close to Hindu thinking on creation and destruction operating in parallel. Another aspect of working with a combination of coping strategies is that one 'allows' a system to choose a particular mode out of several alternatives, depending on what other systems do. This introduces a variation of forms and surprises (diversity and serendipity) that eventually leads to unforeseen consequences and continuous dynamics. The notion of 'solution' rather than 'coping strategy' tends to imply only one choice with a final and static result. Too often we tend to train our students with just such a notion of solutions by offering them 'simple' problems (Schumacher 1972). This leads to one-problem-one-solution approaches, and to linear efforts being undertaken to maintain growth in, for example, a given type of food production. Such an approach is likely to eventually strain systems and their contexts to such an extent that they encounter limiting factors and crises (see Chapter 5 and below in this chapter). In real life it is likely that unexpected combinations occur and that systems diversify (Box 4.3). Dutch farmers have responded in various ways to a series of emerging problems, such as overproduction, environmental impacts, animal welfare, etc. These coping strategies include emigration, buying additional manure quota and/or more land, hoping for better prices, sale of home-products, small-scale tourism on their farm, quitting, etc. Much linear policy-making and teaching tends to shelve small creative efforts as not useful for 'the sector as a whole', or it continues to seek prototype 'solutions' that can be generalised. 'Chaos'-management is keen to identify new exceptions and sees diversity as an opportunity. Creativity is an essential ingredient where mechanistic approaches fail, and 'mess' is important when mode changes cannot be avoided at reasonable cost.

Box 4.2 The importance of context and the inseparable nature of system and context relations.

Context and the active interaction between context and system is pervasive to such an extent that the distinction between context and system becomes blurred. Context acts, for example, where a bee egg that is well fed ('good' context) develops into a very reproductive queen, while the same egg in the context of 'bad' feeding develops into a sterile worker. In other words, the information in the egg expresses itself differently depending on context. It is not *'nature or nurture'* but *'nature and nurture',* nor is it *'external or internal'* development. It is the interaction between the system and its context (if those concepts can even be used in the traditional sense). The same holds true for the seed of a pine tree that develops into a crooked tree once it germinates in an open space (provided it is in a context with enough water, no fire, etc.). In a forest, however, the same seed develops into a straight tree, not after first trying to grow crookedly, but directly at the first attempt. Quite different *and* similar in this connection is the mode-seeking in weather systems: depending on a particular combination of relative humidity, temperature and air pressure, clouds will form, all of the same general shape that belong to that particular type of climate. Other cloud shapes would be formed under different temperature and humidity conditions. Similarly, a farmer operating in densely populated areas has a different view on farming than one operating in the far outback; matter and mind are linked, system behaviour and context are linked.



A fascinating example is the case of the fertilised egg in a conducive context, as shown in the above diagram (I). It splits into two similar ones (II) and so on until the cluster of eggs consists of cells with similar genetic information but different self-induced contexts (IV-VI). Untill stage III all cells have a similar context, though different from their predecessors. After stage IV the 'inside' cells, however, have different context than the 'outside' ones. Somewhere at this stage, the 'whole' system starts to diversify into what could be called epithelium and endothelium cells. Such development has a strong parallel in the development (or co-evolution) of farming systems (Box 5.2). System development in this CSM notion is the result of dynamic relations between system and 'its' partly self-generated context. The HSM notion of a 'frozen' system with a fixed context of *ceteris paribus* needs to be reconsidered if one takes these concepts for more than instrumental value alone. A particular form and process of farming may emerge due to a given context, but sooner or later it is also the farm and farmer that determines the context, and then back again, and forth again, but always onward.

The butterfly effect was one of the discoveries that undid the clockwork notion and re-introduced uncertainty. It matches other work from the second half of the 20th century concerning complexity, also known as non-linear system dynamics and 'chaos' (Klir, 1991). We use the terms complexity and non-linear thinking to stress that this refers to a rather young and not yet well formalised approach. The fact that a change in one part of a system may have an effect elsewhere starts to be hesitatingly accepted in HSM. It is present in the concept of learning systems in SSM, and inherent in the notion of trade-offs (Conway and Barbier, 1990). It is central to the complexity thinking of CSM which states that complex problems have more than one coping strategy (Box 4.3), that several perceptions exist (Box 4.4), that uncertainty is the rule, that certain modes are more likely than others and last but not least, that system and context are inseparable and yet different. Interrelations lead to trade-offs, their existence has more than merely an instrumental significance. Trade-offs and loss of control therefore become part of our world-view. Efficiency gains in one place are likely to cause efficiency losses elsewhere. The optimal use of limiting factors, the timely shift into other modes and, as a matter of ethics, the judicious and respectful use of finite resources and nature then become relevant. Trade-offs occur at and across all levels of system hierarchy (Table 4.1) as illustrated by the following examples:

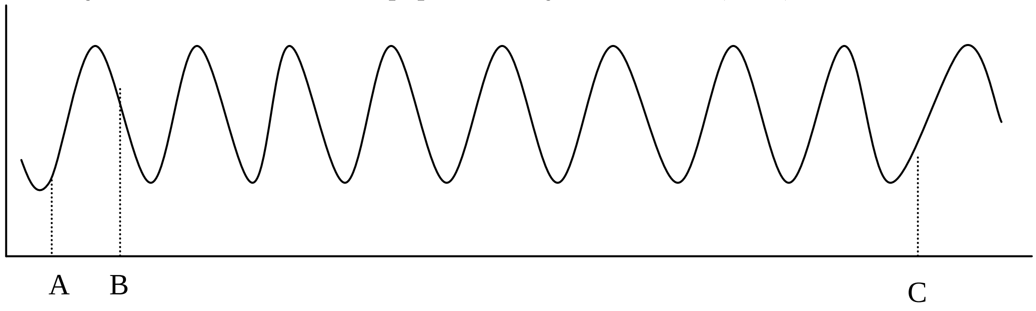
- At crop level, emphasis on total plot yield tends to occur at the expense of individual plant yield.
- At animal level, breeding for breast-meat in turkeys resulted in physical limitations in terms of reproductive behaviour.
- At flock level, attention to high laying percentages in hens implies the 'emergence' of male chicks that have to be destroyed due to inferior meat production characteristics.
- At farm level, profitable forms of mono-cropping may lead to more disease pressure or soil erosion.
- At regional level, a dam for irrigation downstream may displace local populations upstream.

Box 4.3 A one-problem-one-solution approach versus use of combinations of coping strategies
Teaching is often based on questions and problems that have one solution (1+1=2). Some problems, however, have more than one solution ($\sqrt{4} = \pm 2$) and complex problems tend to have no solutions. Taking an example from animal nutrition: it is impossible to mix two feeds, A and B, with 50% and 70% TDN (an energy value) respectively and 10% and 20% crude protein in such a way as to arrive at a mixture with 60% TDN and 18% crude protein. Such 'impossibilities' are common in examining the trade-offs between higher agricultural production and lower resource use, or more 'nature' value (Table 4.2). A strange paradox in non-linear thought is that an infinite number of coping strategies are available once we accept that a particular solution is impossible (or even if we accept that the solution has an undesirable cost). The choice of the observer once again becomes an operative factor e.g. in the decision whether or not the benefit of a 'solution' outweighs its cost. For example, in the case of the feed mixing, it is possible to achieve an infinite number of feed mixes from A an B if they both contain > 60% TDN and > 18% CP. A coping strategy is a way of dealing with a problem in the knowledge that a 'perfect solution' does not exist. One gains something while losing something; your gain may be my loss, or vice versa, some prefer this, others prefer that. In accepting the existence of trade-offs, one should ask which set of options is available for different farmers to cope with a crisis, *including* the option to quit. Complexity and chaos management stresses that more than one option is available, none of them is 100% perfect for all stakeholders, and each one leads to continued system dynamics (co-evolution). The change from thinking in terms of one solution towards a combination of coping strategies requires a paradigm shift from static towards dynamic thought.

Not all feed-backs or trade-offs are negative, indeed at first they tend to be 'positive', but carried too far they tend to 'produce' 'negative' side effects, an essential feature of non-linear system behaviour. Whatever the situation, the choice of criteria and trade-offs determines the analysis and design of new systems; the observer affects system behaviour, man and farming are part of nature. Tensions in farming do not just happen, they are part and parcel of development and they occur at all levels of system hierarchy. In the CSM world-view, the image of agriculture being marred by 'problems' is not an accident, it is the consequence of a combination of different perceptions, past choices, non-linearity and the unpredictable effects of 'God playing with dice'. Continuous alertness to feedback is required, while the need for participation overtakes the notion of mechanistic control. Managers, policy-makers, teachers, researchers and farmers have choices to make and signals to interpret; learning systems are a necessity, not a luxury. So is there any certainty at all?

Box 4.4 Perceptions of fluctuation and stability/resilience by different observers

Different perceptions on the severity of fluctuations in a system reflect an observer's choice for the scale of observation. For example, a farmer having a time horizon for survival between points A and B will experience irregularity, but an administrator dealing with a time horizon scale from A to C will note regularity! This issue has been worked out, for example, in great detail for perceptions about sustainability and size of catch in fish populations by Van Densen (2001).



Form and thermodynamic theory, a static approach.

CSM and 'chaos-theory' stress a strange tension between repetitions of form on the one hand and on uncertainty on the other. Repetition of form can be referred to, among others, as 'fractal behaviour', a term that is related to the concept of fractals. Fractals represent models of systems that repeat themselves at different levels of system hierarchy (Mandelbrot, 2000; Gleick, 1987; Capra, 1997). For example, horses, cows and frogs may all be different, but they all have eyes, kidneys, and digestive systems. Also, trees and bushes are different, but they also have many similarities in terms of form and processes, depending on how time and space scales are defined. Important, not all similar forms need to stem from a single original such as expressed in Plato's 'idea' and/or Sheldrakes 'morphogenetic fields'. The eye has emerged independently several times in the course of evolution; similar clouds form without mutual 'knowledge' of each other; different farmers find similar solutions without consulting each other. Processes such as exchange of resources and mutual adjustment of parts occur in the cell, the organ, a plant, a plot, a farm, a village, and at regional and international levels. Animals and plants all require nutrients and energy, while they excrete waste and dissipate resources, and so do humans, societies and cities. Genotype-environment interactions are not unique to animals or plants, they are expressions of general non-linear system behaviour. Time and space scales may differ, but principles are often similar (Box 4.1).

CSM stresses another apparently paradoxical strange tension, i.e. between a focus on uncertainty and a concomitant stress on the general validity of two laws of Thermodynamic Theory (TDT). The latter can be assumed to determine form and behaviour of all systems, independent of their size. The laws have not been conclusively proven – another strange uncertainty – but their validity can be described as being beyond reasonable doubt. They state that:

- First: energy and matter cannot be created nor destroyed, it can only change form.
- Second: a closed system left to itself tends to greater disorder, expressed in terms of increased entropy.

Often, people from the 'mind' orientation in SSM find it hard to accept that laws of 'matter' affect our perception about life but they should remember, like their 'matter' colleagues of the HSM, that the mind/matter distinction is a man-made construct. SSM thinkers in this respect may take comfort from the notion that TDT reflects system behaviour at a level that cannot be claimed exclusively by 'matter' thinkers. Also, cornucopian thinkers of both the HSM and SSM tradition in agricultural development find it hard to accept this notion of entropy and finite resources. They have a world-view in which human ingenuity can overcome the limitations of nature, and where technology is a gravy train (Chapter 5). This section therefore discusses some aspects of emergence and repetition of forms, together with other implications of TDT for farming.

Emergence of form

The first law of TDT implies that grass can be made into milk; that water, solar energy and nitrogen can be turned into grain, and that energy stored in coal or wood can drive steam engines or keep homes comfortable. It also allows the reverse to take place. However, the second law states that form tends to disappear in closed systems which *'are left to themselves'*. It implies that it is harder to make grass from butter than vice versa. It therefore also implies a notion of irreversibility, as observed for example, when both hard and soft system thinkers find it hard to break certain acquired routines. Too often farming systems, farmers, researchers, and policy-makers of all disciplines become locked in traditional modes. They thus refuse to adapt, i.e. refuse to learn. It is a form of lock-in and delayed feedback that is, for us, a major precondition for unexpected system behaviour.

Another important point is that the second law of TDT, when applied to nature, refers to open rather than closed systems (Bertalanffy, 1968). All systems in agriculture and society are open, because they receive a continuous but variable flow of resources that represents different forms of energy. They are thus not 'left to themselves' and when the resource flux is high enough there is a tendency for local order to appear (Prigogine & Stengers, 1985). Systems self-organise according to the resource flux but, in terms of the second law, this order has a trade-off in the form of greater total disorder elsewhere, which may be hidden from view. For example, the use of petrol to plough a field seems a small price to pay for the re-ordering of the field, but the disorder at molecular level, created by combustion, is much greater than the order created at the level of our perception of reality, the field (Odum, 1971). Indeed, according to the TDT a choice for order in one place implies disorder elsewhere. The 'mode' of order depends on an interaction between the system and its environmental conditions, i.e. on the resource flux (Box 4.5). Seen in these terms, a greenhouse industry in the middle of Australia is less likely to emerge than an extensive sheep ranch. And a potato crop is more likely to emerge in a Dutch polder than in the Australian outback, unless 'control' through enforced resource fluxes is applied from outside. It is a challenge for policy-makers, farmers and consumers to appreciate the implications of the second law of TDT and to match external 'control' with the requirements for sustainable farming. It is another challenge to match the demand of growing populations with realistic expectations regarding access to resources.

Box 4.5 Form and the water-boiling metaphor where the mode depends on the environment, i.e., the resource flux.
The molecules in a vessel of water on a gas burner will first continue to tumble about at random. The flame adds energy as a form of external control to the vessel. The flame also results in disorder of combustion gases and movement at a molecular level outside the vessel. Inside the vessel the movement of molecules is at random; an 'equilibrium situation exists while the supply of energy from the burner is negligible. Small additions of energy can be dissipated without appreciably affecting the organisation (mode) of the molecules. However, beyond a certain point the water boils, molecules become clustered into bubbles. In short, beyond a certain input the equilibrium is disturbed, systems self-organise and new structures appear, some being more likely to occur than others. Square or triangular bubbles are 'less likely' to occur than round ones, due to laws of nature, and given 'reasonable degrees of outside control. In the same way, it is unlikely that sustainable farming systems will be encountered where animal or crop density exceeds the carrying capacity of the resource base (given reasonable levels of system control).

Ceteris imparibus

A system deposits products and waste into its surroundings (context) while simultaneously drawing resources from its surroundings (Figure 4.1). As a result, the total entropy of the system and its surroundings increases and a system changes its own context. Contexts of open systems can be similar, but they are never the same, not in time, nor in space. They are in a constant change of the kind that was mentioned by Heraclites when he said that we never step in the same river twice. We here call this *ceteris imparibus*, as opposed to the notion of *ceteris paribus* commonly used in classical economics. The contrast between '*ceteris paribus'* and '*ceteris imparibus'* reflects what is also called in other disciplines the contrast between 'equilibrium' and 'non-equilibrium' thinking, or between 'control' and 'participation'. *Ceteris imparibus* stresses that new systems and contexts continue to emerge. Only those system-modes çan survive (are sustainable) that find a balance between adjustment to changing contexts and/or maintenance of their own context. And to stress contradiction and strange tensions, only systems that are prepared to change will survive (Chapter 5). Changing contexts may result from endogenous and exogenous 'causes', learning systems involving managerial choices, policy options and God's dice (Chapter 1). In that process of change and repetition of form one can discern various 'patterns' which, with due caution can be generalised for all kind of system behaviours. They also were part of what Aristotle looked for, and some of them will be discussed below

The algae principle: niches for organisms or farming systems

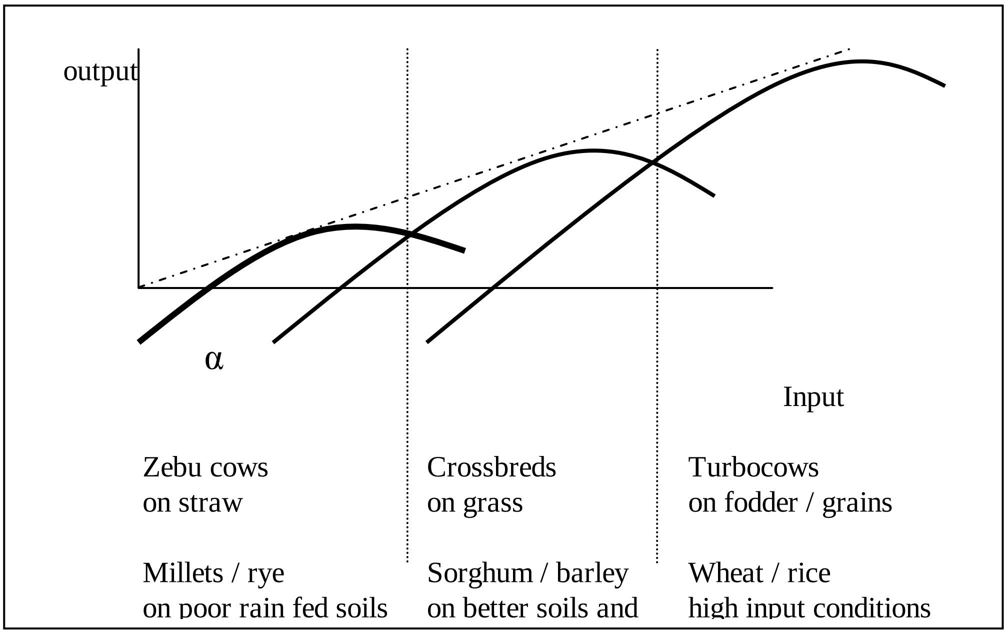
One repeating pattern in the relation between system form and resource flux is the 'algae-principle', which we believe applies to farming systems as well as to any given organism. Box 4.6 shows a non-linear sequence of responses across different systems (breeds of cattle in this case) to increasing levels and quality of input. It also shows that each organism (system) has a 'niche' - a level of input where it performs at maximum efficiency. This principle is likely to be universal at any system scale, from cell to government and beyond (Schiere, 1995). The combination of curvilinear responses across different systems is also a good illustration of the importance of context for the characterisation of a system. It raises the following issues for policy choices at plot, farm, regional and higher scales:

- A system's performance depends on its niche (context) with an associated resource flux. For a resource-driven system, input supply determines the output, as in low external input agriculture (LEIA), but in a demand driven system, output determines the required inputs; as in high external input agriculture (HEIA) (Chapter 5).
- Genotype-environment interactions, as known from animal and plant production systems may be generalised. The question is therefore not whether one system performs better than another, but where, when and how it performs better, as dictated by local resource flows (i.e. contexts).
- Diversity can maximise output and resource use efficiency. Standardisation is likely to be unproductive in the long run if it assumes static *ceteris paribus* conditions that later cease to exist.
- Comparing 'average' resource use efficiencies without specifying context is misleading. A tropical cow may be efficient in the straw niche, a crossbred cow in the medium quality fodder one, etc. A tractor uses oil more 'efficiently' than a horse, but hay-use 'efficiency' of the horse is much higher. Construction of objective measurements to compare the horse and the tractor can be attempted, but the 'objectivity' is lost in the need for subjective choices.
- Efficiency is highest where the tangent (dotted line in Box 4.6) touches the production curve. However, many systems tend to aim for maximum output. At that point the marginal returns become zero, while use of resources tends to become less efficient and, by implication, economic criteria do not always reflect ecological efficiency. The skill of the manager lies in the identification of the limiting production factor, another example of the observer's choice that affects the system, and of the need to avoid unspecified discussions about efficiency (Kruseman and Van Keulen, 2001).
- There is a limit to the efficiency that any system can achieve: the tangent that touches the production curves maintains a rather narrow band of efficiency. Initial improvements in system efficiency are possible, since the first animal or plant or farm of a new type is not likely to be the most efficient one. However, continued efforts at *'improvement'* lead to non-linear jumps (mode-

changes) to other niches, rather than to overall efficiency increases. For example, cornucopian coping strategies gamble on abundant availability and increased use of inputs to meet a specified target. It is a typical HEIA approach that accepts mode changes and dependence on other resource flows as a sign of progress. Other farmers, however, tend to cope by reducing inputs. They participate with 'nature' by accepting that the quality of their natural resource[8] base governs their form and process of farming.

Box 4.6 The algae principle and niches for organisms and farming systems

The algae principle shows that a minimum input of energy is required to maintain the rather simple system of the prokaryotic blue algae. Increased resource fluxes lead to a curvilinear response that eventually results in less than maximum output. However, a more complex organism like the eukaryote green algae in this case, needed a higher resource flux for maintenance, but it also produces more (Elenbaas, 1994; Schiere, 1995; Allen, *et al.* 1999). The diagram shows that a certain input (X-axis) is required to maintain the form of a given system, to offset or to compensate for the tendency of local loss of form or increased entropy, as implied in the second law of thermodynamics. Initially, the output (Y axis) increases as the inputs increase. This continues rather linearly up to the point where the organism cannot cope with more input and where non-linearity starts to show. On proceeding from left to right on the X-axis the resource flows increase. In that case another system with higher maintenance requirements can better use the resource flow in that 'niche' to yield higher output, and so on. The algae-fractal repeats itself in animals (here cows), and with 'improved' plant varieties, for example, as resource flow increases due to increased soil fertility.



Real life systems often display more irregular behaviour than the stylised response illustrated above. For example, organisms with a higher maximum efficiency than those illustrated in the diagram, would lead to a different tangent. However, higher efficiency is always restricted to a particular niche (in other niches they would have lower maximum efficiencies) and systems that depend on higher quality fluxes to give high outputs may not be the most efficient.

[8] The very notion of a resource base is even laden with a "choice" .. is it the resource base of humans, or are we part of nature that can also consider "us" as its own resource base

Co-evolution of form and processes

Thus far we followed a rather static approach by implying constant resource flows, with little attention to system dynamics and *ceteris imparibus*. However, fluctuations in resource flows are part of real life, so much so that we take them for granted, for example in day and night rhythms, seasonal weather patterns, hog cycles, etc. Some of those we even celebrate, such as during harvest festivals, or when we celebrate the return of the light (midwinter) by slaughtering animals that would not survive the winter. Tropical examples are different but in essence the same. Other fluctuations are rather worrisome, such as climate change, emerging diseases, computer viruses, biotechnology and globalisation. In this chapter we use the term co-evolution to stress that systems develop in response to their variable surroundings and vice-versa: learning systems co-evolve. One mechanism of co-evolution is the emergence, also called self-organisation of systems, as discussed above. Two of the many other repeating – fractal - patterns of co-evolution are lock-in and perverse system behaviour. They were mentioned before and briefly elaborated in Box 4.7. Here we deal particularly with predator-prey cycles and Holling's adaptive cycle. They are but two of the many repeating patterns (processes) that are readily recognised in daily life. They can be used to explain or describe many aspects of system behaviour and they may force our thoughts into other modes, away from control. They have more than instrumental value; they imply that we are subject to and are integral parts of these processes, rather than neutral observers.

Box 4.7 Positive feedback, lock-in and perverse system behaviour

'*Successes*' that reinforce themselves are examples of positive feedback, also called path-dependency or lock-in (Arthur, 1990). Lock-in effects can be positive or negative, depending on the chosen time and space scales of the context and on the value perception of the observer. Typically, lock-in occurs when a system cannot shift from a paradigm and adjusts to changing biophysical or socio-economic contexts. For example, the success of greenhouse farming in the Netherlands is associated with the emergence of a support infrastructure that makes it even more successful, though sometimes also more vulnerable to stress. Such vulnerability is real when consumers get fed up with certain products, due to food scares for example. Dutch tomato producers faced such a challenge when German consumers started to nickname the standardised tomato as 'water-bomb'. In other contexts, such vulnerability is real enough in irrigation schemes that initially boost food production and income, based on processes that are accompanied by depletion of aquifers, social change, and eventually *collapse due to success*. There are dramatic cases of systems that 'learn', often in non-linear and abrupt ways. Abrupt learning processes manifest the awareness that one enters, for example new ways of farming after a nasty disease (foot-and-mouth); or a new world 'order' after the twin-tower incident.

Perverse system behaviour is the term used when systems do the opposite of what they are expected to do. For example, well-intended subsidies to provide price support for farmers can obscure true market signals and lead to lethargy, overproduction, and collapse and hardship in the long term. The floor price scheme for Australian wool is a notable example of such perverse system behaviour. In 1990, the Australian Wool Corporation unwisely increased the floor price of wool, leading to the build up of a large stockpile. Eventually, the floor price scheme was abandoned and the last of the stockpile was sold in 2001. This experience caused the Australian government to lose faith in commodity marketing boards and to deregulate marketing in agriculture (Chapter 3).

The predator-prey relation

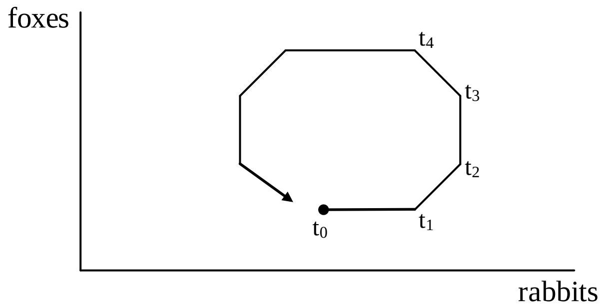
Predator-prey cycles are 'models' of system behaviour that occur in several forms. They can be depicted in different ways, necessarily simplifications, but they have wide applicability, also for agriculture (Holling, 1973). The essence of the predator-prey relationship is that the growth rates of predator and prey populations are dependent on their previous size, they are interdependent, non-linear, and not in phase because of a lag in the growth-response of one population to the other (Box 4.8). In other words, they fulfil the conditions for non-linear chaotic system behaviour as previously described. They also challenge the paradigm of the mainstream world-view in at least three different ways:

- Linear and cornucopian thinking tends to assume that continuous growth and/or control can be achieved through the technological gravy train and/or an expanding resource base (Chapter 5). Conversely, the conservationist world-view argues that 'predators', such as humans, have to adjust their consumptive behaviour to avoid collapse of the resource base. Both paradigms accept the need for change, they differ in their thinking about access to, and need for, conservation of resources.
- Classical economics tends to think that the ratio between rabbits and foxes will eventually stabilise in a dynamic equilibrium. In other words, it assumes that wars against hunger can be won and that 'solutions' are possible. Non-equilibrium thinking assumes that predator-prey ratios will not stabilise and that every coping strategy leads to its specific trade-offs and inherent dynamics.
- Both SSM and CSM stress that there are several coping strategies when predator populations start to encounter stress situations such as in point t_4 in Box 4.8. Standard or 'average' solutions are exceptions rather than the rule. For example, the predator can 'select' from a combination of the following strategies:
    - reduce numbers through migration (Australia accepted immigrants from the land- starved Netherlands) and/or by fighting each other
    - continue to eat and feast while hoping for the best - that the 'dice' will come their way (the Dutch discovered large reserves of natural gas in the 1970s, thus releasing resources for new infrastructures)
    - increase access to the resource base, such as through globalisation and use of resources from elsewhere (see Box 4.9), or
    - modify life styles, e.g. by going organic or by gambling on technological change. In other words, change from one fox-type into another.

Such a series of coping strategies involves ethical choices and challenges for policy setting. In terms of predictability, various options may exist, but the success of one is often determined by what the others might do - *'if he leaves, I can stay'*. Control measures aimed at permanent solutions are counteracted by system uncertainty and the inherent dynamics of learning systems in the broadest sense. Diversity in both ideas and modes of farming is important because it provides options to cope with the future.

Box 4.8. A simple representation of a one-predator/one-prey relationship

The phase-space diagram below, also called attractor by 'chaos' workers (Gleick, 1987), is a simple illustration of a one-predator/one-prey relationship in dynamic equilibrium. It shows how a rabbit population (the prey) can increase rapidly from t_0 to t_1 because at t_0 there are only a small number of rabbits, a relative abundance of food, and few predators. The predator population (foxes) only starts to grow after the prey population has started to grow. The number of rabbits continue to grow from t_1 to t_2, but this growth rate decreases because of increased pressure from predators and/or reduced food supplies. When the rabbit population remains stable from t_2 to t_3, the fox population continues to grow, even from t_3 to t_4 when the rabbit population starts to decline. Subsequently, the rabbit population declines further, leading to weaker foxes, and after some time the rabbit population finds itself growing again with renewed abundance of food and low predator pressure.



Real life situations that resemble this type of model are the decline in quality of resource bases due to exploitative ways of farming and/or consumer behaviour. Degraded sand dunes are part and parcel of Dutch agricultural history but occur around the world more generally. Even the disappearance of 'clean' soil and air as a result of excessive 'waste' from fertilisers, animal manure, car exhausts and (agro-) chemicals is likely to force the predator population that is called society into other modes. Like all models this one simplifies but illustrates real system behaviour.

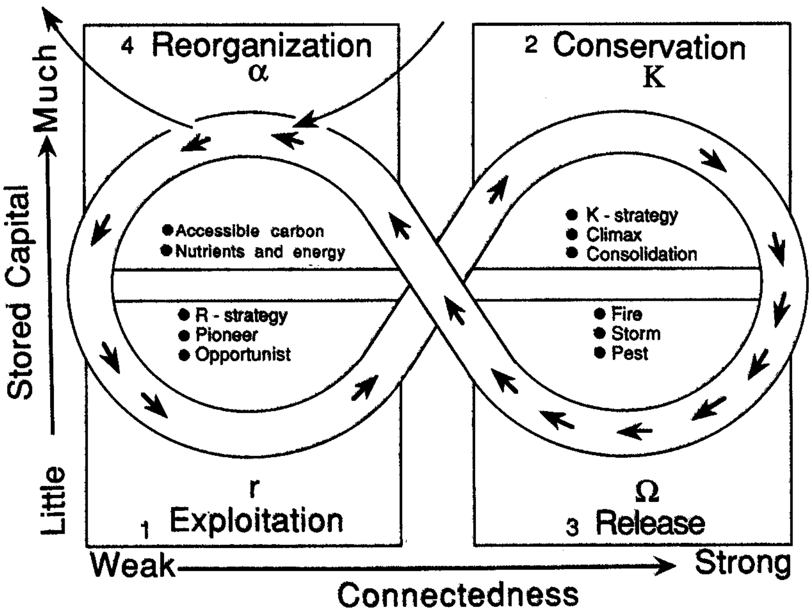
Holling's adaptive cycle

Holling expanded on the predator-prey model by describing mode changes as resource supply fluctuates, partly due to the system development itself (Box 4.9). For example, farmers moving into virgin areas (represented by the top left quarter) can make a 'quick buck' by rapid expansion though not necessarily efficient exploitation of resources (bottom left quarter). However, after some time resources become relatively scarce due to increasing numbers of farmers. In that case the efficiency becomes increasingly important, and mode-changes start to make sense if they conserve resources by recycling within and between systems. This process is apparent in Dutch farming of the past few decades. After WWII, the Dutch agricultural sector had increasing access to resources due to increased access to world markets. High, but 'inefficient' modes of production developed: specialisation and highly productive systems were the order of the day in the 1960s and 1970s. After some time, however, farmers started to face a crunch that forced them into self-inflicted mode change. Resources were still abundantly available but they could not be used as before, due to the difficulty in disposing of produce and waste products. Dutch farming moved to the conservation mode of the top right quarter. It combined individual coping strategies, such as improved efficiency, organic farming, precision farming, off-farm income, added value and recycling between farms. As an important aside, mixing occurred at farm level till the sixties, disappeared in the seventies, and began recurring at regional level 'between farms' in the late nineties, a case of fractal behaviour that shifts over system levels.

Eventually, however, efficient conservation modes can become rigid, a nasty but fundamental trade-off. Slight disturbances may threaten the whole network of interrelated subsystems. Collapse in such a situation occurs due to external changes and/or disturbances from within. Bankruptcy of a supply company or the emergence of a virus can be the straw that breaks the camel's back. Pent up energy is released and reorganisation takes place. The cycle starts again with new but often similar forms and processes while Schumpeter's 'creative destruction' recurs. A major world-view question here is whether policy setting, at whatever scale, should aim for the single 'solution' of becoming a more efficient (and rigid) system part-way through the conservation quarter (Box 4.9). Or should we also 'gamble' for an array of coping strategies. Again, the importance of diversity cannot be stressed enough for efficiency and survival. Unfortunately, and too often, the 'locked-in' ancient regimes tend to hamper rather than to stimulate innovation, mostly from lack of will and methods to cope with change.

Box 4.9. Holling's adaptive cycle (Holling, 1995; Gundersen and Holling, 2002)

The adaptive cycle is most easily understood by entering the 'pretzel' at the top left, a mode that tends to occur after system collapse and/or sudden influx of resources (e.g. after a flood, volcanic eruption, disease outbreak or political instability). At that point there is a relative abundance of unused resources that is captured by fast but not necessarily efficient colonisers (the 'cowboys') in the bottom left quarter. As colonisers multiply resources become increasingly scarce, hence collaboration and resource exchange become advantageous. As a result, the more efficient but rigid systems tend to take over into the top right quarter. Over there, access to resources declines for individual cowboy type organisms, and connectedness increases, until the system breaks down again (the bottom right quarter). Importantly, the release and reorganisation phase may take much less time than the exploitation and conservation phase, as indicated by the different densities of the arrows. Moreover, systems will run in different modes at the same time and at different levels of system hierarchy: a plant or animal itself is quite interconnected and can store as many resources as possible, while organisation at the plot or herd scale may still be relatively 'inefficient'. Mode changes occur at the end of each quadrant and throughout, as well as at different levels of system hierarchy.



Concluding comments

Agricultural systems are subject to mode changes in time-space. This is due to the interaction between their own development and (self-inflicted) changes of the environment, e.g. where population pressure, resource-exhaustion or overproduction ruins the system's resource base. Other mode changes are 'caused' by purely external factors, for example new export regulations, the emergence of new products like (bio-)technologies or new consumer preferences. In CSM the cause-effect question is not really valid, co-evolution is a combination of factors, only some are traceable to early origins and butterfly effects. This co-evolution of agriculture and its matter-mind environment has over the past century been characterised by large yield increases in Australia and the Netherlands, but also by a crisis of thought about its future. Many of the processes can be explained by using various forms of system thinking, some of which themselves hark back millennia. System thinking has oscillated between reductionism and holism; it fruitfully divided issues of matter and mind only to recombine them again in the course of time; it also separated observation and reason only to recombine them again. It accepted and resisted uncertainty, eventually returning from a road emphasising control to one of participation. Major changes in agriculture in the 20th century were made possible thanks to concepts from reductionist and mechanistic thinking in HSM. However, it is increasingly acknowledged that 'parts' interact, that they learn, and that they cannot be seen as being independent from their context (CSM) indefinitely. Past focus on statically defined systems needs to be balanced by a discussion on how systems interact, and on how they are both host to smaller systems and component parts of larger ones: how they combine matter (HSM) and mind (SSM) aspects into the more holistic embrace of CSM.

The curious tension of CSM is that uncertainty and different perceptions are likely to affect our world-view for years to come. At the same time it is 'rather' certain that agriculture is an interacting combination of nature, soil and man in which mind issues are not separate from tangible matter. Agriculture means different things to different stakeholders, but is definitely about more than just short-term food supply. Farmers cannot ignore the functions of apparently useless fauna, nor can urban populations ignore the fact that their own interests and lifestyles are intertwined with well-being and sustainability of agriculture. New processes and criteria are being developed to monitor and co-evolve with system health; learning systems are required to reduce administrative rigidity and locked-in teaching modes, so as to move from control to participation. Diversity in all its forms implies recurrence of forms, it helps to better 'use' resources as well as to prepare for change in terms of mind and matter. Most if not all successful development eventually leads to partially self-inflicted change. Examples of lessons arising from the application of thermodynamic laws (and common sense) are those of *ceteris imparibus*, lock-in and predator-prey cycles. They have more than just instrumental value: they have significance for the world-view of man and for farming practices, agricultural research, policy-making and teaching. Man is a part of nature rather than a ruler who controls it. History repeats itself, but never in the same way, by combining processes of creation and destruction where mankind has choices to be made, on priorities and allocation of resources to alternative coping strategies. This is perhaps the moral and central message of modern system thinking for farming beyond 2000.

Acknowledgements

Hans Lyklema, Piet Elenbaas, Wim Van Densen, Wiebe Aans, Wouter Joenje, Conny Almekinders, Mario Giampietro, Brian Goodwin, Richard Bawden and Gerard de Zeeuw and many others have contributed more to this chapter than they may be aware of themselves. Thanks are also due to Lenny Boonen, Laura Cueva, Arthur Eveleens and Rinske Schiere who helped to get these ideas on paper through a near infinite series of drafts.

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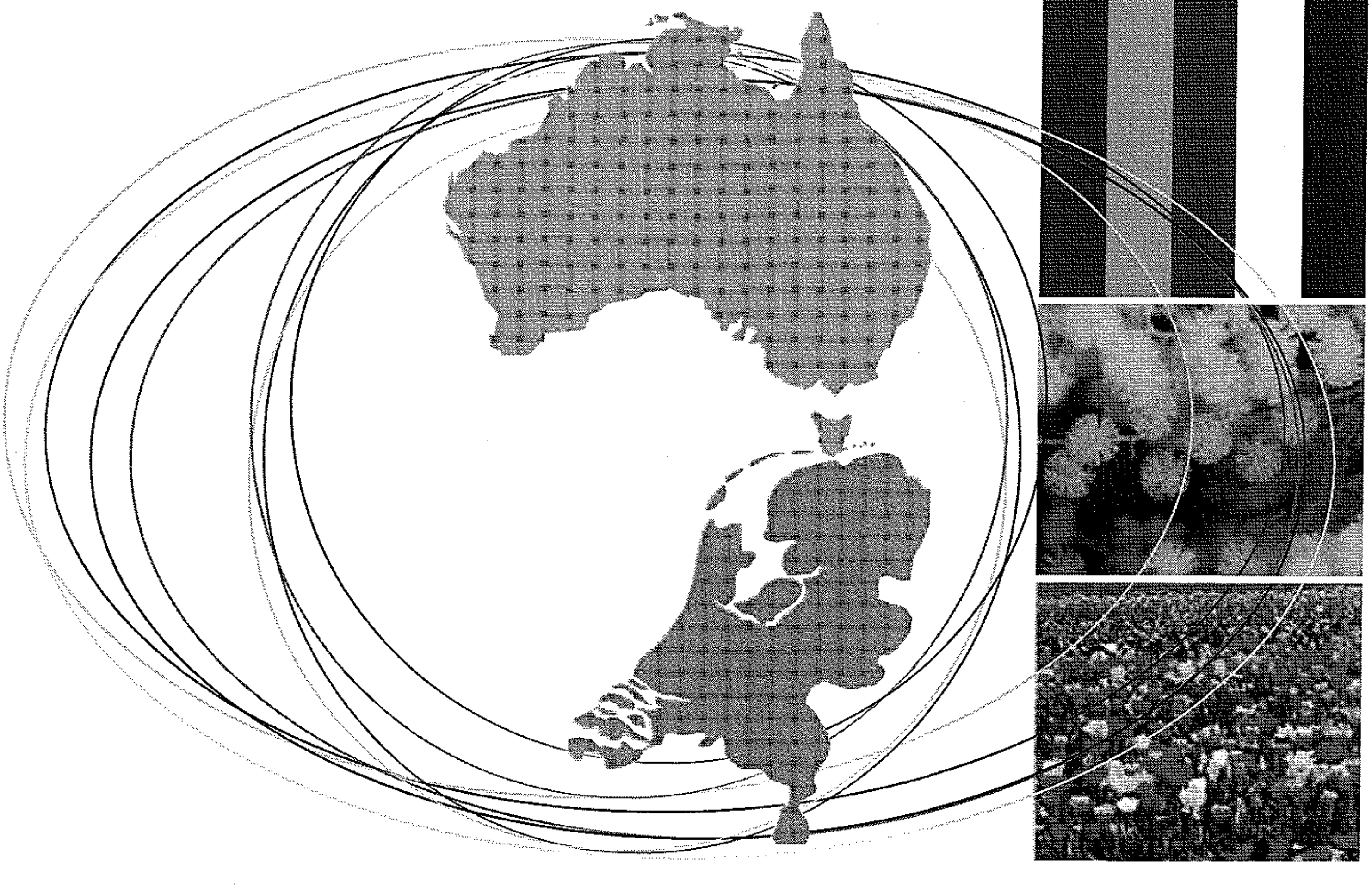

ISBN 0642 58620 9
ISSN 1440-6845

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Edited by Ken Rickert

Publication No. 03/053
Project No. UQ–90A

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Designed and typeset by the RIRDC Publications Unit
Published in May 2004 by RIRDC
Printed by Union Offset