Global change and food and forest production: future scientific challenges

P.J. Gregory a,*, J.S.I. Ingram b

a Department of Soil Science, The University of Reading, PO Box 233, Whiteknights, Reading RG6 6DW, UK
b GCTE Focus 3 Office, NERC Centre for Ecology and Hydrology, Crowmarsh Gifford, Wallingford, OX10 8BB, UK

Abstract

Production of food and forest products will need to increase to meet the world’s projected demand. This challenge can be met by either extensification or intensification but, with little new land available for agriculture in many regions of rapid population growth, intensification will be pre-eminent. Global, average cereal yields will need to rise from the current 2.9 to 4.2 Mg ha$^{-1}$ by 2025. The task of increasing production will be made more complex by the additional and interactive effects of changes in climate, atmospheric composition, land use and other global change drivers. However, increasing production with existing technologies will, itself, enhance these major drivers of global change and have other substantial impacts.

The global change agenda relating to food and forest products considers research into impacts, adaptation and mitigation. Adaptation and mitigation need to be considered together to harness new technologies (including the use of biotechnology and computer-assisted management schemes) and integrate them with existing technologies in production systems. Better economic, finance and trade policies will also be necessary to allow more open trade of food and forest products. These factors, together with the positive effects that increased atmospheric CO$_2$ concentration will have on yield will reduce the degree of intensification required to meet demand, thereby mitigating some of the unfavourable environmental consequences. However, there are several social and biophysical management issues associated with intensification that have proven intractable to past research approaches that urgently require resolution.

Further research on improving nutrient use efficiency and other aspects of agronomic practice is clearly needed both to increase production and reduce harmful effects on other ecosystems. The effects of fluctuations of weather in the short term on agricultural production systems also warrant further study so that the longer term effects of climate variability and change can be better managed. Multidisciplinary research and interdisciplinary approaches to modelling will be required to apply knowledge both from individual crops to agricultural systems and from plot-scale research to regional food supply issues.

© 2000 Elsevier Science B.V. All rights reserved.

Keywords: Adaptation; Extensification; Global change; Intensification; Mitigation

1. Introduction

Global change is a primary environmental concern both to the scientific community and to society at large. Increasing concentrations of atmospheric CO$_2$ and climate change are well known examples of global changes and together with changes in land cover and
land use formed the initial focus for research (as drivers of global change) within the Global Change and Terrestrial Ecosystems (GCTE) Core Project of IGBP (Tinker and Ingram, 1996; Walker and Steffen, 1999).

One area of particular concern is global change and food and forestry production. Changes in agricultural and forestry production systems (e.g. use of fertiliser or application of a particular pesticide) usually occur at local scales but as the frequency of use increases, changes occur that become globally significant. The global change research community has tried to understand the impacts of global change on components of production systems, and hence what this may mean for human concerns such as food security. However, the increasing human demand for food and forest products is in itself a major cause of global change (Gregory et al., 1999), but this aspect has received less attention. For example, human intervention in the global nitrogen cycle has now become so pronounced that more nitrogen is “fixed” in fertilisers and legumes in agricultural systems than is fixed by natural processes (Vitousek et al., 1997). The enhanced losses of N from agricultural land to adjacent areas such as watercourses can have major impacts on ecosystems (Matson et al., 1997).

The need to increase food and fibre production, the complications that global change will bring in achieving this, and the likely environmental consequences of satisfying demand with current technologies, are the subject of this paper.

2. The need to increase production

The growth in human population over the past century has been closely associated with increased production of food and forest products (Dyson, 1996). In the last 30 years or so, grain production has increased slightly faster than population but this increase has not been uniformly distributed and the number of chronically undernourished has remained relatively stable at about 700–900 million (Dyson, 1996). Overall, a population of about 6 billion today is projected to rise to about 8 billion (medium variant) by about 2025 with most of the increase in the less developed nations of Asia and Africa (Fischer and Heilig, 1997). These estimates show regional differences in the expansion of population with large percentage increases in Africa (102%) and West Asia (77%) but with the largest increases in absolute numbers in south central Asia (734 million). Along with this change will be an increasing trend towards urbanisation which will reduce the area of prime agricultural land, decrease the availability of rural labour and increase the pressures toward the intensification of crop production (Alexandratos, 1995).

Given the close association of population and grain production, and allowing for changes in diet towards greater consumption of meat, it is possible to estimate the required grain production (wheat, rice and maize together supply about 60% of the total carbohydrate) to feed the additional human population. Annual population growth of 80 million requires an annual increase in grain production of about 26 million tonnes, more if allowance is made for rising affluence (Crosson and Anderson, 1994). At the same time, the production of forest products will also need to increase to keep up with the projected demands for lumber and paper. For example, Alexandratos (1995) estimates that world consumption of forest products will increase annually by 1.4% for fuelwood and charcoal, 3.1% for paper, and 4.6% for panels in the period 1990–2010.

There are two major means whereby the projected increases in regional food production can be achieved. First, by expanding the area of cultivated land (extensification) and second, by intensifying the production system either by increasing the number of crops sown on a particular area of land or by increasing the yield per unit area of individual crops, or both (intensification). Where other economic activities allow, purchasing food from elsewhere can enhance food supply locally. Globally, no one means will be adopted and different regions will increase production in different ways (Alexandratos, 1995). Table 1 shows that

<table>
<thead>
<tr>
<th>Region</th>
<th>Area</th>
<th>Yield</th>
<th>Intensified cropping cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-Saharan Africa</td>
<td>30</td>
<td>53</td>
<td>17</td>
</tr>
<tr>
<td>Near East/North Africa</td>
<td>8</td>
<td>73</td>
<td>19</td>
</tr>
<tr>
<td>East Asia</td>
<td>34</td>
<td>59</td>
<td>7</td>
</tr>
<tr>
<td>South Asia</td>
<td>4</td>
<td>82</td>
<td>14</td>
</tr>
<tr>
<td>Latin America/Caribbean</td>
<td>29</td>
<td>52</td>
<td>19</td>
</tr>
<tr>
<td>Developing countries</td>
<td>19</td>
<td>69</td>
<td>12</td>
</tr>
</tbody>
</table>

(excluding China)
most (81%) of the increased production in developing countries is expected to come about through intensification via increased yield of individual crops (69%) and intensified use of existing land (12%). In South Asia there is little new land that can be brought into cultivation so that almost all of the increased production will be through increases in yield and crop intensification (e.g. more rice (Oryza sativa) crops per year or rice grown in rotation with an upland crop such as wheat (Triticum aestivum) or a legume). In Central and South America, a large amount of new land is still available for cultivation and a substantial percentage (29%) of the projected increases in production might be met in this way although the costs of introducing infrastructure such as roads is high. In Africa too, there is potential for expansion of the cultivated area but the land is often far from centres of population and infrastructure is poor. Yields will still need to increase substantially on land currently under crops.

The principal conclusion of many such analyses is that yields per unit area will need to increase substantially to meet demand. In fact, this will be a continuation of the past trend which has seen the area harvested per capita decline from about 0.24 ha in 1950 to 0.125 ha in 1993, while global cereal yield has increased from 1.2 to 2.8 Mg ha$^{-1}$ over the same period (Dyson, 1996). Even if the increased production is shared between extensification and intensification, global average cereal yields will need to rise from their current 2.9 to about 4.2 Mg ha$^{-1}$ by 2025.

### 3. Global change as a complicating factor in meeting demand

It is well realised that the changes in the major global change drivers (Walker and Steffen, 1999) will affect different aspects of production systems in different ways, sometimes beneficially, sometimes adversely. Changes in climate and climate variability, in nitrogen deposition and in atmospheric composition are of primary interest as these all have a direct bearing on agriculture and forestry. While some aspects of the direct impacts of individual drivers acting on components of production systems are now relatively well understood (e.g. elevated CO$_2$ on plant physiology, or temperature on insect pest dynamics), the interactive aspects and their effect on global change impact is still far from clear. This makes the development of strategies to adapt to, and therefore cope with, global change impacts difficult. For example, it is well known that temperature can affect the development, growth and yield of many crops but quantifying how a particular climatic sequence will influence production in the field is very difficult. Hayashi and Jung (2000) sought to explain the observed variability in rice yields in Japan and South Korea (Fig. 1). Linear trend analysis indicates a 2.4% per annum increase for Japan and a 4.9% increase for Korea for the period 1969–1996. Even if the increased production is shared between extensification and intensification, global average cereal yields will need to rise from their current 2.9 to about 4.2 Mg ha$^{-1}$ by 2025.
be a complicated and challenging task. It will be complicated still further because global change means that optimum crop and forest management will be difficult to plan.

4. Environmental consequences of increased production

Production systems increasingly play a significant role in enhancing global change and other aspects of environmental degradation. The environmental consequences of producing more food and forest products will vary regionally and depend substantially on whether intensification or extensification is the main pathway for achieving the increases. Different factors operate at different temporal and spatial scales and their effects may be realised both on and off the site of production (FAO, 1996; Tinker, 1997). The effects of changing land use on the environment are potentially different depending on whether extensification or intensification is the principal driver. Fig. 2 relates changes in land use to some current environmental and societal concerns and indicates the different biophysical processes operating in the extensification and intensification pathways.

(a) Land Use Change: Intensification/Extensification

(b) Land Use Change: Intensification/Extensification

Fig. 2. Summary of the different biophysical processes and their pathways and impacts following land-use changes that result in either (a) extensification or (b) intensification.
4.1. Extensification

The main environmental consequences resulting from extensification are: (i) the emission of greenhouse gases (especially CO$_2$) and changes in other climate forcing factors (e.g. albedo); (ii) the impacts on soils and (iii) the destruction of habitats leading to reduced biodiversity and the loss of species.

Most extensification involves the clearing and subsequent burning of aboveground biomass. A major environmental impact of this process is the production of greenhouse gases, although the nature of the vegetation cleared and the method of clearing affect the types of gases produced: hot, rapid fires increase the CO$_2$ : CO ratio. In addition to CO$_2$ production, the transfer of particulates and other trace gases associated with the burn potentially play a role in altering climate (Crutzen and Andrea, 1994; Tinker et al., 1996). They also have a more immediate and local impact in decreasing air quality. For example, widespread clearing of forests in Kalimantan and Sumatra in 1997 resulted in a long-lasting regional haze, poor air quality and loss of life (Tomich et al., 1998; Stolle and Tomich, 1999).

Clearing also has direct physical effects on soils. Erodible sub-surface soil can be exposed, particularly if mechanised methods are used, and other soil physical properties (e.g. bulk density) can be adversely changed (Dias and Nortcliff, 1985; Alegre and Cassel, 1996). At Yurimaguas, Peru mechanical clearing of forest increased bulk density by up to 19% (from 1.16 to 1.42 Mg m$^{-3}$) and reduced infiltration rate from 420 mm h$^{-1}$ before clearing to as little as 35 mm h$^{-1}$ afterwards (Alegre and Cassel, 1996). These changed properties increased the amount of runoff, decreased root penetration thereby limiting crop growth, and decreased the subsequent rate of growth of the succeeding fallow vegetation.

Land clearing also radically reduces a site’s biodiversity because while larger, mobile organisms may escape, the majority of aboveground organisms are destroyed. The amount of damage to belowground organisms depends on the clearing method. Hand felling to leave stumps and occasional trees causes least damage whereas clearing by bulldozer and/or drag chains can remove the surface soil thereby reducing the site’s inherent fertility and depleting the seed stock for re-vegetation. This is especially so if cleared vegetation is pushed into windrows for later burning. While belowground organisms may escape immediate damage, the loss of aboveground inputs may rapidly affect these communities and change ecological complexity. The size, geometry and geography of the sites cleared are also critical to the impact on different species because they affect the opportunities to escape the disturbance, the likelihood of finding a suitable refuge in which to survive, and the ease of re-colonisation during a fallow period, should this occur.

In addition to reducing biodiversity at a site level, removing native vegetation and replacing it with plantations, pasture, cropland and urban areas is leading to a major extinction of species (Leakey and Lewin, 1995). Although precise rates of extinction are uncertain, current rates appear to be 100–1000 times greater than pre-human levels and are still increasing (Reid and Miller, 1989; Pimm et al., 1995; Harvey and May, 1997). Many extinctions have occurred as a result of wholesale clearance of vegetation but more subtle changes in management can also influence the fate of species. For example, dry pastoral lands (rangelands) make up about 60% of Australia and substantial areas of Africa and the Americas and the primary land use is pastoralism where domestic stock (cattle, sheep and goats) have been introduced to graze native vegetation. In Australia, there have been deliberate actions to introduce both animals as stock and exotic species of plants as forage, to clear overstorey trees, to cull a major predator (the dingo), and to provide artificial sources of water. The effects of introducing artificial watering points on the distribution of plant and animal species are substantial and complex (James et al., 1999). Fig. 3 summarises recent work showing that some species of plants and animals are less common where grazing pressure is high (close to water points) and that some species only occur where there is little or no grazing. These latter sites are typically a long way (>8 km for sheep and >12 km for cattle) from water points. Although numerous water points are the recommended best practice for reducing soil erosion, maintaining forage and maximising production, the proliferation of water points is leading to substantial areas where no light grazing exists and to loss of species.

The major areas remaining for continued extensification are predominantly in the tropics where the subsequent effects of clearance on the main drivers
of global change are likely to be large because of the large existing biomass and its diversity. In much of the tropics, extensive agriculture was traditionally practised through shifting cultivation. When yields fell below an acceptable level due to either decreased fertility or weed encroachment or both, the site was then abandoned in favour of a new one (Nye and Greenland, 1960; Sanchez and Benites, 1987; Ramakrishnan, 1994). With low population pressure, the abandoned site might have been left for several decades to develop secondary vegetation similar to the original, before being cleared again for cropping. The inherent sustainability of the practice hinged on the relatively small area that was cleared allowing the biota to move in and out easily, and on the long period of fallow. While there was obvious disturbance to the site during clearance and cultivation, the net environmental impact was slight because: (i) declining soil fertility was reversed during the fallow period; (ii) CO₂ emissions during burning and tillage were compensated for during fallow re-growth and (iii) species returned to the site during fallow which re-built diversity. Soil erosion may have increased locally during the cropping phase but this was hardly noticeable at the landscape scale.

The traditional sustainability of the system is now being undermined because increasing population pressure, especially in forest margins, is shortening the period of fallow (Vosti and Witcover, 1996). The combination of reduced fallow plus increased cropping period leads to a reduced ratio of cropping time to fallow time which is associated with further site-related problems such as increased erosion and compaction (Alegre and Cassel, 1996) and decreased nutrient reserves (Juo and Manu, 1996). Reduced ratios of crop:fallow time reduce soil fertility, which in turn reduce agronomic yields and leads to slower recovery during fallow (Nye and Greenland, 1960).

While increases in local populations per se, due to high human fertility and reduced mortality, are partially responsible for the reduced length of fallows, migration into such areas is often the dominant factor. Well known examples can be found in Indonesia and the Brazilian Amazon, but it is also evident in parts of Africa (e.g. migration raised population in the forest zones of the Ivory Coast from about 15 people km⁻² in 1965 to almost 40 in 1989 while population in the savannah zones over the same period only increased from 11 to 13 people km⁻²; Vosti and Witcover, 1996). A crucial issue is that migrant populations also often arrive lacking the local knowledge required to manage land in an environmentally sound manner.

4.2. Intensification

Many of the environmental consequences of intensification are similar in type to those of extensification (Fig. 2) except that the major emissions of greenhouse gases are as CH₄ and N₂O and that there are often large effects on water supplies through off-site movement of nutrients and agrochemicals.

Intensification of production is normally accompanied by changes in management and genotype, and by increased inputs especially of nutrients, water and agrochemicals (Matson et al., 1997). Globally, fertiliser use has increased in parallel with increases in world cereal production and the human-induced fixation of N through fertiliser production and biological fixation of N by crops (≈140 Tg a⁻¹) now exceeds estimates of “natural” global N fixation (≈110 Tg a⁻¹, Vlek et al., 1997; Vitousek et al., 1997). Nationally, average cereal yield has frequently increased linearly with the quantity of fertiliser applied per unit area (Evans, 1993). In developing countries, fertiliser consumption has also increased from about 4 Tg of N + P₂O₅+K₂O in 1962 to 65 Tg in the early 1990s. On a world-wide basis, the quantity of nutrients harvested can be estimated based on the total production and the typical concentration of nutrients in grain (about 20 kg/Mg N and 20 kg/Mg P₂O₅ and K₂O together) to give removal of 80 Tg
annually (Vlek et al., 1997). Allowing for the fact that cereal grains contribute about one half of the total harvested produce and that straw may also be removed, Bumb and Baanante (1996) estimated that current removals of plant nutrients were about 230 Tg annually (cf. annual fertiliser production of 130 Tg). With the projected increases of yield required to meet the growing world population, projected demand for fertilisers in the developing world will increase from 62 Tg in 1990 to 122 Tg in 2020 (Bumb and Baanante, 1996). Although the global use of fertilisers has increased substantially in the last 30 years, the distribution of use is uneven. Fertiliser applications to crops of rice and wheat in Asia have increased considerably since 1960 (Greenland, 1997) but in sub-Saharan Africa fertiliser use is uncommon and depletion of soil nutrients is common at various scales in many countries (Smaling et al., 1997).

In those regions using fertilisers, the chief environmental concern with the current levels of use is the off-site effects in relation to losses to both the atmosphere and surface and ground water bodies. Typically, 20–60% of the N fertiliser applied is recovered by a wheat crop, 20–60% remains in the soil and, on an average, 20% is lost from the soil/plant system (Pilbeam, 1996). Global emissions of N₂O from cultivated land are currently estimated at 3.5 Tg annually, of which 1.5 Tg is directly attributable to fertilisers (emissions are typically 1.5±1% of fertiliser applied; Smith et al., 1997). Such studies clearly indicate that the greater the amount of fertiliser applied, the greater the likely losses.

Losses of nutrients by leaching and runoff to watercourses are serious locally and in the short-term because they affect supplies of drinking water and other ecosystems. Though the link between fertiliser use and leaching is normally indirect (Addiscott et al., 1991), increased nitrate concentrations in rivers and aquifers have given rise to concerns about the quality of drinking water. For example, Whitehead (1990) quoted annual average nitrate-N concentrations in the Thames at Walton, UK, rising from 4.2 to 7.7 mg l⁻¹ between 1968 and 1979 and in the Great Ouse at Bedford, UK concentrations similarly rose from 6.1 to 9.0 mg l⁻¹ between 1971 and 1985 (Addiscott et al., 1991). The recent assignment of nitrate exclusion zones around wells and on land overlying aquifers in the UK has been a significant development in ensuring the future quality of water supplies and heralds a change in the management of N in intensive cropping systems.

Leaching of P in solution is usually slight because of adsorption by soil colloids and P loss to water normally only occurs in suspended soil colloidal materials via erosion. However, in sandy soils close to water such as occur in the coastal plain of south western Australia, direct leaching of P can deliver sufficient P to estuarine systems to render them eutrophic. Treatment of selected parts of catchments with highly adsorbing bauxite waste may reduce P treatments to the estuary (Summers and Pech, 1997) but, more generally, improving the management of P fertilisers to avoid over application should reduce the export of P from farm land (Weaver and Reed, 1998).

Intensification has also resulted in increased use of other agrochemicals to control pests, weeds and diseases, though the history of their development is more complex than that of fertilisers (Evans, 1993). Losses of yield due to these factors are substantial (probably typically in the range 15–65% but up to 100% in some parts of the tropics) but precise measures of impact are difficult to obtain because of the wide variety of crops and interactions with pests, weeds and diseases that are possible. The use of herbicides continues to increase as labour for weeding becomes scarcer but improvements to the efficiency of insecticides and fungicides and the development of integrated methods of pest control are gradually reducing the scope for harmful off-site effects. Residues in food and the adverse effects on other wildlife continue to cause public concern and such concerns are unlikely to abate.

5. Future scientific challenges

Food supply and food security in the 21st century will continue to depend on the interaction of socio-economic, political and biophysical factors. In reviewing the long-term prospects for food security, Pintstrup-Andersen et al. (1997, 1999) concluded that: (i) soil fertility must be improved to increase sustainable agricultural production; (ii) supplies of fresh water are becoming a constraint to food production in some regions and (iii) better economic, finance and trade policies will need to be implemented in many countries. In addition to these influences, and that of
Table 2
Summary of future scientific challenges

<table>
<thead>
<tr>
<th>Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop better crop models for systems analysis</td>
</tr>
<tr>
<td>Improve crop plants to increase yield in adverse environments and reduce reliance on agrochemicals</td>
</tr>
<tr>
<td>Improve cropping systems to minimise the inefficient use of inputs (especially chemicals) and maximise C sequestration</td>
</tr>
<tr>
<td>Determine the role of biodiversity in agroecosystem functioning (segregation vs. integration)</td>
</tr>
</tbody>
</table>

land-use change, must be added the complications caused by fluctuations of weather in the short term and of climate change in the long term. The independent and interactive effects of these “drivers” of global change present a formidable research challenge. Table 2 summarises the major biophysical research challenges that arise from global change and potential feedback and feedforward issues and can be classified into three main areas: impacts, adaptation and mitigation.

Throughout these three areas, however, the issue of scaling is common. Because most crop production models were developed for plot-level analyses, considerable effort is needed to develop methods to “scale-up” results from this level to that of the whole farm, locality or region. As the scale of interest increases, the nature of the biophysical determinants of production may also change; a phenomenon at plot-scale may be irrelevant at land-scale scale, and vice versa. The many and complex socio-economic aspects of agriculture also become increasingly important, and these must be included in the analyses. The challenge of “scaling” is therefore to gain sufficient understanding to build new models that both accommodate changing biophysical aspects and integrate diverse socio-economic parameters across temporal and spatial scales.

5.1. Impacts research

Impacts research concerns the effects of changes in environmental variables on production systems. Several major syntheses of the potential impacts of global change on production systems have recently been undertaken (e.g. Gregory et al., 1999; Rötter and van de Geijn, 1999). From these it is clear that most work has considered the impacts of changed temperature and CO₂ concentration on individual crop and forest species at plot level, with the more complex issue of global change impact on production systems receiving relatively little attention. Models of agricultural systems need to be developed which are spatially robust, so that they can be used with confidence to explore the impacts of changed environmental scenarios on production. First, however, the “mono-crop” models for wheat, rice, etc. need to be improved by the specific inclusion of edaphic and biotic constraints to plant growth. The most significant impacts of global change may come about through changes in the incidence and severity of pests and diseases, in plant-available nitrogen due to changes in soil organic matter dynamics, and in water availability. Models of complex systems involving spatial and temporal mixtures of species also need to be developed to analyse global change impact on smallholder agriculture.

5.2. Adaptation research

Adaptation research is aimed at developing technologies and systems to help “cope” with global change. Given that global change is happening, albeit with different aspects manifesting themselves at different rates, farmers, foresters and other land managers need to have appropriate strategies to hand as the nature of global change becomes clearer for given regions of the world. For long-rotation systems (e.g. boreal forest crops) in particular, but for all systems to some extent, these strategies must draw in part on the impacts research discussed above; it is difficult to plan for the unknown. Production systems need to be developed to be buffered against deleterious aspects of global change, and to exploit the beneficial aspects of global change. This will necessitate an integrated approach involving, from a biophysical viewpoint, (i) plant breeding and emerging aspects of biotechnology to develop plants and animals more resistant to abiotic stress; (ii) improved management of soil and water, and of other
aspects of the natural resource base to protect in situ biodiversity and (iii) the development of models to explore the robustness of given management packages to global change drivers, including their interactions with pests and diseases.

5.3. Mitigation research

Some communities will be vulnerable to the impacts of global change unless measures are taken to minimise the principal global change drivers. Increased production of food and forest products is a major contributor to global change, but may also offer possibilities for mitigating some aspects, particularly those relating to climate forcing. Research challenges for mitigation fall broadly into two categories: first minimising further global change “forcing”, e.g. greenhouse gas emissions, and second, actively removing CO$_2$ from the atmosphere by sequestering carbon in soils and biomass.

Extensification makes a large contribution to CO$_2$ emissions so that a major means of mitigating further emissions is to minimise further extensification by intensifying production in areas that are already cropped; this may also serve to conserve biodiversity. An estimate by Nelson and Maredia (1999) showed that the introduction of high yielding varieties as part of the “green revolution” saved 170 million hectares of forest from cropping in Africa, Asia and Latin America in the period 1970–1990. Assuming an average carbon stock of 100 Mg C ha$^{-1}$, this represents a saving of 17 Gt of carbon, equivalent to 2–3 years of total global C emissions. Intensification can, then contribute to reducing CO$_2$ emissions. However, the carbon stocks of forests do not account fully for the changes wrought. More recent analyses by Grace et al. (personal communication), in which a full carbon accounting approach was taken including the C costs of N fertiliser production and consumption, increased CH$_4$ production from paddy rice, and the burning of increased crop residues, showed emissions of about 13.3 Gt for the same period. The net effect (about 7.7 Gt C) was therefore considerably lower than the biomass-saved calculation, although it must be remembered that the primary goal was to produce more food, and this was successfully met.

The other approach to mitigation where agriculture and forestry can play a role involves actively removing carbon from the atmosphere and sequestering it in soils and biomass. The dynamics of carbon turnover in biomass and soil organic matter are relatively well understood, at least at the plot-level. The scientific challenge here is to scale-up these plot-level estimates and to make effective links with models and other research output relating to land-use change and policy. Improved modelling tools are needed to explore the efficacy of various land management options, underpinned by an improved understanding of the competing uses to which land is put. This will determine the most appropriate ways to sequester carbon in soils. As with the hidden costs of C involved in crop intensification, Schlesinger (1999) has drawn attention to the hidden carbon costs involved in management to increase the soil organic matter content of soils. Conservation tillage may have an important contribution to make but applications of fertiliser, manure and irrigation all involve carbon costs in terms of CO$_2$ emissions to the atmosphere.

Overall, adaptation and mitigation research must be closely linked and developed in concert with research aimed at intensifying production. The trend towards intensification of crop production, the loss of food diversity, and the use of breeding programmes to reduce the amount of non-harvested biomass, raise critical questions about the direction of agricultural research in developing new systems of production especially in non-temperate regions. In essence, the issue is whether to segregate the elements of agriculture into ever more specialised and intensive units and deal in turn with the environmental consequences (which include conservation of biodiversity) or whether production can be integrated in approaches to land use (Van Noordwijk et al., 1997). Van Noordwijk and Ong (1999) examined the hypothesis that agroecosystems can benefit from resembling both the structure and function and the diversity of natural ecosystems. Such a hypothesis is particularly relevant to the integration of trees and crops in forested regions of Asia and Africa. It is noteworthy, though, that the integration of multiple functions of “use” into the landscape is also becoming an issue in Europe where urban populations no longer view food production as the only, or primary, function of rural areas. For many reasons, then the segregation–integration nexus is an important research issue.
5.4. Improving nutrient-use efficiency

Closed nutrient cycles with low losses to water and the atmosphere are a typical feature of low intensity, sustainable agricultural systems, where multiple species are often managed on the same small plot of land, akin to more natural vegetation. Clear evidence is starting to emerge that there are advantages to both productivity and the environment if managed land-use systems mimic the patterns of resource use exhibited by natural ecosystems in the same location. For example, integration of perennial vegetation and rotation of annual and perennial crops can tighten N cycling in agricultural landscapes. Fig. 4 shows the profiles of nitrate concentrations beneath maize, banana and woodlot patches on smallholder farms in western Kenya. Subsoil nitrate (0.5–4 m) after maize harvest was 37 kg N ha\(^{-1}\) beneath good maize crops but only 2 kg N ha\(^{-1}\) beneath the woodlot and hedgerow resulting in potentially less nitrate loss off farm where trees were grown in rotation with maize (Shepherd et al., 2000).

Closing nutrient cycles to sustain intensive systems remains a considerable challenge for the future. In addition to reducing greenhouse gas production and other forms of pollution, improving the efficiency with which inputs are used will increase profitability and conserve natural resources. The real challenge is therefore to develop more productive, yet more environmentally-benign production methods. Essentially this means improving the efficiency with which nutrients (particularly nitrogen), water and other inputs are used.

6. Conclusions and the scientific challenge to GCTE

The increasing demands for food and forest products coupled with the uncertainties introduced by global change require modifications to the global change research agenda. Much of the research to date has been on the potential impacts of global change but given that global climate change, in particular, is now widely recognised, a greater emphasis on adaptation and mitigation research is now warranted. The major scientific challenges are to:

1. Improve crop plants to increase yield and decrease reliance on agrochemicals.
2. Improve cropping and forestry production systems to minimise the inefficient use of inputs (especially chemicals) and maximise C sequestration.
3. Develop better models for systems analysis and methods for scaling-up.

For GCTE and other components of the global change research community this changed research emphasis will be achieved by:

1. Expanding interest in adaptation and mitigation to complement current impact studies.
2. Promoting collaborative studies on global change impact such as those on climate variability and the
use of new forecasting techniques so that the improving capability of the meteorological community to forecast seasonal weather can be evaluated in terms of crop response and used in scenario planning.

3. Developing new and improved models of production systems for use at a range of scales.

This biophysical research agenda will need to be better linked to the policy requirements of the political institutions seeking to use our science for the benefit of humankind.

Acknowledgements

P.JG and JSII thank the Natural Environment Research Council (NERC) of the UK for financial support. We are grateful to Dr. Cheryl Palm and Dr. Bernard Tinker for their suggested improvements to an earlier draft of this paper.

References


CSIRO, 1999. Biograze; waterpoints and wildlife. CSIRO Division of Wildlife and Ecology, Alice Springs, NT.


