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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Farming: closing the cycle

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Farming: closing the cycle

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The natural cycle of plant and animal life involves recycling materials through the open environment. Thus carbon dioxide and many waste substances are released to the soil or atmosphere and returned to be taken up by plants.

Modern agriculture has intensified the production of many substances, with unwanted effects on the atmosphere (including global warming and acid rain), water and soil. Moreover, because most drops are grown as monoculture, competing plants, and pests and diseases, are controlled through a wide range of agrochemicals which also affect the environment; herbicides remain a major case of drinking water failing to meet the required standards.

A 'clean technology' approach is urgently needed, and current research is showing the way. Research on the nitrogen cycle indicates, for example, that nitrogen losses from intensive dairy production can be reduced by up to 70%; however, changes to the whole farm system are needed to achieve results. Both engineering and biological approaches offer ways of reducing pesticide use; we can use computer control and decision support to improve the precision with which chemicals are applied; we can seek new understanding of chemical–insect–plant interactions which allow new control techniques (such as semiochemicals, which influence insect behaviour) to be derived.

Agriculture can also provide a sustainable source of clean energy and could also supply industrial products such as oils and fibres, reducing our dependence on petrochemicals.

1. Introduction

Agriculture provides the food we eat and is a completely natural and clean process. It is also an open process in which carbon dioxide is recycled through the atmosphere and essential nutrients are returned to the soil by plants and animals to be taken up again as the cycle continues. In the last two centuries the human population has exploded from 1 billion to 5.5 billion today and a further increase to 8 billion is expected in the next 20 years. These people all need to be fed and farmers have responded by extending the area of agricultural land, by applying artificial fertilizers and other agrochemicals to increase yields and by using improved crop varieties. At its most intensive, modern agriculture now produces yields that are almost an order of magnitude larger than those of natural plant communities.

Intensification presents environmental problems because of both direct and indirect effects. Direct because agriculture now occupies a very significant proportion of the land area in many countries (e.g. 85% in the UK) and there is less room for natural

Table 1. *Environmental concerns from agriculture*

air	methane nitrous oxide carbon dioxide	greenhouse effect
	ammonia	acid rain, nitrogen deposition
	odour	public nuisance
water	slurries silage effluents fertilizers biocides	surface water and aquifer pollution
	pesticides	drinking water
soil	heavy metals erosion	loss of production
landscape, ecosystem	loss of insects, weed seeds	fewer birds, butterflies, etc.

ecosystems and wild species. Indirect because agriculture is an open system and whatever it does influences the whole of the biosphere. Thus an agriculture that is nitrogen rich emits more ammonia and nitrous oxide, giving higher atmospheric concentrations and higher deposition rates; and all but the most readily degradable of pesticides find their way in small concentrations into natural ecosystems and water courses and exert a subtle change on the balance of organisms present.

In this paper we aim to give an overview of the environmental impact of agriculture and to show how large the effect is compared with other industries. We then consider two examples, the nitrogen cycle and the use of pesticides and herbicides, and show how the principles of clean technology are being applied. Finally, we note that agriculture can provide a clean source of energy and many of the raw materials we need.

2. Environmental concerns

Farming in the UK has both positive and negative effects on many aspects of the environment. There is cause for some concern over emission of greenhouse gases, air pollution, water quality, soil quality and changes to landscape and ecosystems (table 1); and we will consider the contribution that agriculture makes to each compared with other industries.

(*a*) *Atmospheric effects*

Global warming is caused primarily by increases in the atmospheric concentration of carbon dioxide, methane, nitrous oxide and CFCs (Duxbury 1994). Over the last decade, 55% of the effect comes from carbon dioxide (figure 1), caused primarily from the combustion of fossil fuels in power stations, industry and domestic heating and transport. However, a quarter of the total CO_2 increase is attributable to changes in land use and agriculture, including deforestation and conversion of natural grassland to arable cropping. This figure is somewhat controversial and some authors (e.g. Duxbury *et al.* 1993) suggest that native ecosystems and improved agricultural production are now providing a net sink for CO_2 in some regions.

Methane has caused 12% of global warming over the last decade and two thirds

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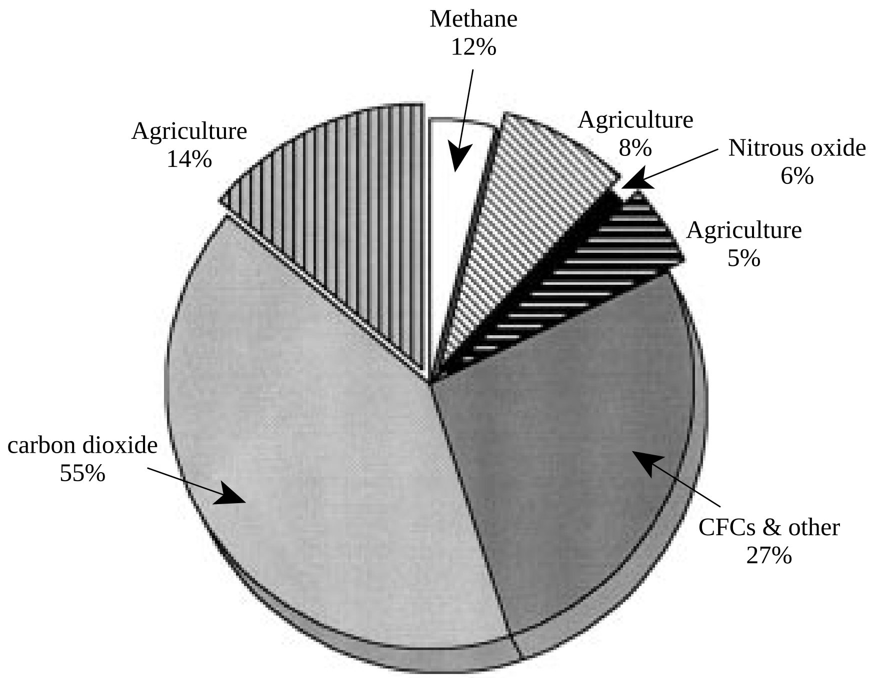

Figure 1. Global contributions to atmospheric warming from 1980–1990 (Duxbury 1994).

of this comes from agricultural sources. Globally, it comes equally from animals and rice paddy fields, though where animals are the only significant agricultural source in the UK, dairy cattle are the worst offenders and account for three quarters of all agricultural output. More than half their emission comes directly from the animals themselves and the rest arises from the slurry. Aerobic soils are, however, an important sink for methane, contributing up to 15% of its global destruction. However, intensive agricultural use of the soil greatly reduces this capacity, thus increasing the net accumulation of atmospheric methane.

Nitrous oxide contributes approximately 6% of the total global warming and most of this comes from agriculture, mainly from nitrification and denitrification processes in soil, but also from animal excreta. Although nitrous oxide makes a comparatively small contribution to global warming at present it is potentially serious because of its long residence time (over 150 years) and its additional contribution, along with CFCs, to the destruction of stratospheric ozone.

Taking all of these contributions together, agriculture worldwide accounts for approximately 25% of global warming.

Ammonia is also an important pollutant. It comes almost entirely from agriculture and is comparable with amounts of oxidized nitrogen that come from mobile sources and combustion. It contributes to acid rain through reactions with acidic gases in the atmosphere (e.g. SO_2, NO_x) to form ammonium salts which are readily transported and deposited over large areas. Direct deposition of ammonia can also change the balance of sensitive ecosystems such as heath land. Ammonia comes mainly from the enzymic degradation of urea in urine, with over half coming from cattle and another 30% from pig production; for both, half of the emissions come from land spreading of slurries with the rest arising directly from animal houses or from slurry stores.

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(b) Water pollution

In 1994 there were no less than 25 415 confirmed water pollution incidents in England and Wales (NRA 1995) and farming contributed to only 13% of these. When considering serious events involving major death of fish or closure of water abstraction this proportion rose to only 16%. The large majority of cases involve cattle production, with effluent from silage clamps, yard washing, burst slurry stores and run-off from land spread manure and slurry all contributing.

Farming is a serious cause of failure of drinking water to meet the necessarily strict standards; however, 73% of all such failures are being caused by herbicides (Thames Water, personal communication). A range of herbicides have caused problems and it is isoproturon, used in winter cereals, which has been the major culprit since 1994.

(c) Soil losses

Soil is an invaluable resource on which agriculture is totally dependent and it is essential that we use it in a sustainable way (Houghton 1996). Worldwide there are very serious concerns about the degradation of soils, with estimates that if degradation continues at its present rate the reserves of agriculturally usable land will probably become scarce by the year 2015. Globally the problems come almost equally from deforestation, over-grazing and poor agricultural management. In Europe industrial activities and urbanization account for 10% of loss of land and the proportion is rising in other continents.

Water erosion is a major source of soil loss worldwide. The problem is less serious in the UK, though sandy and silty soils on sloping land are vulnerable and 15% of arable land is at risk in some years. Of greater concern is the damage caused by roads blocked by mud and the silting up of rivers.

Peat soils have been disappearing fast due to oxidation since they were drained in the last three centuries and 85% have now been lost.

Heavy metal pollution is also a cause for concern where sewage or animal wastes have been spread on the land. Copper comes mainly from pig slurry with some input from sewage and zinc comes equally from poultry waste and sewage. Although these heavy metals have not been shown to affect the yield or quality of crops, there is a measurable effect on soil microbial populations in experimental plots that have received high application rates.

(d) Landscape and ecosystems

Intensive agriculture has led to continuous change in our landscape as hedgerows have disappeared and many farms, especially in East Anglia, have large fields and grow almost continuous cereals. At the same time, populations of butterflies and birds have declined. The RSPB cite (Everett 1996) more than a dozen species of farmland bird whose population is now only a quarter to a half of what it was 20 years ago and the list contains not only the rare corncrake and stone curlew, but also more common species such as the grey partridge, skylark and corn bunting. The reasons are not always clear, but would seem to include the loss of winter food in the form of weed seeds, a decline in insects and other invertebrates and a shortage of nesting sites.

3. The nitrogen cycle

We have already noted that nitrogen in various chemical forms is released and recycled in natural ecosystems. But intensive agriculture has boosted this cycle by

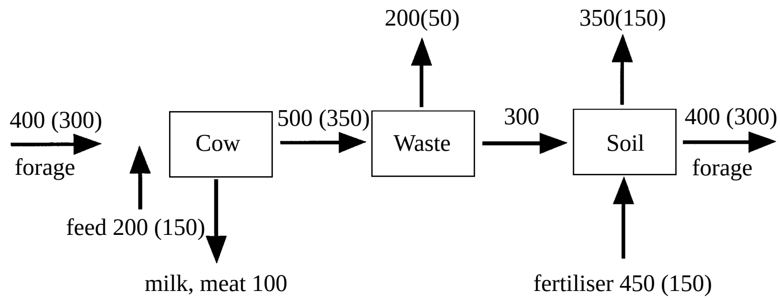

Figure 2. Nitrogen flow (kg) to produce 100 kg of nitrogen in dairy products on an intensive Dutch dairy farm (Aarts *et al.* 1992). Also, shown in brackets are the target figures for the de Marke experimental farm (de Vries 1995).

almost an order of magnitude, so that emissions and depositions now cause serious problems. The question that must be answered is whether we can reduce the nitrogen emissions or losses without also decreasing the amount of food production. As dairy farming and beef production make the largest single contribution to emissions of ammonia and nitrous oxide and to nitrate losses, we will consider those in depth and see how they might be improved.

Aarts *et al.* (1992) produced a very detailed balance sheet for nitrogen flows in an intensive Dutch dairy farm and a simplified version (figure 2) shows the main components needed to produce a 100 kg of nitrogen in milk or meat.

The cow is fed with home-grown forage, typically grass, containing 400 kg of nitrogen and supplemented with 200 kg of nitrogen in bought-in concentrates and roughage. Thus 500 kg of nitrogen is excreted and the cow is converting nitrogen in feed to useful protein output with an efficiency of only 17%.

The nitrogen-rich excreta is removed from the cattle building and stored as solid manure or as slurry before being spread on the land. In current practice, approximately 20% of the nitrogen is lost as ammonia or nitrous oxide directly from the animal house or waste store and another 20% is lost as ammonia during land spreading. Thus 300 kg of nitrogen penetrates the soil and can potentially be used by the growing crop. However, an additional 450 kg of nitrogen as an artificial fertilizer is also applied and almost a half of the total nitrogen supplied is lost to the atmosphere as nitrogen gas or nitrous oxide through nitrification and denitrification, or is leached into surface or underground water as nitrate. In summary, therefore, for every 100 kg of nitrogen exported from the farm in milk or meat, 650 kg is imported in feed or fertilizer and 550 kg is lost to the atmosphere or to water systems.

Aarts *et al.* (1992) went on to show how dairy production might be improved (figure 2) and their ideas are being tested on the de Marke experimental farm (de Vries 1995). The cow is inefficient in converting nitrogen in feed into useful output because the energy to nitrogen ratio of the feed is too low. The maximum nitrogen conversion efficiency that can be achieved is 43% for lactating cows (van Vuuren & Meijs 1987). This may never be achieved in practice, but an increase from 17 to 25% is possible by using less nitrogen fertilizer to grow grass, or by switching to silage maize which has a lower protein content.

The greatest single reduction in ammonia emissions can be obtained by cultivating the soil immediately after land spreading or, better still, by injecting slurry directly into the soil. This gives a maximum reduction of 90%, but probably 50% is the best that can be achieved nationally. Direct loss from the house can be reduced by

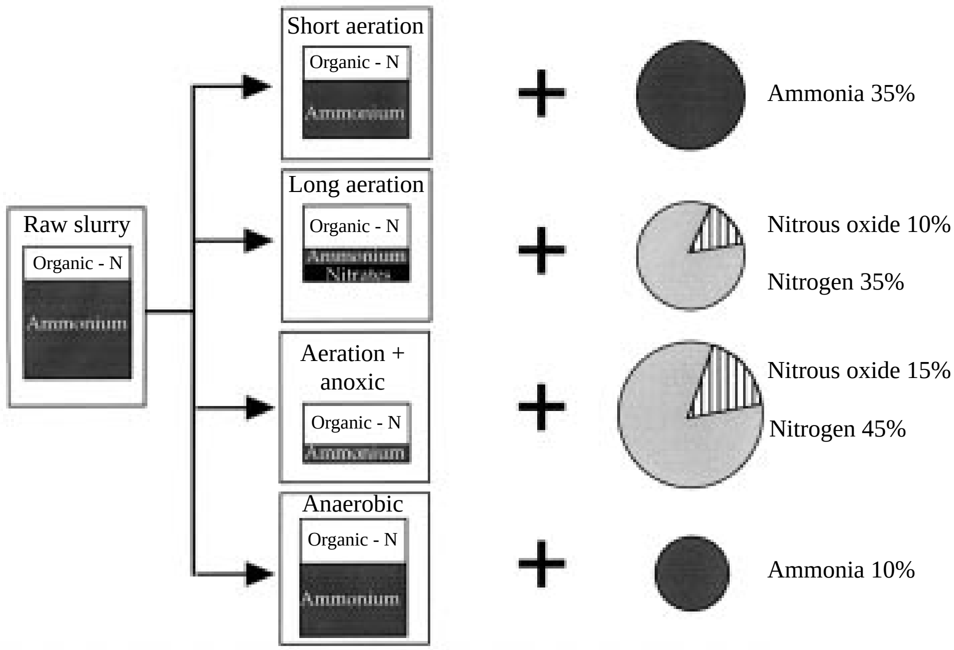

Figure 3. Slurry treatment options to manage nitrogen.

frequent removal of faeces from the stalls and by washing down with recycled effluent (Kay & Cumby 1995), but all of the options are expensive.

Losses of ammonia from slurry can also be reduced by treating it whilst in store (Burton *et al.* 1993). The options (figure 3) show that long periods of aeration (more than three days), or alternate aeration and anoxic treatment, greatly reduce ammonia emissions and leave much of the nitrogen in the store as relatively stable organic nitrogen, thus increasing the opportunity for up take by a growing crop. Much of the nitrogen is lost to the atmosphere as harmless nitrogen gas, thus completing the cycle that starts with the extraction of N_2 from the air to make ammonia as a feedstock for the fertilizer industry, but the emission of small amounts of nitrous oxide cannot be avoided. Anaerobic digestion initially looks attractive, as ammonia emission is reduced, but the nitrogen remains in the treated slurry. The process produces methane and although this can be used as a fuel it is not cost effective on a small scale.

Nitrogen losses from the soil must also be reduced and it is essential that slurry is applied when the crop can use it, and also that the nitrogen is in the right form. Thus storage and treatment in store are crucial. The farmer also needs to know the exact nitrogen content of the slurry and we are currently working in a European project to develop and incorporate rapid methods of measurement in an improved system for slurry use. A decision support system will take account of slurry nutrient content, crop state, soil type and moisture content, and weather forecast, so that risks can be minimized and nitrogen use increased. The combined effect of using slurry more efficiently and growing crops such as maize, which demand less nitrogen than grass, is that inorganic fertilizer application can be reduced by a factor of three and nitrogen losses cut by 70%.

The overall target of the de Marke experimental farm is a 75% reduction of ni-

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trogen losses and they have achieved 70% in the first two years. But there are two words of caution. First, savings in the UK will be smaller because our dairy industry already uses less nitrogen fertilizer per hectare than the Dutch measures proposed and secondly some of the savings will be far too expensive to implement. For example, the cost of reducing UK ammonia emissions by 17% has been estimated (Cowell & ApSimon 1997) at £40 million per year; almost double the value of the nitrogen saved. Savings of 25% would cost £520 million; almost 20 times the value of the nitrogen saved.

4. Pesticides and herbicides

Pesticides and herbicides are an essential part of today's high output farming. When used correctly they cause very little off-site environmental damage, but in practice small amounts of drift, occasional spillage and leaching of more persistent herbicides seem to be unavoidable. Within the target area damage is also caused by, for example, killing non-target insects that do little crop damage and may be ecologically beneficial.

One approach to the problem is to develop pesticides that are more selective in their action and less persistent. Agrochemical companies have been successful in doing this, but as environmental legislation becomes tighter this is now extremely difficult and expensive. The number of new pesticides that come on to the market each year is now only half what it was 25 years ago and for insecticides it has fallen from six or seven per year in the 1960s to only two or three per year in the 1980s. Furthermore, half of the 20 most widely used chemicals in the UK (in order of area treated) are now 20 years old and only four were introduced in the last ten years (Hartnell 1994). At the same time, more than 500 insect species are known to have developed some resistance to existing insecticides. Similarly, at least 55 species of weed worldwide are known to have evolved strains that are resistant to triazine herbicides (Putwain & Mortimer 1989). It was also found (Clarke & Moss 1991) that 7% of the English black grass population is resistant to chlorotoluran, with a further 17% marginally resistant.

It is important, therefore, that we find ways to improve the precision with which existing chemicals are used. The scope for this would seem to be huge, as Graham-Bryce (1977) estimated that as little as 0.03% of a foliar sprayed insecticide is absorbed by the intended target. He also quotes the maximum efficiency of uptake for paraquat as 30% in a greenhouse experiment, but many herbicides are applied to very low populations of weeds and uptake must often be at least an order of magnitude lower.

(*a*) *Precision farming*

One approach is through precision agriculture, in which pesticides are sprayed only to those areas of a field where they are needed. The most advanced example is the control of weeds in cereals. Many of the most pernicious weeds, including black grass and wild oats, grow in the same patches year after year and although the patches can be quite small the damage, if uncontrolled, would be severe. The first and most difficult step is to obtain a map of the weed patches. This cannot be done automatically, but it is possible to streamline the process by using aerial photographs followed by field walking with a portable computer and satellite navigation system (GPS) (Stafford *et al.* 1996). The maps generated are then entered into a computer on board the tractor and used to control the sprayer. The experimental 'patch' (*a*) (*b*)

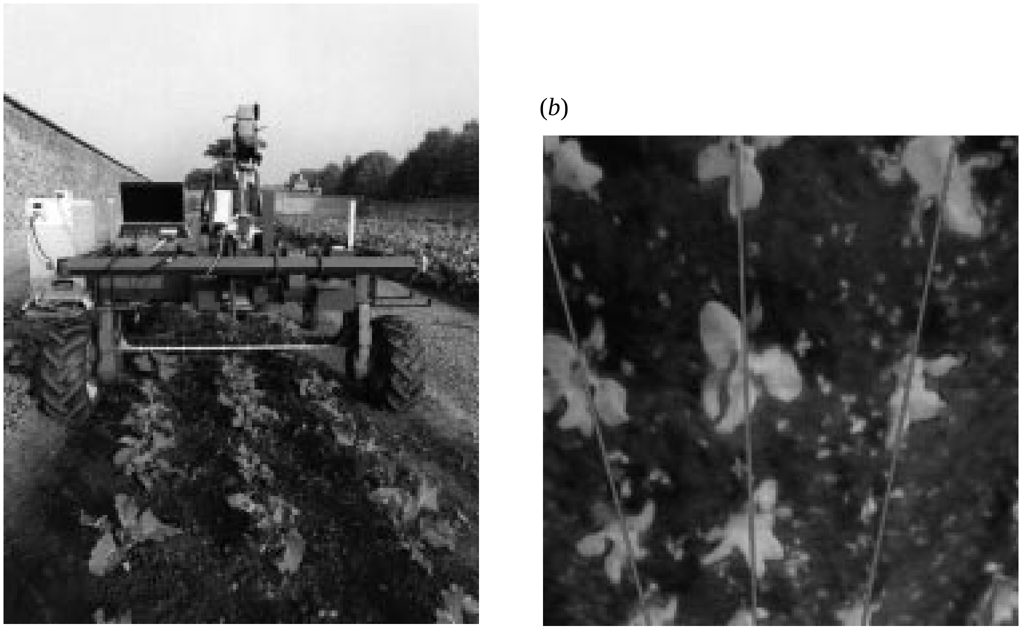

Figure 4. (*a*) Autonomous vehicle guided by a video camera. (*b*) Image of cabbages in infrared with the line of rows fitted by analysis.

sprayer we have developed (Miller *et al*. 1995) has twin booms divided into 2 m sections that can be switched on and off independently. In addition, the bulk liquid tank contains clean water and any combination of two herbicide concentrates can be injected into the flow line at the desired concentration. It is thus possible to spray the whole field with a low level of wide spectrum herbicide and to spray patches down to 2 m square in size with a combination of more potent or more expensive herbicides. Field experiments have shown that applications of some herbicides, such as fenoxaprop-ethyl used for controlling black grass in winter cereals, can be reduced by 50–75%.

Even more precise application may be possible in the future, by using small autonomous vehicles guided by a video camera and software to recognize individual plants (figure 4). Such a vehicle has been developed at Silsoe Research Institute and it can distinguish between crop plants and weeds. It is very early days for this technology, but it would be possible to destroy weeds mechanically without damaging the crop, or to apply specific chemicals to individual crop or weed plants.

Precision agriculture also demands that pesticides are applied at exactly the right time and there is considerable evidence that fungicides, for example, are often wasted. We are therefore developing a 'Decision support system' that is computer based and will give the best possible information to farmers or consultants on what needs to be sprayed and when. The system will take account of crop and variety, stage of growth, prevalence of the pest or disease, soil type and condition, recent past weather and weather forecast. It will then use the best available scientific knowledge to indicate the likely financial gain or loss and the associated environmental hazards from a range of actions.

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(*b*) *The biological approach*

Increased selectivity and reduced volumes of insecticides are also likely to be achieved through a better understanding of the pests we are trying to control. For example, Salt & Ford (1996) have shown that spray drop size and concentration can be tuned to the behaviour of the insects, with best control coming from composite sprays targeted for both short and long term control. More recent work (M. G. Ford, personal communication), therefore, has shown that small drops of highly viscous formulations are most effective against caterpillars that drag their bodies over the plant surface; whereas low viscosity formulations are needed for highly mobile beetles that tread carefully over the surface.

Still more spectacular results can be achieved using pheromones or other semio-chemicals that influence insect behaviour. The most widespread use of pheromones is in traps used for monitoring and Jones (1994) reported systems for no less than 257 pest species. Insecticides are not used until the pest is detected in the pheromone trap and spray timing is thus optimized. In many cases where pest numbers are small, spraying may be avoided completely.

Semio-chemicals can also be used for mating disruption, or for 'lure and kill', but such uses are not widespread. Greater efficiency is likely to come only when the chemical–insect–plant interactions are fully understood and the push-pull strategy (Pickett *et al.* 1997) would seem to offer greatest potential. The push comes from a plant-derived anti-feedant or repellant applied to the crop and the pull comes from aggregation or sex pheromones applied to a sacrificial or trap crop where a selective control agent, such as a fungal pathogen, can be used to kill the pest. It is not hard to imagine such strategies being applied by the autonomous vehicle described earlier. Ideally, the vehicle would be equipped with insect sensors. It could not, with present technology, detect the insect pheromones directly, but could inspect insect traps and take appropriate action when the catch exceeded a given threshold.

Transgenic crop plants will also play a role in the battle against pests and diseases. Genes that confer resistance to insects, fungal and viral diseases have now been identified and transferred to many crop species—notably tobacco, potato and oilseed rape. In some cases the genes are derived from other plants, particularly wild species, that have retained greater resistance than cultivated species (Pickett *et al.* 1997). For virus diseases, fragments of the viral genome are introduced as part of a transgene and can be adapted to operate against most types of plant virus. There are no biohazard problems because the viral transgene need not encode functional viral proteins or indeed any protein at all; the resistance operates at the RNA level (Baulcombe 1996).

Although dramatic progress has been made in the development of transgenic plants, it must not be assumed that they will solve all the problems. Some changes in public perception and legislation will be needed before they can be introduced; some diseases may prove more difficult to combat than others; and transgenics do not offer an obvious approach to weed control without herbicides. It is therefore essential that other approaches, including engineering, continue to be developed in parallel.

(*c*) *Farming and ecosystems*

So far we have focused on ways to reduce the amounts of pesticides used. Although this reduction is highly desirable, we must remember that falling populations of birds, for example, do not come primarily from the direct action of the pesticides themselves, but from the lack of insects and wild plants. If we are to support higher populations of birds and mammals we must find ways to farm that also support a

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much richer ecosystem with higher populations of wild species and continuity in their food chains. The farm must also, of course, continue to provide an increasing amount of human food and it is this dichotomy that needs considerably more research if an effective compromise is to be found.

5. Farming as a source of clean materials

All our major supplies of energy and carbon based chemicals have originated from plants. Fossil sources of gas, oil and coal have offered concentrated supplies at extremely low cost, but there is an environmental price to pay as the carbon is converted back to carbon dioxide. A completely clean alternative is to use the products of current photosynthesis as a source of raw energy and also as a very versatile source of organic chemicals.

To put the energy fixation into context, a crop of winter wheat converts solar energy into a wheat grain with an overall annual efficiency of 0.5%. For this the input costs, including labour and capital, are only 50 pence per square metre. If the most efficient farms were growing for fuel not food they could probably double the output for the same input costs. To compete with this any other solar collector would need to operate with an efficiency of, say, 10% and total operating costs of 50 pence per square metre, or it would need to produce energy of higher value. A study of many renewable energy sources (DTI 1992) showed that none could compete with fossil fuels, but if the price of electricity rose to 7 pence per kWh, crop biomass could provide half of the UK's electricity, more than double the combined potential output from all other renewable sources. These estimates are now being tested at pilot scale in three areas of the UK. Both are growing coppiced willow as the fuel crop, each plans to supply a 5–8 MW power generator from approximately 2000 ha of land.

Crops could also supply many of the fibres that are currently produced from petrochemicals. Some crops, such as linseed and hemp, contain very strong fibres and they could be used for textiles, non-woven fabrics, geotextiles and reinforcement in resin-based composites. Our research aims to find better ways to extract the fibres and we have shown that mechanical separation, which is far cleaner than traditional chemical or enzyme retting, gives acceptable results for many applications.

Crops are also the source of many natural oils. Some, such as palm, soy bean, sunflower, linseed and rape oil, have been produced for many years and are widely used for both food and industrial applications. They offer a fairly restricted range of oils, but the potential range has been vastly increased by the advent of recombinant DNA technology (Murphy 1996). This will allow us to develop new varieties of existing oil crops with completely different oil contents, or to domesticate some of the many hundreds of wild species that contain different and valuable seed oils. The most dramatic developments have been with the transgenic rapeseed and of the 12 new varieties being developed around the world, six are already being tested in the field. They contain a wide range of oils, industrial enzymes, polyhydroxy butyrate, which is the precursor for biodegradable plastic, and novel peptides needed in the manufacture of many pharmaceuticals.

6. Conclusions

Worldwide agriculture and changing land use contribute about a quarter of the increase in greenhouse gases in the atmosphere. In the UK agriculture produces most of the ammonia that is released. Farming causes only 13% of water pollution incidents, however, and this is remarkably low considering that approximately 85% of the surface of the UK is farmed. Soil acting herbicides remain the major cause of drinking water failing to meet the required standards, though relatively few compounds are implicated and it should be possible to overcome the problem through improved guidelines or legislation. The erosion of top soil is a major concern worldwide, especially in the tropics, but is also significant in the UK where early action needs to be taken to avoid a long term and perhaps irreversible effect.

Examination of the nitrogen cycle, especially for intensive dairy production, shows that environmental improvements require changes to the whole system including the feeding regime, slurry handling and management of nitrogen in the soil. A demonstration farm in The Netherlands has achieved reductions of nitrogen loss of 70%, though this could probably not be achieved on less intensive farms in the UK. Also, some of the measures taken, especially to reduce ammonia emissions, are likely to be expensive.

There are major opportunities to reduce the amounts of pesticide and herbicide used. Satellite navigation and field maps showing weed patches that can be sprayed selectively will give reductions of 50–75% for some herbicides and reductions of a factor of ten and more may be possible using machine vision to guide individual plant applications. Much of this technology will be cost effective to apply, but requires a sustained research effort before it can be commercialized.

A major challenge for the future is to develop new crops that will produce clean raw materials for industry and reduce our dependence on petro-chemicals. At the same time we must develop a new systems approach to farming that allows intensive agriculture to co-exist with natural ecosystems if robust populations of wildlife are to be preserved.

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Discussion

G. D. W. Smith (*Department of Materials, Oxford University, UK*). Would Professor Legg like to comment on the UK Government's 'set aside' policy? This seems to pay money to farmers not to use some land at all, while continuing to farm the remainder in as intensive a fashion as possible. Would there not be some benefits in farming more land less intensively, or would this be 'uneconomic'?

B. L. Legg. In this debate on set-aside and on intensive versus less intensive farming two extreme positions are often considered. In one the whole land area is farmed less intensively so that some wildlife can coexist with agriculture. In the other the land is divided into intensive areas with high food production but no wildlife, and the rest is preserved for wildlife with no food production. In my view neither of these extremes is acceptable. What we must do is to modify all agricultural practice to allow increased populations of wild species with minimum loss of production, and then we must note which species are unable to coexist with agriculture and provide for these through set-aside areas on farms or through dedicated reservations. This is a complex optimization process, but I believe it could be achieved if the right research were done.

A. Greenwell (*The Environment Agency, UK*). Professor Legg stated that his aim (in improving agriculture) is to increase the output of food, but this does not seem to be so. He states that a pig is 40% efficient, and that a cow is 16% efficient (in producing food), but people can eat cereals, fruits and vegetables, and this is 100% efficient. He has admitted that animal intensive farming causes a great deal of pollution. Over consumption of animal products also causes health problems in the general population. The Environment Agency is currently dealing with a massive waste disposal caused by mismanagement in agriculture (i.e. the BSE culling). Surely cleaner technology and a more sustainable agriculture would involve increased production of fruit, vegetables and cereals and reduction of intensive animal farming?

B. L. Legg. I do not disagree with this argument, but increased vegetarianism, for example, was contrary to what the majority of people wanted. It is important, therefore, that we explore all possible ways of producing animal products that are environmentally acceptable. Also, in many parts of the world, animals are produced on marginal land that could not support plant crops. In these areas the consumption of animal products does increase the total amount of food available.

J. Skinner (*The Earth Centre, London, UK*). The historical record does not support Professor Legg's contention that only intensive chemical farming can solve the problem of the growing world demand for food. First, the human species has survived for many millennia by using methods akin to what is now called 'organic farming', up until the introduction of chemical farming in the last few years. Secondly, organic farming, as practised in parts of China and elsewhere, is still the only system that is actually proven to be sustainable over millennia. Thirdly, it is the system used in those areas where the highest productivity levels in the world are achieved in terms of production of food per hectare. Fourthly, where modern scientific knowledge has been applied systematically and site-specifically to improving natural sytems of farming, without using imported inputs, the results can prove to be at least comparible with chemical intensive farming in the medium term (cf. Fukuoka).

By contrast, chemical solutions to agricultural problems are notoriously short term, as Professor Legg himself admits. Continuously introducing and withdrawing new kinds of chemicals, as they are found to be dangerous and/or counter-productive, is a profitable business for chemical companies, but it can play havoc with the health of consumers and farmers as well as damaging the environment. We do not hear much about the 'Green Revolution' these days—large tracts of formally fertile irrigated land are now salinated and useless, as a result of using Green Revolution farming techniques. Reclaiming them is prohibitively expensive and we can ill afford to lose them.

Instead of accepting chemical intensive farming as the norm and trying to improve it by making it less damaging, it might be wiser for us to re-examine natural systems and try to understand them. By doing so it may be possible to find ways of increasing production on a sustainable basis without using up non-renewable resources. Our overall ignorance of natural systems and of the impact of farming on local ecologies is so huge that noone is in a position to state catagorically what is the best answer or indeed if there is one—at some point population will inevitably outstrip resources if it continues to expand at present rates indefinitely.

There is ample evidence that ignorant tinkering with natural systems through chemical and other kinds of ill-judged interference is likely to prove counter-productive in the long run—even though it may swell the short-term profitability of chemical and biogenetic companies. Unfortunately, massive R&D funding is being poured into the kind of 'end-of-pipe' research described by Professor Legg and scarcely any into researching natural systems. It was interesting that he implicitly acknowledged this, where he referred to the need for more research on IPM, reintroduction of 'weeds' and other ways of restoring an ecological balance.