AN AGRONOMIST'S ODYSSEY

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INTRODUCTION

I am going to begin by confessing to an emotional involvement with the cotton crop, a confession which may send shock waves of horror among you. Agronomists are both professionals and scientists, with a commitment to objectivity on each count. Can I remain objective and confess to emotional involvement? I suggest that the theme of our conference, *Science with its sleeves rolled up*, implies emotional involvement that tests our objectivity. Why else endure the heat and burden of the day under the blazing sun collecting data; why else do the lights in the lab burn late when the administrators have long gone home; why else travel on a shoestring to attend a conference? There has got to be some passion there!

I have enjoyed my career as an agronomist because of a life long love affair with cotton. The distinctive features of its physiology, derived from its indeterminate habit and xerophytic origins, captivated me, and continue to captivate me. Its social and political impact on history are equally fascinating. Cotton is one of Australia's major agricultural exports, yet it has rarely featured at this Conference. From these various threads I am going to try to weave a colourful and somewhat personal tapestry.

In an apparent change of metaphor, I have entitled this an Agronomist's Odyssey. The Odyssey was the journey of Ulysses, the Greek war hero, as he wandered for ten adventurous years on his way home from the Trojan war. My professional life has been a bit like that, taking me to several countries and through a number of intellectual adventures. To restore the metaphor, Ulysses' wife Penelope promised her suitors she would remarry when she finished the tapestry she wove while waiting for his return. This then is that journey and that tapestry.

SOME HISTORY

Today cotton is the world's biggest industrial crop, but this distinction started less than 200 years ago. The invention of the spinning jenny and the cotton gin, and America's Declaration of Independence took cotton textiles out of the luxury trade into the mass market. Cotton production expanded rapidly in the south-east of the USA and for some an era of prosperity began. Cotton was produced with slave labour with production evaluated in terms of yield per slave (25). Even after the termination of the slave trade, so valuable was cotton and so dependent on labour that the emancipation of slaves was delayed for half a century in the south, and precipitated the Civil War (21). In 1858, the US Senate was told: *You dare not make war on cotton. Cotton is King!*. Thus the South expressed its perception of economic reality in the USA prior to the Civil War, a perception that was used to justify slavery and as an economic weapon to intimidate the North. The South was humiliated, and in the USA ordinary people still pay the price. As we shall see, events that affected the cotton industry in the USA reverberated around the world, with political and social repercussions in many countries including Australia.

AFRICA - THE JOURNEY BEGINS

My professional career began in Malawi as a District Agronomist. Cotton was one of several crops grown, and was a legacy of Britain's dependence on cotton. Exports of cotton from the USA to Britain had increased from 85 tonne (t) in 1791 to 500,000 t in 1858 just prior to the Civil War. Cotton began the industrial revolution in Britain and was a pillar of economic prosperity. Just prior to World War I, when Britain's power was at its peak, the cotton trade employed directly or indirectly nearly one-fifth of the population and accounted for one quarter of the exports (42). In 1904 at the opening of parliament, the King expressed concern about *the insufficiency of the supply of the raw material upon which the great cotton industry depends* and referred to *the efforts being made in various parts of my empire to increase the area under cultivation*.

In response to a shortage of cotton supplies resulting, first from the American Civil War, and later from the boll weevil, exacerbated by a shortage of foreign exchange following World War I, colonial powers in Europe encouraged the production of cotton in their dependent territories, seeing their role in terms of the dual mandate (24): on the one hand, to foster the welfare of the indigenous population, and on the other to secure both raw materials and markets for the industries of the colonial powers. Cotton seemed an ideal means of discharging the mandate. In some countries the population was compelled to produce cotton at the expense of food crops (1). Willis (42) claimed that *cotton growing ... has made the difference between poverty and comparative prosperity... and marks the healthiest development from barbarism to civilisation*, while half a century later Arnold (3) said, *In many developing countries in Africa, cotton has become one of the key factor in economic development accounting for earning foreign exchange and also in providing productive employment for large sections of the community*. Today the legacy of the colonial mandate sees the economy of countries like Egypt, Pakistan, the Sudan, Tanzania and Uzbekistan heavily, if not totally, dependent on cotton.

Cotton and Insect Pests

In Malawi my very first assignment was to take John Munro, a visiting Cotton Specialist, in my shiny new Standard Vanguard station wagon to see some cotton. Before ever we got there he had me stop at a baobab tree to look for cotton pests! I met the pests before I met the crop! The perception that cotton appears to suffer more from insect pests than any other field crop is supported by Dover and Croft (8) but not by Cramer (6). Cotton agronomy cannot be isolated from entomology.

When production began in the US, the crop was isolated from its ancestral home in Mexico, and remained free from serious pests until production spread westward and eventually came into contact with the ancestral ecosystem of the crop where the boll weevil, *Anthonomus grandis,* was waiting. In 1892, the weevil crossed the Rio Grande into Texas. Over the next 40 years it spread relentlessly eastward throughout the cotton-growing areas of the USA. Production fell drastically, prices shot up and the use of arsenical insecticides induced the development of secondary pests, a pattern often to be repeated. Insect pests have dominated cotton cropping systems throughout the world for the last 100 years (16). Injudicious use of insecticides has induced a well recognised succession of phases in cotton cropping ecosystems: subsistence, exploitation, crisis, disaster and recovery (37).

In the 1960s, over half the pesticides used in the USA was on cotton, but there was a massive reduction in the 1970s attributed largely to integrated pest management. This decline was also reflected world-wide, with cotton dropping from first to third place (8). Even so, cotton still accounts for nearly 30% of all insecticides used world-wide.

Production strategy has completed two full cycles in the USA during this century in response to pests. Before the arrival of boll weevil a long season strategy was used with *indeterminate* varieties with prolonged flowering. Short season production with early maturing more *determinate* varieties was developed to escape the boll weevil. With the advent of synthetic organic insecticides after World War II there was a return to full season production. In the last two decades, in response to insecticide resistance, emergence of secondary pests and fears of environmental pollution, short season production has again been adopted with less fertiliser and irrigation. It will be interesting to see if transgenic insect resistant cottons trigger a third cycle.

THE YEMEN - INTELLECTUAL ADVENTURES

My work in Malawi started in extension but with little to extend, I began to experiment. This seemed to impress some people so I got into research by the back door without the PhD apprenticeship. My interest in cotton increased and I got a job in the Empire Cotton Growing Corporation (ECGC) in the Yemen to work solely on the crop as a breeder/agronomist. The ECGC was another legacy of Britain's dependence on cotton.

Water Relations

In the Yemen, cotton is grown in a unique and instructive way which gave me invaluable insight into the ecology of cotton's wild ancestors that explained the behaviour of modern crops. Erratic floods are impounded on the fields in order to store water in the deep alluvial soil. The crop grows entirely on this stored water. These conditions are remarkably similar to the natural environment of the wild ancestors of cotton, strikingly illustrated by the occurrence of an indigenous wild species as a weed in cultivated crops, both utilising the same adaptive features. The root system explores the soil to the depth wetted, and the indeterminate shoot develops at a rate unaffected by the amount of stored water, until approximately three quarters is exhausted, whereupon morphological development and vegetative growth stop abruptly, and the crop matures the fruit already set. Thus the size of the plant and the number of fruit produced depend on the duration of development, which in turn depends on how long it takes for the water to run out.

This pattern of development is well adapted for survival in arid and semi-arid environments where the water supply from rainfall or floods is erratic and can vary greatly from one season to the next. The indeterminate habit allows the plant to make full use of variable water supplies by growing a large or small plant according to the supply. The plant appears to recognise a signal indicating that the water supply is running out, and in response stops development, sheds young fruit and matures the fruit already set. Passioura *et al*. (33) have accumulated evidence from several sources that plants react to drying soil in response to signals from the roots. The development of rainfed and irrigated cotton are but variations of this basic pattern. A succession of drying cycles replaces the single prolonged cycle.

There appears to be another signal at the wet end of the range that triggers the rank growth syndrome. Most bolls are shed, unable to assert their priority for assimilates, while vegetative growth is excessive indicating no shortage of resources. It is a vestigial response of wild species programmed to maximise vegetative growth and delay fruit setting when conditions justify it.

Both signals are keys to managing cotton crops.

Origins and Domestication

Domestication involves a couple of intriguing mysteries that are, I believe, unparalleled in other crops. Only one of the 40 wild diploid species, *G. herbaceum*, has spinnable lint, and is regarded as the ancestor of all cultivated cottons. It is only found wild in southern Africa. Primitive cultivated forms are now found in Arabia and southern Asia. The first mystery is how did the ancestors of the domesticated form get from southern Africa to Arabia or Asia? Archaeological finds in the Indus valley and in Arabia suggest that it was domesticated 6000-7000 years ago. No food crop plants were domesticated in Africa south of the Equator, and those north of the Equator were not introduced into Asia until at least 3000 years later (10).

Modern varieties are tetraploid, *G. hirsutum* and *G. barbadense*, which originated from hybridisation in western South America between the lint bearing *G. herbaceum* of the African genome and a member of the indigenous genome, probably *G. raimondii*. The second mystery is how did the exotic *G. herbaceum* get from Africa to South America? Speculation involves the competing claims of a trans-Pacific land bridge, ocean currents, or man migrating by sea or via the Bering Straits. A recent suggestion that this occurred 1-2 million years ago rules out human agency (41). The wild forms are found in tropical America where they were domesticated 4500 to 5500 years ago.

The genus *Gossypium* consists of over 40 species of perennial xerophytic shrubs. They are frost sensitive short day plants found along banks and beds of dry streams. Though the genus is pan tropical, individual species have limited distribution and are of relic status with little genetic diversity suggesting a declining genus. All species except two are diploid. The diploid species are divided into five genomes, each of which is largely confined to one continent. Australia has a rich flora of wild species, some very rare, none of which has contributed to commercial varieties yet.

Lint consists of seed hairs that collapse in cross-section and form convoluted ribbons when mature allowing them to be spun into yarn. Apart from *G. herbaceum,* the other wild species have the stiff seed hairs that cannot be spun. Domestication did not require loss of photo-periodicity nor acquiring the annual habit, as plants were grown as commensal perennial shrubs. These traits were selected after domestication and allowed cotton to be grown in temperate regions, together with selection for longer and finer fibre and heavier yield.

Crop physiology

While I was in the Yemen, I did lots of agronomic experiments. I wanted to do more than obtain empirical recipes for growing cotton; I wanted to be able to design the recipes. I was frustrated in this in that I could not explain how the treatments caused the variation in yield, and predict how yield was determined by the environment. The problem was particularly obtuse in cotton. Variation in yield is associated mainly with variation in the number of mature fruit produced. Two distinctive features of the plant appeared to be involved: its indeterminate habit and its propensity to shed fruit under stress and with rank growth. As a consequence of the indeterminate habit, the plant produces flower buds in a regular and orderly way, so that the rate is predictable, but the duration is not. Production of mature bolls tracks along behind bud production but the rate is not predictable because of shedding.

It is like a school. There is an intake of students every year who progress through the system for a number of years. Every year some drop out for various reasons, and the survivors graduate. After a number of years the school closes its door and accepts no more students, but those already in the system can complete their courses. Reduce the time scale from years to days and you have a picture of a cotton crop. Why does the crop close its doors, and why do some bolls drop out?

As a student I had been taught that it was not enough to apply treatments and measure the yield. Yield components should be measured and ‘developmental studies’ done during the season. These mainly consisted of counting things like branches and fruit and flowers buds. I accumulated lots of data and they did not help me very much to understand or explain yield.

Then I discovered crop physiology! I read Watson (40) whose aim was *to analyse yield in terms of antecedent growth* because *this was the kind of knowledge that can be put to practical use in crop husbandry.* Here is science rolling up its sleeves! I was also strongly influenced by Hugh Bunting (5) who was closely associated with ECGC, and who introduced crop physiology as a subject at my *alma mater* (university) in the decade after I was a student.

Watson dismissed these ‘developmental studies’ and argued that it was *more logical to base an analysis of yield on weight changes that occur during growth than changes in morphological character.* I readily agreed... and did crop physiology on cotton, analysing increases in dry weight in terms of the size and efficiency of energy capture system, that is the crop canopy. I was confident that I would soon understand yield in cotton. When Professor Donald challenged us to use physiological criteria in crop breeding instead of pure empiricism, I wrote with misplaced confidence to assure him that for cotton it would soon be done! I was wrong. I accumulated lots more data and not much more understanding.

Although Balls' work on cotton was seminal in the history of crop physiology (he coined the name), and although others followed in his footsteps (reviewed by Watson (40), Evans (9) and Wilson (43)), like Ulysses we seemed to have lost our way. Looking back on the development of the discipline in cotton, I could see the two distinct lines of investigation that I have already referred to: the study of development and the analysis of dry weight increase. I call them the numbers game and the weight watchers, and they rarely made contact.

There are two reasons for the preference for weight watching in Crop Physiology. First, weight watching tends to emphasise similarities between species and allow generalisation, whereas study of development tends to accentuate differences. Second, in weight watching it is the implicit assumption that, since the major part of yield consists of the products of photosynthesis, the study of photosynthesis would inevitably lead to an understanding of how yield is determined. This is not necessarily so.

UGANDA - LOST IN THE WILDERNESS OF DATA

In 1966 I moved to ECGC's main Research Station at Namulonge in Uganda, where Hutchinson *et al*. (18) had done their pioneering work on water relations of cotton. They were the first to apply Penman's methods to a row crop, and used a simple water balance model to show that rainfall accounted for most of the variation in yield among seasons and sowing dates. I followed in the footsteps of Farbrother, only to discover he had travelled the same route, but in the opposite direction. He started as a weight watcher and turned to the numbers game and developed composite plant diagrams of cotton to analyse and display the effect of environment on the production and retention of fruit to determine yield (27), a technique that has recently been re-invented in the USA as plant mapping.

Crop physiology at that time had not reached its present state but was developing rapidly, as Prof. Wilson described in the Donald Oration four years ago. I was not in the mainstream as he was (to use his metaphor). Mine was a view from an eddy near the bank. This was the period he referred to when he said that general agronomists *went to the work place quite unconvinced that crop physiology served a useful purpose*. Having been convinced, I was becoming unconvinced! In the course of my Odyssey I wandered in a wilderness of data, catching occasional glimpses of where I was heading, only to have my hopes dashed.

I discovered that Wally Stern in Australia had reached the same point. After noting the voluminous studies of the growth of cotton undertaken in the previous 60 years, Stern (38) commented *In spite of the large amount of information available, there is little from which general principles may be deduced to predict the behaviour of the cotton crop in a new region*; or it, could be added, in any regions. My colleague Victor Sadras, while preparing the review cited later on compensation in cotton for pest damage, commented that in the 1960s there was a change in the type of investigation; physiological studies were neglected in favour of observation of yield and yield components. This was because the more we knew, the less we understood. The volume of data we were accumulating contrasted unfavourably with our dearth of understanding.

On the rare occasions when the weight watchers had played the numbers game, i.e. when development and growth were studied together the results were fruitful. Mason (26) postulated that a cotton plant retained as many fruit as it could supply with nutrients (mineral and assimilates). This has become known as the Nutritional Theory of Shedding. It has taken a fair battering over the years, particularly at the hands of research into plant hormones. The theory has survived virtually unscathed and is fundamental to understanding the dynamics of fruiting, and is incorporated in all cotton simulation models.

I tested the theory as best I could with data collected in the Yemen, and did not find it wanting in a series of somewhat turgid papers (11). I still think that was my most significant publication, though only one person really understood what I was on about, a Dutchman called Mutsaers (28), whom I have never met. It showed that the most significant event in the life of a cotton crop was not identified by phenology, but occurred when the number of fruit was sufficient to utilise all the assimilate supply. The crop then 'cutout', to use popular jargon. Further development stopped, no further bud or leaf production, no further fruit set, all young fruit shed. It needed both the numbers game and weight watching to show it! We were making progress; we could explain but we couldn't yet predict! The significance of 'cutout' as a pivotal event in the management of the crop is now widely recognised largely as a result of the work of Oosterhuis *et al.* (29), who has developed an index of 'cutout' from plant map data.

In 1969, after publishing these results I went to Wageningen and met de Witt. I wanted to use his 1965 model of photosynthesis to develop these concepts further. In retrospect I can see I was groping towards a model. He told me to forget his static model and introduced me to dynamic simulation.

AUSTRALIA - THE END IN SIGHT

The scene changes to Australia. Cotton had been grown experimentally from time to time in the first half of the 19th century, but it took those reverberating events in the USA to induce large scale production. The world shortage of cotton during the Civil War and later after the depredations of the boll weevil, exacerbated in the later case by shortage of foreign exchange after World War I, stimulated production of rainfed cotton in Queensland. In the early 1960s, restrictive US Farms Bills persuaded Californian growers to bring their methods of intensive irrigated production to Australia. So began the modern Australian industry. Over the next 30 years, the industry expanded dramatically and in the course of 15 years Australia swung from being an importer of cotton to the world's 4th largest exporter. Cotton ranks third in Australia in value as an export crop.

The Ord

I came to the Ord in 1970 in time to witness the ecological coup in which King Cotton lost his throne, when *H. Armigera* became resistant to DDT. I was, and remain, challenged by the similarity of the environments in the Sudan Gezira and the Ord valley, both in terms of climate and soil. I was impressed that Norm Thomson's varietal work showed that adaptation to the economic environment (intensive mechanised production) was more important than adaptation to the physical environment (soils and climate). Nevertheless production was abandoned on the Ord, but continues in the Gezira. I always thought research was abandoned prematurely; it was like cowardice in the face of enemy fire. *Heliothis* said *boo!*, and we all ran away. It is a source of great satisfaction that cotton research has been resumed on the Ord with new technology and a lot of hard won wisdom. Intensive cotton production in the tropics is a great challenge; it is afflicted by the interaction of pests and rank growth and is rarely successful. Synthetic growth substances and transgenic varieties now offer hope of success.

Narrabri

Narrabri introduced me to temperate production. Cotton is king in the irrigated valleys between the 22nd and 32nd parallels in eastern Australia. The crop has brought much prosperity and wealth to those valleys, to their towns and to individuals who live there, and even to the nation as a whole. Such are the economic realities. But when we consider the ecological realities, cotton is a usurper, a pretender to the throne. King cotton is an ecologically disruptive crop commanding a vast army of mercenaries to maintain his rule. Production on the Vertisol plains is intensive, highly mechanised, with heavy inputs of nitrogen (up to 200 kg/ha), irrigation water (up to 9 ML/ha), and pesticide (1 or 2 herbicide and 8-10 insecticide sprays). King Cotton had survived an abortive coup in eastern Australia, similar to the one in the Ord Valley, since then he has consolidated and extended his rule. Is cotton to be an ecological tyrant or a constitutional monarch, or better still, with the republican winds of change blowing, an ordinary citizen? This question reflects the conflict embodied in our terms of reference: to develop sustainable systems of cotton production.

Modelling

In 1970, I entered an agronomic culture in the CSIRO Division of Land Research that was buzzing with crop simulation, led by people like Henry Nix and Calvin Rose. Simulation modelling was what I needed and what cotton needed. It provided the means of consummating the love affair. FORTRAN became the language of poetry to describe the beauty of the beloved!

Simulation models are now widely accepted as powerful tools in plant and crop physiology and agronomy (23, 34, 43), despite the overselling that took place in the early years, and Passioura's (32) doubt that modelling is not science. Crop models have always been polarised into the simple and the complex. This was evident in 1970 when I joined the Division of Land Research, with the mechanistic models of Rose's group on one hand and the empirical models of Nix's group on the other. Although Henry Nix then thought they were moving towards each other, the spawning of new models at the poles for the next 25 years has stubbornly kept the poles apart. Wang *et al.* (39) observed that complex models (mechanistic) are as difficult to understand as the biological system they mimic, and tried to *capture the middle ground*. Loomis (22) made a plea for *a few really good models* to replace the many single purpose simple models. The pleas have been answered and the middle ground is occupied by a *plethora of models* (32), the best based on the concepts of modern crop physiology: interception of radiation, conversion to carbohydrate and partitioning among organs (34, 43). Yet the polarisation persists (32, 43).

You all know what I mean by simple and complex models, but they are hard to define. It is easy to put labels on them, 'mechanistic' or 'process based' for the complex, and 'empirical' (sometimes used somewhat pejoratively) for simple models, but that does not define them. It may be better to define models by their purpose or by their method of construction. We need models for two reasons: (i) practical models to solve problems; (ii) research models to understand processes. Most simple or empirical plant or crop models are used as sub-models in an ecosystem or agricultural system model. We build models in two ways: (i) 'top down' starting with the production system and breaking it into components and describing the relationships among them, (ii) 'bottom up' starting with some physiological relationships and trying to integrate them. Many mechanistic models seem to say *have physiology, will travel* - solutions in search of problems.

Passioura's (31) analysis is helpful. Crops are layered, or hierarchically organised, systems. Going down through the levels we might have: ecosystem > community > plant > organ > tissue> cell > organelle > membrane > molecule > sub-molecular. What happens at one level is explained by what happens at the level below and is given significance (or meaning) by what happens at the level above. A description or empirical statement at one level is the basis for an explanation or mechanism for the level above. So one person's empirical model is another's process model. This analysis gives no room for intellectual snobbery about models. Most simple or empirical plant or crop models start at a level high in the hierarchy. Most complex or mechanistic plant or crop models start somewhere in the middle and work up through the levels. Of course, in practice, it is not as simple as that. Most models are not constructed at a single level, but a composite of several levels.

This analysis of hierarchical systems brings into sharper focus the issue of understanding. Understanding is a much over-used, and perhaps misused, word in the agronomist's vocabulary, particularly in grant applications and introductions of scientific papers. What do we understand by *understand*? We claim to do things to improve our understanding because, we say, improved understanding is essential for better management, but often the project and the paper fail to demonstrate either.

Passioura (31) used an effective visual parable consisting of a picture composed of dots of varying sizes. In order to see the picture - to grasp the meaning or significance at a higher level - we have to abandon almost all the detailed information about the dots. To use another analogy, the printing on this sheet of paper could be described in terms of physics (differences in reflection of light by plain paper and paper impregnated with ink), chemistry (differences in chemical analysis of the two categories of paper), or co-ordinate geometry (the location of the black and white areas of paper). None of these descriptions would tell us the meaning of the words. One description at least, the geometric one, would enable us to mimic the appearance of the sheet. That is what a word processor does. Depending on our purpose, it may be adequate. We need to select the level appropriate for the purpose. This is what systems analysis is all about, and many models show no evidence of it.

To understand something in a hierarchical system involves relating it to the level above for significance or meaning and to the level below for explanation. The crucial issue for modelling is how much detail in the lower level. Multiplying the amount of data is not the answer. For example, Wilson (43) reminded us that harvest index is only a final description and tells us nothing of how we got there; making regular observations during the growing season is not necessarily any better. Each observation is a final description of the period since the previous observation, and still tells us nothing of how we got there! We need an example.

The OZCOT story

All this philosophy seems a far cry from *science with its sleeves rolled up!* For me modelling was however not only the consummation of my passion for the cotton plant, but a practical means to solve crop management problems. King Cotton was threatening to become an ecological tyrant in the 1970s. The change of metaphor captures the public perception of the crop in contrast to my personal involvement. The use of pesticides and irrigation water on cotton greatly concerned the public. Simulation modelling was a weapon in our struggle. We needed a model to explore the options for pest and irrigation management at tactical and strategic levels. At a tactical level, we wanted to use fruit counts to evaluate the potential for pest damage during the season. At a strategic level we wanted to identify the 'best bet' strategy for using limited irrigation water supplies in the face of uncertain rainfall. We needed to extrapolate the results of our experiments in a few years and locations to any year, and any location in the cotton-growing regions.

I had tried first to build my own model. I realised I was trying to reinvent the wheel and used other people's models. I also rejected these as they needed too many inputs as well as local calibration. We concluded in agreement with Conway (7) that simulation models at that time were of little value in tactical pest and crop management (17). We used a non-dynamic trajectory of yield development consisting of the number of fruit needed at any time in the season to achieve a specified yield by a specified date. Actual numbers were compared with the trajectory to determine how much pest damage could be tolerated.

The fruit model in SIRATAC was then built in a succession of steps (15):

1. The number of counted fruit that would survive and contribute to harvest was estimated. The day degree requirement for fruit development was used to build an age profile of the fruit counted. The proportion of young fruit shed was estimated as a function of the fruit load (the number of older fruit).

2. Production of flower buds was estimated as an empirical function of the cumulative number of flower buds and the fruit load. The former provided positive feed back and the latter negative feedback. The form of the function took account of the geometry of the branching structure.

3. The model crystallised around the concept of carrying capacity, which is the fruit load that reduces the rate of bud production and rate of fruit survival to zero. The concept implicitly incorporates the carbon economy of the crop; the ratio of fruit load to carrying capacity is a surrogate for the carbon demand/supply ratio for fruit.

The result is a simulation model that is simple and elegant, and which captures the dynamics of cotton fruiting when water and nitrogen are not limiting. It saw more than 10 years service in the SIRATAC pest management system.

We asked 20 years earlier, *Why does the crop close its doors, and why do some bolls drop ou*t? In this model we are saying, *because the older bolls compete against other sinks for the limited assimilate supply, and are successful*. Twenty years previously we could not predict when the crop would stop producing flower buds and how many fruit would shed, or whether crop would compensate for pest damage. Now we could. We had no more data than when these questions were asked. We had got more understanding - relevant understanding. In terms of Passioura's hierarchical scheme, we had to go one level deeper than the three he suggested, not for data, but for concepts on which to configure the empirical descriptions.

	Level in hierarchy	**Activity**
Significance (level n+1)	Ecosystem or cropping system	Management
Description (level n)	Plant	Model
Explanation	Organs	Data

(level n-1)		
Explanation (level n-2)	Carbon economy	Concepts

The centre of our attention (level n) is the plant. We wanted a model that would describe its behaviour in terms of yield and response to pest attack. The significance of this description of the plant is found in the layer above (level n+1) in the behaviour of the ecosystem which we want to manage. The explanation of the description is found in the layer below (level n-1), the numbers of fruit in different age classes through time. We needed a description at this level that could be used in the model of behaviour at level n. In order to describe the changes in the numbers of fruit at level n-1, we had to go down to level n-2 to the carbon economy of the plant. At this level, we did not need data on assimilate supply and demand. What we needed was the concepts of competition amongst sinks for limited supply of assimilates, and the priority of the older fruit over other sinks, both young fruit and the buds generating more fruit.

In the course of use over 10 years a shortcoming became apparent in the SIRATAC fruiting model. At the very high yield levels which some farmers can now achieve, the model predicted compensation for pest damage but the real crops did not compensate (4). This is the subject of current research by Victor Sadras (36). What Victor is doing is extending the descriptions at levels n-1 and n-2. The crucial issue is how much additional detail will be needed. Getting more detail is not difficult; selecting the right detail is.

The OZCOT and hydroLOGIC models were developed from the SIRATAC fruit model by linking it to the Ritchie (35) water balance model for use in situations where water and nitrogen are limiting. Ritchie's model had already been used with a stress day yield function to analyse strategies with limited water supplies (14). A leaf area generator, a boll growth model and a rudimentary soil nitrogen model were added, and photosynthesis included explicitly. OZCOT and hydroLOGIC have been widely used as management tools (12). We had answered Loomis' (22) plea by having one model instead of two, though whether it is *a really good* model is not for me to judge!

A new model, CERCOT, has been built by linking the plant model from OZCOT with the soil water and nitrogen models from the CERES family of models, in order to simulate soil and plant nitrogen dynamics more realistically. Light interception and conversion to dry matter are done in the way pioneered by Monteith and followed in CERES, and partition is linked to the fruiting dynamics. CERCOT is currently in the final stages of validation.

Our modelling has thus gone a full circle. We started by turning our backs on simulation models and using a static model. A simple dynamic model was then built which has been made progressively more complex over the years. At no stage was it more complex than it needed to be to solve the scientific problems being addressed.

Information technology is a good medium to express our knowledge and understanding in the form of simulation models. At first sight, information technology also seems a good medium for delivery of that information to the end users, but I am not convinced. It becomes the tale of two technologies, and problems with information technology compromise the credibility of the crop technology. The tale is not finished but it is one we need to be aware of (13).

Agronomy and Engineering

I greatly enjoy John Passioura's penetrating and stringent commentaries on simulation modelling (30, 32). In his latest paper, he commends the wisdom of the Dutch in calling their agricultural graduates ‘engineers’. Many other countries also do the same, and in the USA in most agricultural research laboratories about a third of the staff seem to be agricultural engineers and most don't work on agricultural machinery!

Passioura draws an important distinction between science and engineering: *Science is about finding how the world works. Engineering is about solving practical problems*. He goes on to suggest that simulation models are more in the domain of engineering than of science, a conclusion especially valid for models constructed for management. Much confusion and tension arise from this, particularly in relation to modelling. In the profession of agronomy, science and engineering are intermingled. As *solving practical problems* is the role of engineers, then the engineering component of our profession is very relevant to our theme *Science with its sleeves rolled up*.

After reading a paper in Nature in 1962 about engineering education (19) I came to the conclusion that agronomy is to plant sciences what engineering is to physical sciences. Johnstone and Passioura acknowledge that a person can be both an engineer and a scientist, but we do well to distinguish the roles and to recognise the inherent tension between them. Bearing this in mind some statements from Professor Johnstone's paper are worth quoting, substituting 'agronomist' for 'engineer'.

A scientist is concerned with knowledge... and is judged by his publications. An engineer is concerned with achievement... is judged by his achievements. He can be a great engineer without publishing a word.

Basically an engineer is not trying to do science. Science is a means to an end, and its quality as science is irrelevant so long as it works.

If you think of an engineer as an applied scientist, it is difficult not to think of him as a second-rate scientist.

Engineers are not second class citizens in the empire of science; they are masters of an empire of their own, of which science is only a part.

Other important things follow when we regard agronomy in general, and simulation modelling in particular, as an engineering activity. Modelling for problem solving is an essentially pragmatic activity. We have moved beyond asking *is it plausible*? (30) to *does it work*? The scientist may say there is not enough data, let's get some more. The engineer makes best use of what data is available.

The basis on which we make value judgements depends on whether we make them as scientists or agronomists. Science can only make value judgements about the way the science is done, not about the worth of the results to the farmer or the public. The scientist can say the experiment was well designed and executed in a workmanlike way. To that extent we can say the results are good, but a scientist has no authority as a scientist to say one treatment is better than another. In the *Biocrats*, a book which highlighted this in relation to medical research, Leach (20) argued that society rather than scientists should decide what is 'good'. We know this as scientists, but Appleyard (2) warns us that often the public does not, and is seduced by science into thinking because it is effective, because it works, because it delivers, it has values and these are good. Science is neutral and we carry into science an agenda from outside science to make value judgements. We need to be up front with that agenda.

We solve the problem of making value judgements by switching hats from scientist to professional. As a professional I am under an obligation to look after the interests of my client. Who is my client? The person who pays me. This used to be simple; it was the farmer, or the Government on behalf of the farmer. But now we have the big S word, *Sustainability*. I have two clients, the farmer and the environmentally aware public. Their interests can clash. What is 'improved' for one client may not be for the other.

This tension came into sharp focus during the development of the SIRATAC pest management program. Many farmers thought we had sold out to the environmentalists, while the environmentalists thought we had sold out to the farmers. A colleague commented, that when we get the same amount of flak from both sides we know we are in the right position. That may be true, but it is not a very comfortable place to be! We have to find a better way.

The tension between science and engineering surfaces when we seek funding. The researchers want to do science and the funding bodies want problems solved, and so we invoke the 'better understanding' argument.

Passioura (30) has said simulation is an art rather than science. I agree. This relates not only to the way we do it as in craft, nor in its aesthetic appeal, but in its value. A novel recognised as a good literature can be a valid comment or insight on life without every character representing a living person. A model can be a valid representation of, or insight into, an agricultural system without every process representing an actual process. Good visual art is not a photographic mimicry of every detail of the real world, but should display an economy of line and avoid fussy distracting detail. Likewise models at the problem solving end of the spectrum are simple.

Some people are better at modelling than others. It is probably related to personality type. Bob McCown's group at Townsville used personality typing to understand the dynamics of their research group, and has been rewarded by their productivity. The reductionists and the synthesiser respect each other and recognise the important contribution of each. Research on the cognitive function of the brain has shown that the left and right sides of the brain process information differently. The left side is analytical and deals with numbers and language. The right side is concerned with synthesis, spatial and temporal relationships, and a global view. An art educator suggests that most people don't draw well because the analytical left side tells them what the object ought to look like and overrules the right side that processes the spatial relationships the eye actually sees. I suggest modelling is a right side activity. It can be learnt, unless inhibited by an overriding left side reductionist mind set!

CONCLUDING REMARKS

I have introduced you to a crop that is always fascinating and sometimes maligned, a crop that has shaped the history of many countries. The range of environments and economic circumstances in which the crop is grown is remarkable, from tropical to temperate, small scale subsistence holdings to large and intensive corporate farms. There has been a dark side to cotton - slavery, colonial exploitation and alleged environmental vandalism. It is the crop the media and the environmentalists love to hate, a crop alleged to exhaust the soil and require the use of excessive amounts of insecticides and irrigation water. But none of these is inherent in the crop itself, though they may say something about the people who grow it, motivated by self interest and greed in common with the rest of humanity. Yet it is the crop that clothes the rest of humanity in natural fibre. Its absence from the agenda of International Research Institutes and Relief and Development Aid agencies is therefore notable, and due I suspect to prejudice of administrators and self interest of donors. Unlike food crops, cotton does not strike a humanitarian cord.

When science rolls its sleeves up they should be the sleeves of a cotton shirt! I have asked some of the questions that arise when science rolls its sleeves up, and not given you any answers. Perhaps I have given you something to think about.

Thank you for recognising my work. I am honoured, but also humbled to be associated in this way with Professor Donald, a great agronomist and a great Australian. Any professional success I have had is a result of this love affair with cotton, with a fair measure of serendipity rather than skill, or luck as some would have it, though I prefer that three letter Anglo-Saxon word - God.

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