CONSULTATIVE GROUP ON INTERNATIONAL AGRICULTURAL RESEARCH

TECHNICAL ADVISORY COMMITTEE

Environmental Impacts of the CGIAR

An Initial Assessment

TAC SECRETARIAT

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

This document comprises:

(a) Extract from *Summary of Proceedings and Decisions*, CGIAR International Centers Week, 1999, Washington, DC, USA

(b) Foreword by Hans Gregersen, Chair of the CGIAR Impact Assessment and Evaluation Group (IAEG)

(c) Report of the Study – Environmental Impacts of the CGIAR: An Initial Assessment

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A Report from
TAC's Standing Panel on Impact Assessment (SPIA)
formerly known as the
Impact Assessment and Evaluation Group (IAEG)

TAC SECRETARIAT

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

October 2000

Consultative Group on International Agricultural Research - CGIAR

From: The Secretariat December 1999

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IAEG Study on the Environmental Impacts of the CGIAR[1]

Details of the IAEG's study on the impact of CGIAR activities on the environment were provided by Mike Nelson of New Zealand. Given the complexity of tracing these linkages between research and environmental impacts, the Panel decided to focus initially on the land-saving implications of productivity-enhancing innovations, fully recognizing that the whole range of positive and negative impacts will need to be included eventually.

The preliminary analysis revealed that land saved from deforestation as a result of productivity research in seven key mandated food crops was in the range of 170 to 420 million hectares, with another 50 million hectares in reduced requirements for permanent pasture attributable to forage/livestock research. Assuming that average carbon storage per hectare is 100 tons and has a value of $1 per ton, the environmental savings may be placed at $10-25 billion over 2 decades. Also assuming that 40 percent of the lands developed would have been cleared forests with an average value in biodiversity of $5 per hectare, additional environmental savings amount to $200-500 million.

The environmental benefits associated with a reduction of deforestation of this magnitude – biodiversity, carbon storage, erosion or downstream damage – can reasonably be expected to be highly significant and important from a global perspective.

Plenary Discussion

The Group endorsed the IAEG's preliminary reports on the CGIAR's impact on poverty eradication, food security and environmental protection, and urged the IAEG to move quickly into the next phases of these studies. IAEG was commended for its work on the impact reports, which are seen as a significant step forward. Special thanks was given to Hans Gregersen for his leadership in directing the IAEG's solid, scientifically rigorous, and transparent studies to produce information on CGIAR impacts. Centers are playing a key role in the impact assessment activities, and both IAEG and the Centers are benefiting through the interactions.

[1] Extract from *Summary of Proceedings and Decisions*, CGIAR International Centers Week 1999, Washington, DC, USA.

CGIAR Secretariat • Mailing Address: 1818 H Street, N.W., Washington, D.C. 20433, U.S.A. • Office Location: 701 18th Street, N.W.
Tel: (1-202) 473-8951 • Cable Address: INTBAFRAD • Fax: (1-202) 473-8110 • E-mail: CGIAR@cgiar.org or CGIAR@worldbank.org

Members praised the studies for including the viewpoints of NGOs, multi- and bi-lateral donors, and the private sector. Members also agreed that the linkage of IAEG's evaluation work with TAC's overall priority setting and overall evaluation is a positive development.

IAEG FOREWORD

In a relatively short time, the IAEG Panel, consisting of Dr Mike Nelson of New Zealand and Dr Mywish Maredia of India, has assessed the environmental impacts of research undertaken by the CGIAR and its partners and has been able to clarify a number of the issues surrounding the impacts of such research on the environment. It has also developed a useful preliminary assessment of the adoption of productivity-enhancing research on land use and the consequent environmental impacts. In view of the lack of data on causal relationships, the Panel had to limit its assessment to scenario analysis. A great deal of work remains to be done to develop a more comprehensive and quantitative assessment of the various environmental impacts associated with agricultural research. However, the Panel has made a good start.

It is clear from the Panel's analysis that CGIAR research to enhance productivity has had a significant indirect impact on the environment through a reduction in deforestation resulting from agricultural expansion. Even if, to be on the conservative side, one reduces the estimate of land saving by a further 50%, the resulting figure of over 200 million ha is still significant. Particularly considering that the areas that would have been brought into production are likely to have been the more fragile montane tropical forests that have greater value in terms of environmental protection than the lowlands (plains and slopes under 30°) already cleared.

The Panel correctly notes the argument that in the absence of CGIAR's contribution to productivity growth, the amount of additional land needed to meet the present output would not have been available in all regions, one example being Asia. If this were the case, this would have meant that there would have been less food available, more food insecurity, more starvation and a need for less-endowed countries to increase food imports to the detriment of their development prospects. Research by the CGIAR has contributed to lessening these problems. Thus, in such regions, while the environmental impacts associated with estimated land saving would be less (because of unavailability of land), the development impacts are larger (a greater amount of starvation and food insecurity has been avoided because of the CGIAR contributions).

Important insights are provided by the Panel's review of the available literature on assessing the impact of agricultural research on the environment, particularly in relation to the lack of previous empirical work on such impacts. The contribution of agricultural research to land-saving increases in productivity is often the most important. However, to date, the effects of such research have not been sufficiently analyzed in the literature.

The Panel's development of a conceptual framework to assess environmental impacts provides a sound basis for their future evaluation. Its clarification of the paths from research to its effect on the environment is helpful in terms of developing operational approaches to environmental impact assessment. At the same time, its exploration of the generic nature of environmental impacts associated with different kinds of CGIAR research is illuminating and useful in terms of initiating future assessment of such impacts, and establishing relevant monitoring and evaluation systems.

In moving forward, the IAEG believes that the Group should come to some consensus on appropriate terminology related to environmental impacts. At present, definitions vary widely and lead to confusion in discussions on the subject. The Panel provides a clear set of definitions and concepts that can provide a starting point for the discussion.

A good indication of the nature and direction of the major positive impacts of CGIAR research related to land saving, due to the productivity-enhancing technologies developed by the Centres and their partners, is given in the Panel's assessment and its preliminary conclusions to date. Such research accounts for fully half of the expenditure on research in the System.

The IAEG is planning to move on to more substantive longer-term assessment of the impacts of CGIAR research on the environment. In doing so, it will need to grapple more fully with a host of issues and challenges brought up by the Panel. These include answering at least the following questions:

- *What is the best way to address the site-specific nature of many of the most relevant environmental impacts?*
- *How can one develop estimates of the global System-wide impacts of research, given this site specificity?*
- *What is the best way to come to grips with the equity implications of environmental impacts, especially in the context of the primary CGIAR goal of poverty eradication?*
- *How can the research types, identified within the System, be defined and subjected to monitoring and evaluation so as to permit assessment of complementarity, supplementarity or substitutability in addressing environmental management issues?*
- *Should the IAEG evaluate the specific impacts of research on natural resources management research on the environment and if so, how?*

The Panel has moved into an area that requires considerable speculation, as there is little previous substantive assessment of the impacts of agricultural research on the environment. IAEG feels that the Panel has made good headway in terms of exploring the issues, developing an analytical framework, and providing some preliminary estimates of impacts related to the environmental benefits associated with reduced pressure on forests and other wild land for conversion to agriculture. However, much remains to be done. Many interesting questions regarding environmental impacts have been raised, and several promising avenues of approach have been identified and remain to be explored in future IAEG activities.

The IAEG thanks the Panel for its initial foray into uncharted territory, congratulates it on the progress made, and looks forward to further association in refinement and expansion of the analytical assessment activities it has initiated.

Hans Gregersen
Chair
CGIAR Impact Assessment and Evaluation Group

CONSULTATIVE GROUP ON INTERNATIONAL AGRICULTURAL RESEARCH

TECHNICAL ADVISORY COMMITTEE

Environmental Impacts of the CGIAR
An Initial Assessment

Study Panel: Dr. Michael Nelson
Dr. Mywish Maredia

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INTRODUCTION

Research projects undertaken by the Centres of the Consultative Group on International Agricultural Research (CGIAR) have implications for the rate of use of renewable natural resources (RNR). That is to say, the depletion or conservation, through induced change (adoption), that influences production, distribution and consumption associated with developments in agriculture, forestry or fisheries. The 'direct' or development impacts of such changes are poverty alleviation, sustainable food security, and environmental protection and enhancement. Until recently, the achievement of the third goal concerning the environment had not been systematically and explicitly articulated. Rather, this had been treated as an unspecified 'indirect' or environmental impact that may be positive or negative. However, this goal is likely to be critical to the CGIAR's strategy for sustainable agricultural development in terms of unaccounted environmental benefits and unplanned environmental damage.

Thus, the Impact Assessment and Evaluation Group (IAEG) decided that evaluating these indirect impacts – referred to here as 'environmental impacts' – would be one of its priorities during the 1999-2000 period. This initiative concerns the impact of all types of CGIAR research on the environment and the sustainable supply of natural resources, and will focus on alternative means for ex post environmental impact assessment (EIA) of the full range of CGIAR research. It is expected to provide operational insights for assessing the opportunities, constraints and tradeoffs in design, and monitoring and evaluation (M&E) of those aspects of future research project and programme cycles specifically related to protecting the environment (TAC 1997). A major contribution of the IAEG's ex post activity is expected to be clarification of measurement issues for ex ante EIA.

The first phase of this study focuses on the question of what may have been the unplanned and unaccounted for environmental costs and benefits attributable to past research. The IAEG elected to focus initially on evaluating changes in use, management and conservation of land resources that may be attributable to agricultural research. The present stage of IAEG's EIA activity is not concerned with the more traditional accountability question as to whether or not adoption of CGIAR research led to planned changes in the biophysical condition of the environment, such as levels of soil stabilization, water quality changes and so forth, as it is felt that this type of assessment is best carried out at Centre level.

This document reports on progress in an exploratory Phase 1 exercise aimed at defining the options (scope, methodology and information requirements) for progressively providing the Group with environmental analysis relevant to operational decisions on research policy, project design and M&E. The initial assessment has been carried out by an independent panel consisting of Dr Michael Nelson (New Zealand) and Dr Mywish Maredia (India) working in close association with the IAEG. Jan Groenewold of the Technical Advisory Committee (TAC) Secretariat provided much appreciated support in data collation and analysis.

Under the terms of reference the scope of Phase 1 has been restricted to:

- establishing a clear and unambiguous operational definition of environmental impacts, what environmental impact analysis entails in the context of this definition and what outputs it should be expected to deliver (Chapter 1);
- a preliminary review of the literature on methodology of EIA applicable especially to agricultural research and experience in applying this methodology to obtain empirical results (Chapter 2);
- a preliminary assessment of the land saving that may be attributed to adoption of a CGIAR research output. The Panel and the IAEG believe that this is the most obvious example of a positive environmental impact resulting from the System's activities. The direct and indirect impacts

associated with land saving are likely to be in orders of magnitude greater than any other positive impact that could be identified (Chapter 3 provides a progress report on this work).

In conclusion, Chapter 4 provides thoughts and recommendations on how the IAEG should proceed from here to embrace a broader set of potentially important impacts on the environment.

CHAPTER 1. Conceptual and definitional underpinnings

Research carried out by the CGIAR Centres has few significant direct impacts on the environment. Rather, the major environmental impacts come indirectly through the adoption of the technologies and other innovations that result from such research. However, these indirect impacts can be crucial in terms of meeting the CGIAR's goals of poverty eradication, sustainable food security, and environmental protection and enhancement.

The range of impacts related to the environment and natural resources is broad, and is associated with, among other factors, changes in soil quality and movement, water quantity and quality, natural resource sustainability and biodiversity conservation. Each category of change needs to be evaluated and linked to impacts on humans in different ways by the use of different techniques and approaches.

Many, if not all, of the relevant impacts are associated with changes in land and water use that have occurred because of adoption of the innovations derived from research undertaken by the CGIAR and its partners aimed at increasing food supply and security. In other words, the use of rural land in the world would have looked quite different in the absence of the productivity-enhancing and resource-conserving innovations resulting from CGIAR research.

Environmental impacts as 'externalities': unexpected impacts on human welfare associated with biophysical changes due to the application of CGIAR research

The basic model used by the Panel to assess environmental impact is shown in Figure 1. The following elements and relationships were considered.

- CGIAR research is planned and carried out with **development impacts** in mind. These are characterized as any impact on human welfare (living standards, health, equity) that was initially planned for and incorporated into the calculus of projected value to be derived from the research being considered.
- Environmental impacts may be positive or negative. On the positive side is avoidance of damage to renewable resources, in particular land saving. Negative impacts relate to unintended side effects such as increased hardship due to more competition for limited supplies of water, higher costs to protect the environment at a level that would have existed without the CGIAR-generated technology, or increased environmental losses due to the use of CGIAR technologies (e.g. salinization and waterlogging, health problems due to irrigation, heavy fertilizer and/or pesticide application).
- Development impacts are always explicitly included in research project calculations and are directly or indirectly linked to **biophysical changes** – changes in erosion rates, soil fertility, nutritional content of crops, water quality and quantity, crop losses, vegetative cover.
- The planned biophysical changes are necessary conditions for achieving agricultural productivity goals. However, the new technologies may also generate unplanned biophysical changes and the planned changes themselves may result in chain reactions leading to additional unplanned changes in the biophysical environment downstream. When any of these unforeseen changes are associated with negative or positive consequences for long-term human welfare, they are termed **environmental impacts**, e.g. flood damage, sedimentation or potential loss of valuable biodiversity.

- For the purposes of this assessment these impacts occur when application of research results leads to: (i) expected biophysical changes that create unexpected impacts on people and their welfare; and (ii) unexpected biophysical changes that impact on human welfare. It is these impacts on people that we refer to as 'environmental impacts'.

The key point here is that **only those unexpected and unplanned impacts on people that result from biophysical changes are included as environmental impacts in this first phase of IAEG EIA activity.** This is an anthropocentric view of environmental impacts and should be tempered by the crucial recognition that unexpected biophysical changes, due to adoption of a given CGIAR innovation, are important in and of themselves, even if they do not have any currently identifiable impact on human welfare. Indeed, the reason environmental impacts arise in an ex post sense is because a biophysical change, expected or unexpected, turned out to have an impact on human welfare, or alternatively, it became evident that these changes had the potential to cause such impacts in the long run. It was only with advancing knowledge and information gained from experience that we were able to identify them. Seemingly harmless biophysical changes today may have impacts on people and their welfare in the indefinite future. This emphasizes the dynamics of environmental impacts and adds urgency to the ecological view of the necessity of tracing as wide a range as possible of the biophysical changes associated with adoption of broadly defined agricultural research.

To sum up, if impacts on the environment had been adequately understood and internalized in a Centre's original research design and M&E activities, then they would have already been incorporated within the context of direct and indirect development impacts. However, qualifying impacts as 'environmental' in the present exercise means they were **not** internalized in initial research design because they were unknown, seemed highly uncertain at the time, or the value attached to them in earlier days was considered to be low or zero according to the prevailing state of knowledge.

A major reason for the current IAEG evaluation of environmental externalities is the concern of some members of the Group that insufficient attention has been given to environmental externalities (positive and negative) in past decision-making on research policy, and design of research projects and programme. The general consensus would seem to be that there is room for a better understanding of these externalities aimed at a progressive improvement in their identification and quantification. This would provide a sounder basis for internalizing environmental aspects in decisions on research approaches at all levels of the Group's operations (Fig. 2).

Identifying environmental impacts

Application of most CGIAR research results eventually leads to changes in the biophysical environment, either on-site where an innovation is applied or off-site. The primary concern in this phase is with off-site biophysical impacts; two types can be identified. (The Panel's interpretation of these various types of impact is illustrated in Figure 3). The first comprises site-linked impacts, i.e. downstream impacts that stem directly from the biophysical changes in the on-site environment (primarily rates of soil loss and water quantity, flow regime and quality) attributable to planned and unplanned adoption of CGIAR research findings. The second is output or price-linked impacts, which result explicitly from the consequences on land use of increased sustainable agricultural production and income attributable to CGIAR commodity research.

In the case of land use, there is a clear potential for positive environmental impacts associated with adoption of research that reduces the rate at which new lands are incorporated into agriculture or converted to more intensive use. This applies particularly to the conversion of forests and native pastures to intensive crops, and over-exploitation of resources for purely subsistence purposes by the rural poor. The environmental benefits are accounted for on the basis of savings such as reduced loss of biodiversity, increased carbon storage or avoidance of negative environmental impacts that would have occurred with accelerated forest clearing and changes in land use. It is this type of impact that is addressed in Chapter 3.

To be relevant to decisions on management, these biophysical changes must have the potential to impact on human welfare. However, it is difficult *a priori* to decide which biophysical changes have no potential for socioeconomic impact and should be left out of the evaluation. Thus, in undertaking a general evaluation on the impact of CGIAR research on the environment it is necessary to:

- find appropriate methods and approaches to trace the chain of biophysical changes attributable to adoption of a given research innovation, and establish the nature and magnitude of the relationships; and then
- evaluate whether these biophysical changes have past, current or future potential to impact on human welfare (i.e. economic or social impacts);
- assess whether it is possible to increase efficiency in carrying out these sequential tasks by developing a clear concept of the links between biophysical changes and impacts on humans. This implies developing a clearer understanding of how biophysical changes came to have value to humans, i.e. the links over time between biophysical change and impacts on humans as individuals or groups.

Links between biophysical changes and impacts on humans

From the foregoing discussion the basic premise is that adoption of CGIAR innovations results in biophysical change, i.e. alteration in the state of RNR. Classifying these changes as positive or negative depends entirely on whether they carry a social or economic implication for the welfare of present or future generations. **In sum, a given biophysical change, or change in the environment, tends to take on meaning to decision-makers mainly in the context of how it affects human welfare.** That is the main reason why the Panel distinguishes between: (i) the many biophysical changes associated with adoption of CGIAR research innovations or impacts of research adoption on the biophysical environment; and (ii) more restricted environmental impacts or impacts of biophysical changes on the welfare of people (Box 1).

The same change can have positive or negative value depending on context

A given biophysical change can result in values that run along a continuum from negative to neutral to positive. For example, a technology resulting from CGIAR research may affect water flow downstream from where it is applied. The ultimate impact of that change on people can range from negative, if it contributes to the magnitude of flooding for example, or exacerbates the problem of drought, to neutral if adequate flow occurs with or without the innovation, to positive if the change contributes to water flow continuing longer into the dry season. Again, the same biophysical change can have negative or positive impacts on the welfare of people, depending on the timing of changes and the condition of the external environment – in this case the amount of water in an area and the timing of the water flow from precipitation. Therefore, such environmental impacts are quite site-specific.

Some CGIAR productivity-enhancing innovations require more water than is required without the innovation (e.g. CGIAR crops that require irrigation). This, again, is a biophysical fact. However, whether this has any implications for people (any potential environmental impact) depends entirely on whether the increased water use negatively affects the amount of water available for other uses.

Box 1. Biophysical Changes and Environmental Impacts

The following example illustrates the difference between biophysical changes and environmental impacts. Assume that widespread adoption of a CGIAR innovation results in a reduction of soil loss or erosion equal to five tons per ha per year, and that the cumulative effect of this reduction in a watershed is a significant reduction in river pollution flowing through the watershed. So far, this is a factual biophysical change, however, in and of itself this reduction has no particular negative or positive value associated with it. It would not be relevant to most decision-makers unless they perceived that this biophysical change would have an impact upon people.

In fact, the same biophysical change (soil-loss prevention) can have a quite different 'value' to humans, depending on how it affects them. Thus, in one case assume that the river flows through an uninhabited valley and through an uninhabited coastal plain into the ocean. The impact on people downstream is close to zero. In another case, assume that the very same change in siltation occurs in a river that flows through a heavily populated region where flooding is reduced because the river channel can carry more water, and the river empties into a dam reservoir where there is a significant reduction in the cost of dredging silt to maintain the capacity of the reservoir. Fish, that the population depend on for food, are in greater abundance with higher water quality. Downstream from the reservoir there is greater flood protection and more water is available for irrigation. All of these biophysical changes have social and economic counterparts to which negative and positive values can be attached. With knowledge of these values the decision-maker now becomes interested. Are these 'environmental impacts' or 'social-economic impacts' that we are considering? Here we call them environmental impacts.

The basic points to be made are that: (i) most CGIAR innovations eventually will result in changes to the environment or in biophysical conditions; (ii) when discussing environmental impacts associated with such biophysical changes in the context of negative or positive values, the changes have to be linked to impacts on people, i.e. be given in social and/or economic terms; and (iii) it is when looking at the dynamics and the context of such impacts, i.e. changes over time, that issues of sustainability enter the picture. Although this anthropocentric perspective on the relative value of biophysical changes and therefore environmental impacts is dominant, particularly in political decision-making, one should not and cannot ignore the rest of the biophysical changes brought about by adoption of CGIAR research. In the future, such changes may also have implications in the long-term for human welfare.

Losses, damages or costs avoided are as valuable as production gains

Another conceptual and definitional issue relates to the links between losses or costs avoided and production gains. An important and widespread type of positive impact derived from CGIAR innovations is avoidance of loss or damage to the environment. For example, after adoption of a CGIAR innovation, there can still be a decline in a biophysical condition, but less than if the innovation had not been adopted. This difference can legitimately be registered as a beneficial effect due to CGIAR research and the adoption process. Losses avoided are often in key areas of research activities focused on the environment, e.g. watershed management, pest management, and forest, soil and water conservation. These are highly relevant to the work of a number of CGIAR Centres.

A parallel type of benefit is costs avoided. If an action based on the adoption of a CGIAR innovation results in a saving of costs that would otherwise be incurred to restore or protect the environment, then that is a benefit. An example of this is given in Box 1, where reduced siltation resulted in less money being spent on dredging to maintain reservoir capacity and the same level of human welfare.

One of the major benefits for the environment, which also has an impact upon people, is land saving due to increased productivity and effective yield per ha through sustainable agricultural intensification. Without the benefit of CGIAR research innovations many millions of hectares of new land would have had to be converted from forest, watershed and other wild land uses in order to produce the same volume of food for CGIAR mandate crops as that produced today. Such changes could have resulted in significant losses of biodiversity, watershed protection benefits and so forth. Avoidance of these losses is indirectly due to CGIAR innovations.

Integrated pest management (IPM) research provides an important example of research that leads to avoiding losses and reducing risks. Technologies developed by CGIAR Centres and others, such as those related to biological control of the cassava mealy bug, have reduced the need for pesticides, resulting in avoidance of costs and eventual environmental damage. Water-conserving technologies have reduced the need for expensive technology to reduce problems of waterlogging, salinization and water transport. These examples of damage avoidance from research on natural research management (NRM), in contrast to the land saving discussed above, illustrate the difference between losses avoided directly and those avoided indirectly (unplanned) due to new technology developed by the Centres. This relates to the ongoing and widespread debate on developmental versus environmental impacts. CGIAR research leads to the large-scale application of technologies such as live tree barriers, zero tillage, forest conservation and watershed management. These are cases where soil and water conservation is a specific objective of the research in order to sustain productivity over time. One would expect justification for this type of research to be based on a forecast of yields and/or costs of production with and without the new technology. The on-site difference between with and without (e.g. the avoidance of yield decline due to pests, water stress, reduced fertility or salinization) is the development impact.

Site specificity issues in moving from biophysical change to environmental impacts

A major constraint to assessment, as one moves from biophysical changes to environmental impacts, is the site-specific nature of such impacts. Biophysical changes, such as alteration of vegetative cover, chemical content of water or physical soil structure, reflect some cause/effect relationships that can be generalized. However, the socioeconomic consequences of these changes will be highly location-specific and related to the number and characteristics of the inhabitants, and the nature and extent of existing and potential economic activity affected. For example, damage avoidance downstream, as a beneficial impact of CGIAR research, would appear to be largely restricted to the examples cited for specific situations and areas, such as extended reservoir life or a decrease in maintenance costs, reduced flood damage and land saving (Box 2). Such estimates depend on knowing exactly where the innovations will be adopted and applied.

Box 2. Site Specificity of Environmental Impacts

An environmental assessment undertaken by the International Fund for Agricultural Development (IFAD) in 1993, of a hillside agricultural development project, illustrates the site-specificity issue in dealing with upstream-downstream relationships.

The San Juan de Maguana development project in the San Juan river basin (Dominican Republic) called for reforestation, agroforestry, soil conservation and improved technology in the 100,000 ha upper and middle catchment area that supplies the Sabaneta hydroelectric dam. In the upper catchment (45,000 ha) it was estimated that average erosion intensity was 9 tons/ha for forest, 93 tons/ha for fallow, 110 tons/ha for pasture and 1120 tons/ha for agriculture. This latter land use occupied 0.8% of the area and accounted for 17% of total erosion. In the middle basin, on less sloping lands, the erosion intensity for forest and fallow was 50% of the upper catchment and 15% for agriculture.

The conservation project in the upper basin would prolong the remaining useful life of the dam from 36 to 43 years. Increasing the forested area from 1800 ha to 4000 ha would extend dam life to 46 years. A simulation model for sedimentation of the reservoir estimated the net present value of the initial six-year saving at a rather modest US$125,000 at 10% discount (US$380,000 at 3% discount). However, if this same reforestation had been undertaken in strategic locations within 5-10 km of the dam (rather than 90 km upstream in the upper basin) the estimated net present value of savings would increase to over US$4 million.

This example illustrates the sensitivity of estimates of environmental impact from deforestation to:

- slope of land cleared;
- the type of land use which replaces forest;
- the type of downstream development at risk from change in water quality or flows and sedimentation rates;
- the distance of downstream socioeconomic activity potentially at risk from the area deforested;
- the discount rate applied in estimating net present value.

IFAD, *"San Juan de la Maguana Agricultural Development Project, Dominican Republic: Environmental Assessment".* Rome, 1993

Types of CGIAR research with potential to generate environmental impacts

In order to develop an analytical framework to evaluate development impacts with the potential to generate environmental impacts, an operational research typology is needed through which the sequence of such impacts can be traced to specific types of research. The fundamental challenge is to specify the development impact of CGIAR research as the prerequisite to estimating the chain reaction leading to biophysical change and thence to its long-term environmental consequences for human welfare. Altogether seven types of CGIAR research can be identified for which it is progressively more difficult to estimate development impacts likely to change the rate of natural resource use:

a) the simplest would be the gross yield and quality impacts (change in gross production and nutritional value due to germplasm research in mandated commodities);
b) followed by the impact on gross production of mandated commodities through CGIAR management 'packages' e.g. 'maize-based' technologies which may also change the quality of land and water, incorporate germplasm benefits and change production in non-mandated commodities;
c) next, would be the impact on net consumption due to post-harvest and market research in mandated commodities;
d) more complicated would be the impact on gross production (all commodities) and change in watershed, river basin, regional or global patterns of land and water use from NRM research;
e) similar difficulties would arise for the same impacts identified in (d) derived from eco-regional research;
f) significantly more complex would be impacts on gross production and net consumption (all commodities) and direct changes in natural resource use induced by policy and institution-building research;
g) finally, and most difficult would be the synergistic impacts on gross production, net consumption and direct changes in natural resource use through the integration of the above six types of research.

It is recognized that for all its theoretical merits, the above typology has little relevance to operational questions currently faced by the CGIAR in classifying its projects or project components for planning, budgeting, impact assessment or cost-effectiveness evaluation. Although it is not the task of this study to estimate development impacts, the disaggregation of such impacts and their attribution to different areas of research would facilitate the specific evaluation of the impact of all kinds of CGIAR research on the environment and the sustainable supply of RNR. Under these circumstances, the concept should be addressed in the design of an overall ex post evaluation of environmental impacts attributable to CGIAR research. In order to focus on operational issues, a set of preliminary scenarios of links between type of research and sequential impacts is provided below.

Likely scenarios of the linkage – development/biophysical/environmental impact

1. Germplasm research in mandated commodities resulting in fertilizer-responsive, high-yielding varieties (HYVs)

- *Development impacts:* sustainable increased gross production through yield plus expanded area, lower cost of production, increased income to producers, lower prices to consumers, increased employment and improved equity.
- *Biophysical impacts*: expansion of production onto marginal lands, and increased chemical residues in soil and ground water on-site, and in downstream surface and ground water off-site, as a result of higher fertilizer application.
- *Environmental impacts*:
  negative – damage to structure and fertility of marginal lands through intensified production and deforestation to expand cropping (with the potential to offset land-saving benefits by the contamination of drinking water affecting human and animal health on- and off-site, and the build-up of aquatic plants in downstream water bodies with prejudicial effects on fisheries, bird life, recreation and transport;
  positive – land saving (reduced intensification of land use and less conversion of forests to crops) with benefits from biodiversity conservation, and less erosion and reduced downstream damage from

sedimentation, flooding, uneven water flows and chemical contamination of water.

2. Germplasm research resulting in drought-resistant or salinity-resistant varieties
   - *Development impacts:* same as (1) above.
   - *Biophysical impacts:* expansion of production onto marginal lands.
   - *Environmental impacts:* same negative land-use and positive land-saving impacts as in (1) above.
3. Germplasm research resulting in disease-resistant varieties
   - *Development impacts:* same as (1) above.
   - *Biophysical impacts:* same as (2) above.
   - *Environmental impacts:* same as (2) above plus potential benefit to on-site and downstream water quality due to reduced use of agrochemicals.
4. Germplasm research in mandated commodities resulting in higher nutrition value, reduced post-harvest loss and/or longer shelf life
   - *Development impacts:* sustainable increase in net food available for consumption per ha in production, lower prices per kilo or per calorie to consumers, higher farm-gate prices with increased income to producers.
   - *Biophysical impacts:* same as (2) above.
   - *Environmental impacts:* same as (2) above.
5. IPM research
   - *Development impacts:* same as (1) above.
   - *Biophysical impacts:* same as (2) above.
   - *Environmental impacts:* same as (3) above.
6. Research on mandated commodity-based soil/water/vegetation management packages
   - *Development impacts:* same as (1) above.
   - *Biophysical impacts:* same as (1) above plus improved soil management on-site with less erosion, higher water retention and lower, but more even, downstream flows.
   - *Environmental impacts:* same as (1) above plus potential for higher positive downstream impacts in cases where water is not a limiting factor, and for higher negative downstream impacts in cases where water is a limiting factor.
7. Research on post-harvest losses, processing and market development
   - *Development impacts:* same as (4) above.
   - *Biophysical impacts:* same as (2) above.
   - *Environmental impacts:* same as (2) above.
8. Research on NRM

Although the development impacts in the above seven types of research are classified as sustainable, NRM research is primarily focused on environmental protection where a necessary condition is achievement of the same impacts as in (1) above, with the exception of potential expansion of area in production. Environmental protection is an explicit development impact. Thus, although there will be biophysical changes in the use of RNR, there should be no environmental impacts either positive or negative. However, as stated initially, this concept is still not fully operational. For purposes of ex post evaluation, NRM research in irrigation, forestry, agroforestry, forest frontier development and fisheries could have had negative environmental impacts. It is assumed that any positive impacts on the environment, by definition, should be classified as development impacts.

Irrigation management

- *Development impacts:* increase in production through expansion of area in irrigation from the same water supply, increased yields, rehabilitation of saline areas, drainage, reduced rate of salinization and efficient exploitation of additional water plus impacts outlined in (1) above.

- *Biophysical impacts:* same as (1) above, plus draw-down of ground water on-site and reduced ground water and surface flows downstream.
- *Environmental impacts:* same as (1) above.

Forest management
- *Development impacts:* increased production.
- *Biophysical impacts:* change in the state of soils, vegetation and water.
- *Environmental impacts:* positive by design.

Agroforestry and management of forest margins
- *Development impacts:* increased production.
- *Biophysical impacts:* change in the state of RNR.
- *Environmental impacts:* positive by design.

Coastal and ocean fishery management
- *Development impacts:* increased production.
- *Biophysical impacts:* change in fish biomass, state of coastal wetlands.
- *Environmental impacts:* positive by design.

Understanding other perspectives of environmental impacts

The importance of understanding the EIA of agricultural research is that it enables an assessment of the type and scale of the costs and benefits involved, an identification of the different stakeholders who face these costs, and the implications for the national economy. This, in turn, assists in decision-making, and the prioritization of investments and policy measures. Therefore, the Panel's first task was to undertake a literature review to better understand:
- What is the evidence for a changing natural resource base and the environmental impact of agriculture?
- What is the 'state of the art' in EIA?
- What is the evidence linking research with changes in the natural resource base and the environment?

The following section provides an overview of the Panel's findings in this regard. Using examples from the literature, this overview presents a framework for understanding the relationship between agricultural research and the environment, and presents empirical assessments of such a relationship. The review is not intended to be exhaustive but only representative of major themes. It traces the complex linkages between research and environment, and discusses conditions under which technological advancement helps or harms the environment.

Its focus is primarily on the relationship between the yield-increasing technologies – research types (a) to (c) described in the introduction to this section – and the environment. Emphasis is given to technologies developed with major contributions from the CGIAR. These include improvements in varietal technology accompanied by improvements in agronomic practices based on capital inputs (fertilizers, pesticides, irrigated water, etc.).

The research types (4) to (7), outlined in the introduction to this section and broadly grouped under NRM research and social science research, are important components of the CGIAR research portfolio. However, the relationship between outputs of these types of research and the environment are not a subject of detailed review in this report for several reasons. First, the impact of improved resource management practices on the environment is not a source of controversy, although concerns about the efficiency and effectiveness of NRM research do prevail. Second, the impacts of these kinds of research have generally received less attention in the literature (especially social science research). Methodological difficulties and measurement problems in assessing their impacts are the main reasons for the lack of attention on these important categories of research outputs.

Fig. 1. The Pathway from Research to Environmental Impacts

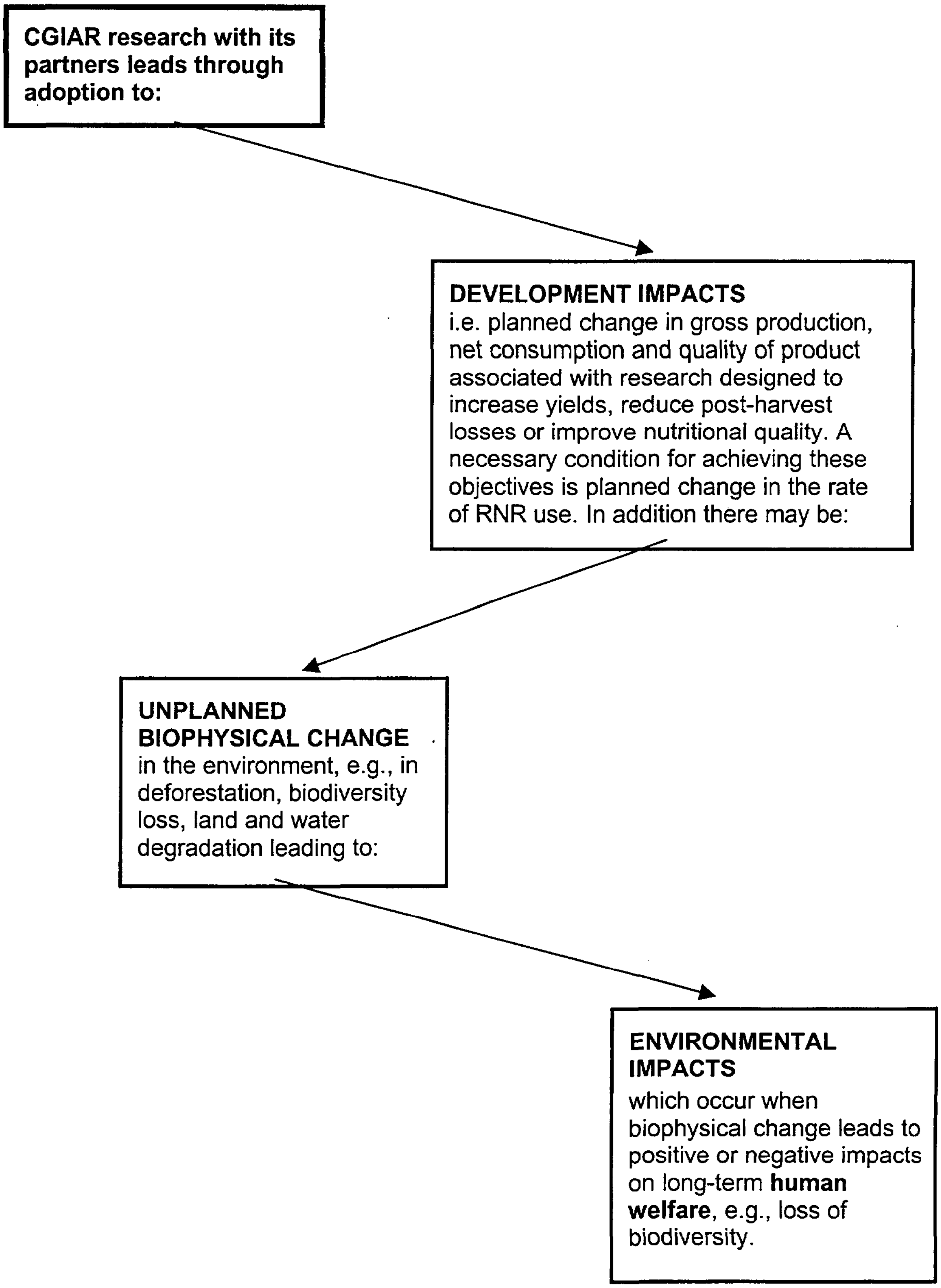


Fig. 2. Internalizing the Lessons from Environmental Impact Evaluation

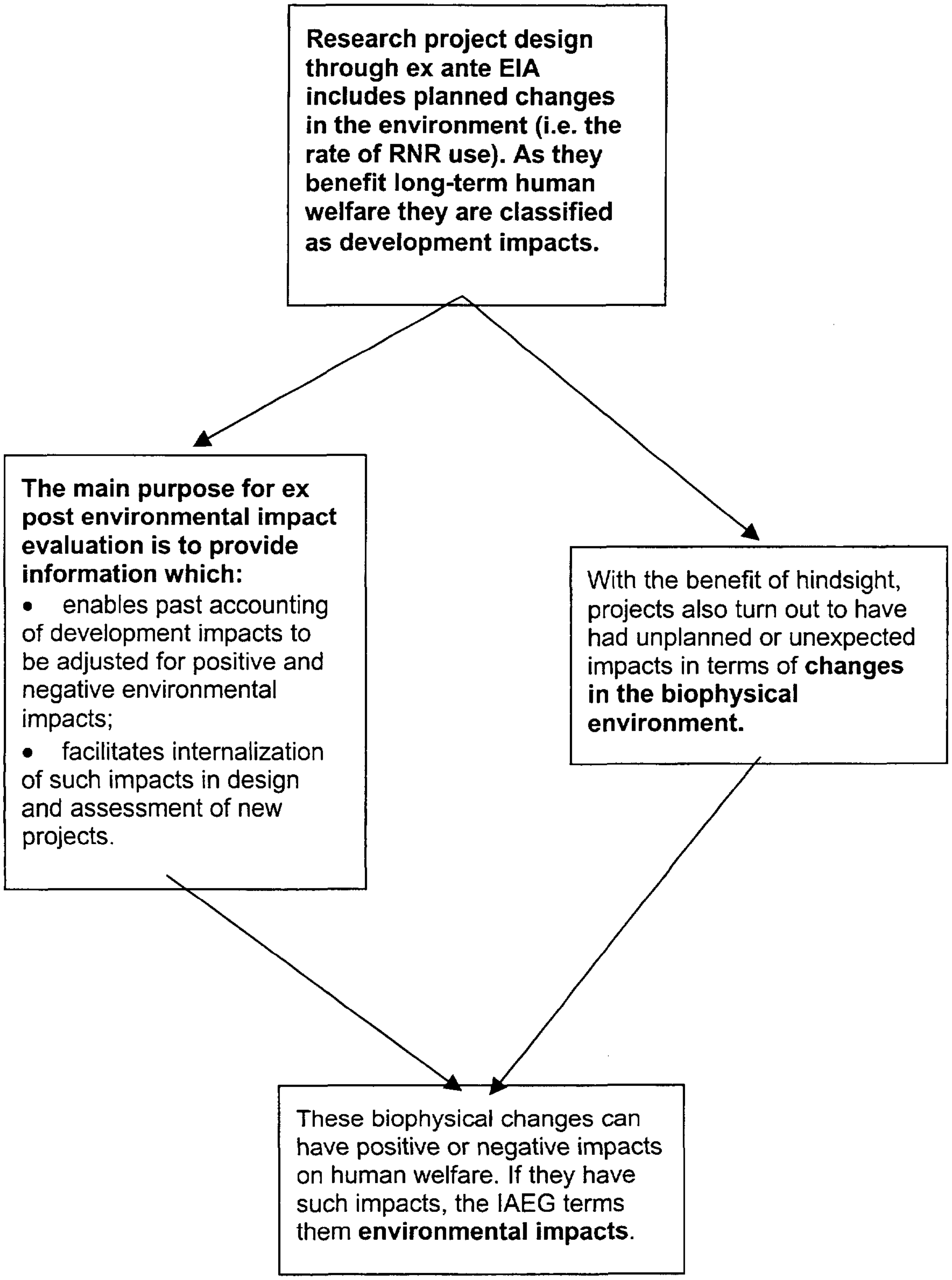
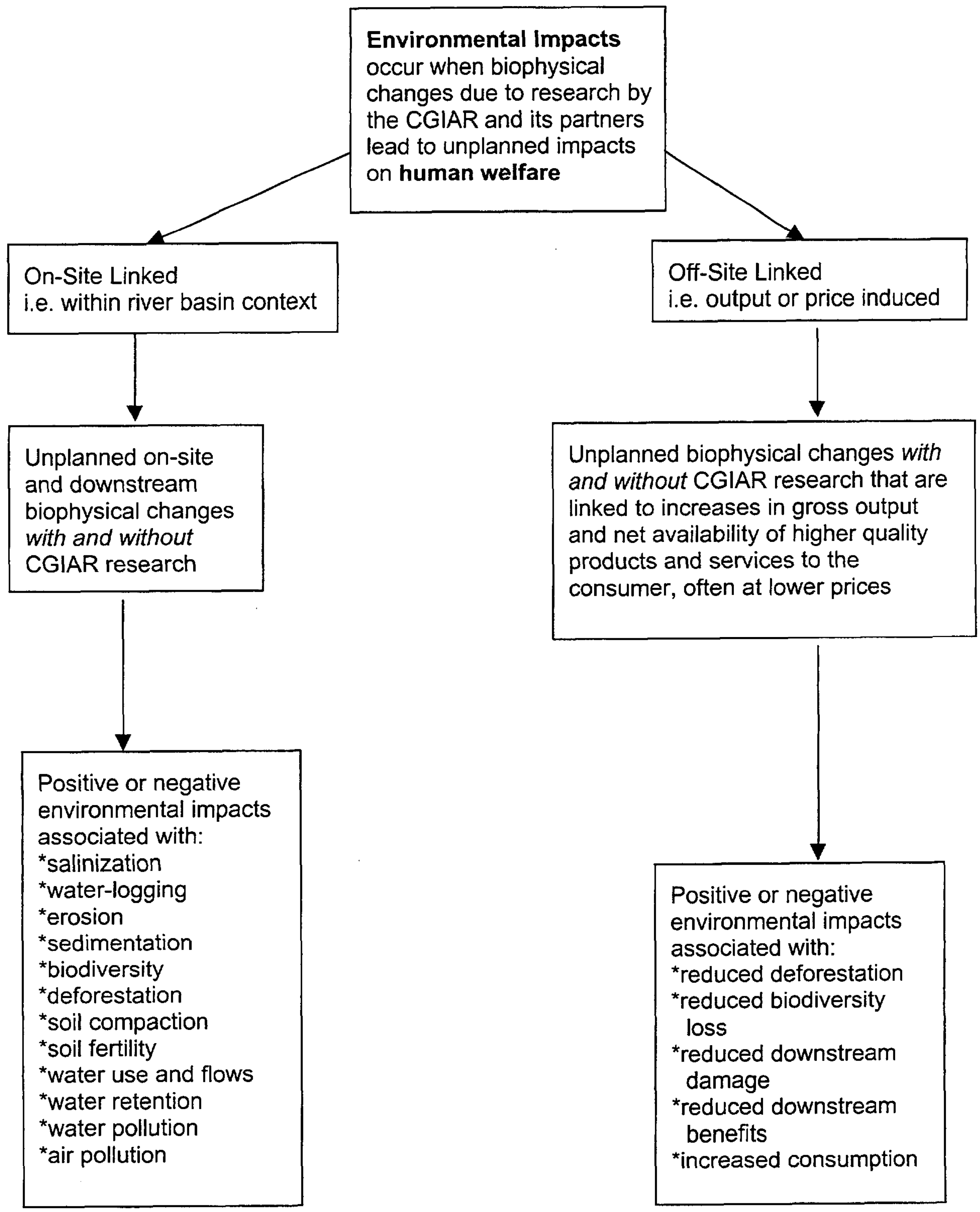


Fig. 3. 'Site-Linked' and 'Output-Induced' Environmental Impacts



CHAPTER 2. Impact of agricultural research on the environment – evidence from the literature

Agriculture and environmental consequences

The earth's environment is continually changing through natural processes and human intervention. While some changes are for the better others are for the worse. The negative impact of human activities on the earth's resources has become a matter of international concern, leading to several international conventions, global-level initiatives, detailed studies and research projects.

While industry is often to blame, agriculture is becoming increasingly prominent as a contributor to global environmental problems (Tolba and El-Kholy 1992). The literature is loaded with examples and data that show that many widely employed agricultural and forestry practices have significantly adverse effects on local and regional soil conditions, water quality, biological diversity, climatic patterns and long-term biological and agricultural productivity. Some of the agricultural practices associated with environmental degradation include intensification, overuse and misuse of chemicals and water resources; overgrazed rangelands; destruction of forests; and overexploitation of fisheries. Agriculture is also considered a highly significant and growing contributor to the total production of globally important gas emissions. Individually or in combination, these gases contribute to acid deposition, the depletion of stratospheric ozone, the build-up of ozone in the lower atmosphere and global warming (Conway 1998). Dale *et al.* (1993) estimated that tropical deforestation is responsible for approximately 25% of the total radioactive effect of greenhouse gases emitted as a result of human activities. An important environmental consequence of forest conversion is the loss of biodiversity. Even conservative estimates suggest that tropical deforestation results in a loss of at least 4000 species a year (Ehrlich and Wilson 1991).

The degradation of land resources is often cited as the most important environmental problem facing agriculture. The most comprehensive assessment of global land degradation (Oldeman *et al.* 1990) classifies the main types of land degradation as soil erosion from wind and water, chemical degradation (loss of soil nutrients, soil salinization, urban-industrial pollution and acidification), and physical degradation (compaction, waterlogging and subsistence of organic soils). Oldeman *et al.* (1990) estimated that 1964 million ha of land under forest, woodland, permanent pasture and agriculture have suffered from some degree of degradation. For agriculture, chemical degradation accounts for 40% of the estimated 562 million ha of degraded agricultural land (Oldeman *et al.* 1990).

Scherr and Yadav (1996) point to 'hot spots' where land degradation is a significant threat to the food security of large numbers of poor people and to local economic activity, and hence poses potentially negative environmental impacts. The cumulative effect of agriculture-related RNR degradation is seen in declining crop yields and the total factor productivity (TFP) of agriculture itself. There are many studies that estimate the effects of the changing RNR base on crop production. Scherr and Yadav (1996) summarized national-level estimates of the effects of land degradation on crop productivity in more than 10 developing countries. These show rates of production loss in seven African countries ranging from 0.04% to 11% annually. A continent-wide study on Africa by Lal (1995) estimated the crop-yield loss due to past erosion to be in the range of 2% to 40% across countries with a mean of 8.2% for the whole continent and 6.2% for Sub-Saharan Africa. Estimates of the cost of land degradation assembled by

Barbier and Bishop (1995) range from under 1% to over 15% of GNP in several developing countries.[1]

The extent and effect of land degradation on agricultural production (environmental impact) remains a hotly debated issue in the literature. Some perceive that land degradation poses a serious threat to global food supplies over the long term and endangers human wellbeing (Brown and Kane 1994; Pimentel *et al.* 1995; Kasperson *et al.*1996), while others argue that land-degradation problems are localized and are relatively unimportant to global food supplies (Crosson 1994). A US study by Crosson and Anderson (1992) found very little long-term effects on yields of soil erosion. If erosion rates continued at the same rate as in 1982 for 100 years, national average yields would be 3-10% lower than in the absence of erosion (Crosson and Anderson 1992).

A recent literature review by Scherr (1999) on soil degradation and its impact on food security concludes: "The early, high estimates of soil degradation have not been substantiated. Degradation appears not to threaten aggregate global food supply by 2020..." (Scherr 1999). However, the review does point to the serious effects of degradation evident in many subregions of the developing world. These include regions with soils prone to degradation (especially in Sub-Saharan Africa), inadequately managed irrigation (as in South Asia), and regions where intensification is rapidly expanding without economic incentives or technologies for good resource husbandry, as in densely populated regions in developing countries and in marginal lands in frontier areas (Scherr 1999).

The Panel's preliminary assessment of the literature confirms that RNR degradation is severe in many areas and in some cases it poses negative environmental impacts on human wellbeing. This raises several important questions. Are environmental consequences due to agricultural research or lack of it? What evidence is there to link RNR problems such as land degradation, deforestation and loss of biodiversity to past technologies developed by agricultural research centres? Are improved technologies the only source of changes in RNR and the environment?

To address these questions we first looked at the evidence of the impacts of research on agriculture in general, and then traced the links between the environmental consequences resulting from these impacts and past research. A major emphasis of the discussion is on the yield-improving technologies associated with CGIAR research types (a) to (c) identified in the introduction to Chapter 1.

Impacts of past research on agriculture

In the 1960s and 1970s, the main preoccupation of agricultural development was how to feed a rapidly increasing world population. Then, the obvious solution was to devote research efforts to increasing per capita food production. The resulting green revolution has been cited as the success story of modern agricultural research. Its success was due to the introduction and successful adoption of HYVs and the development and application of chemical fertilizers and other agricultural chemicals, accompanied by investment in institutional infrastructure and irrigation. There is a great deal of literature measuring the developmental impacts and the subsequent environmental consequences of the green revolution technology (e.g. Herdt and Capule 1983; Lipton and Longhurst 1989; Dalrymple 1986; Shiva 1991). The major themes emerging from this literature are summarized below.

Developmental impacts

Green revolution technology has had dramatic impacts on the developing world, particularly in terms of increasing the yields of the staple cereals wheat, maize and

[1] Barbier (1998), however, cautions that these calculations are often more illustrative than definitive due to the paucity of empirical data and various methodological problems.

rice. The greater part of Asia and Latin America has managed to avoid a decline in per capita food availability mainly due to the introduction of improved wheat and rice varieties. India, for example, doubled its wheat production over a six-year period. Many other countries, including Mexico, Pakistan, Turkey, Indonesia and the Philippines, also increased cereal production dramatically (FAO 1991). It was estimated that in 1993, 60-70% of the combined rice, wheat and maize area in developing countries was planted with HYVs (Byerlee 1996).

The introduction of HYVs and the adoption of associated input packages have led to **intensification** of agriculture and **crop monoculture**, phenomena often linked with environmental woes in developing countries. Intensification decisions can take a variety of forms. Some decisions to intensify imply a substantial change in land-use practices. Replacing traditional crop varieties with HYVs and their associated package of purchased inputs is one example of such a major change. Another example is the introduction of irrigation, which enables cultivation of very different crops and extends the cultivation period into the dry season. In other cases, intensification occurs as the cumulative effect of many decisions, such as choice of crop and variety, use of retained or purchased seed, and choice of inputs and quantities. Whatever the source of decisions on intensification, the term is taken to mean the following three interrelated processes that lead to changes in the use of RNR:

- increased frequency of cultivation (resulting in double- or triple-cropping per year);
- labour intensification per hectare; and
- capital intensification per hectare.

Crop monoculture (or monocropping) refers to the practice of growing a single plant species in one area, usually the same type of crop grown year after year. Monocropping is generally accompanied by a trend away from inter-cropping and crop rotation. There are many studies that link environmental impacts with **intensification** and **monoculture,** both of which are frequently associated with the green revolution.

Changes in RNR and environmental consequences

The literature on the consequences for RNR and the environment of intensification can be grouped into two kinds: (i) changes in the on- and off-site land and water resource base; and (ii) changes in the biological resources (pest population, genepool, spatial and temporal genetic diversity, etc.).

Impact on land and water resources

Studies by Pingali and Rosegrant (1994; 1998) provide an extensive review of the existing evidence on land and water degradation induced by crop intensification in Asian rice monoculture systems, as well as the rice-wheat systems prevalent in the Indo-Gangetic plains of South Asia. They show that intensification and rice monoculture impose significant environmental costs due to negative biophysical impacts. The most common consequences on RNR of lowland intensification cited are: (i) build-up of salinity and waterlogging; (ii) depletion/pollution of (ground) water resources; (iii) formation of a hardpan (subsoil compaction); and (iv) changes in soil nutrient status, nutrient deficiencies and increased incidence of soil toxicity (Pingali and Rosegrant 1998).

Many HYVs are highly water-intensive. Their short duration enables multiple cropping, thus increasing the overall demand for water. Postel (1989, cited in Pingali and Rosegrant 1998) estimates that 24% of the irrigated lands worldwide suffer from salinity problems, with India, China, the USA, Pakistan and the Soviet Union being most effected. Poor irrigation-system design and management are primary factors leading to salinity problems. One author estimates that because of these difficulties, old irrigated lands in South Asia are going out of use almost as quickly as new irrigated lands are coming into production (Paarlberg 1994).

In parts of the north China plain, ground water levels are falling by as much as 1 m per year. In Tamil Nadu, water levels have decreased by as much as 25-30 m in a decade (Postel 1993). In India, the first green revolution wheat varieties consumed three times as much irrigation water per hectare as the varieties used previously. Pingali and Rosegrant (1998) provide examples that show declining soil nitrogen supply, micronutrient deficiencies, soil toxicity and long-term changes in the physical characteristics of soil caused by intensive rice monoculture.

Other changes in RNR, often documented in the literature, are the increased production of methane and ammonia due to increased rice cultivation in Asia and increased emissions of nitrous oxide with the use of nitrogen fertilizers. In the intensively farmed lands of both the developed and developing countries, heavy fertilizer application produces nitrate levels in drinking water that approach or exceed permitted levels. Increased and inefficient use of pesticides and nitrogen fertilizers produces severe pollution but is mostly local in its effect.

Green revolution rice and wheat technologies are also associated with soil fertility problems in many areas. Rice and wheat monocultures replaced traditional crop rotations that included soil nutrient-replenishing legume crops. In South Asia, this has led to nutrient depletion requiring the addition of large nutrient inputs. Short-stature rice and wheat also produce less biomass; the impact of this on RNR is that fewer plant residues are available to be ploughed into the soil or to be used as feed for livestock.

Impact on biological resources

Other adverse effects of intensification and monoculture frequently cited in the literature are loss of genepools in centres of crop diversity and the narrowing of the genetic base (Kloppenburg 1988; El Hinnawi 1991; Wilkes 1992). The introduction of HYVs has frequently supplanted native varieties, many of which are now in danger of extinction. In the Philippines, the introduction of HYVs of rice is thought to have displaced hundreds of traditional varieties. Homogenization has also been extensive in high-value export crops; for instance nearly all coffee trees in South America are descended from a single tree from a botanical garden in Holland (El Hinnawi 1991).

Livestock also suffer genetic erosion. Modern intensified livestock operations have tended to bottleneck biodiversity as they streamline their activities by concentrating on a few highly productive breeds or strains. FAO estimates that at least one breed of traditional livestock is lost each week somewhere in the world as farmers focus on new breeds of cattle, pigs, sheep and chickens. Of the more than 3800 breeds of cattle, water buffalo, goats, pigs, sheep, horses and donkeys that are believed to have existed at the turn of the century, 16% have become extinct and a further 15% are under threat. These losses weaken breeding programmes that could improve livestock hardiness. However, the extent to which the introduction of improved varieties and breeds erodes traditional varieties and breeds is not well understood. Several studies suggest that modern varieties complement rather than replace local varieties; for example, traditional basmati rice varieties continue to be planted alongside HYVs in India and Pakistan.

One of the problems associated with monoculture often mentioned in the literature is increased vulnerability of crops to insect pests and diseases. For example, in 1970 a virulent fungus plague swept through the corn belt of the USA, spreading at up to 150 km a day. As a result of the fungus, maize production in the USA was reduced by 15%. However, increased development efforts and research on maize have lessened the impact of such outbreaks – the alternative varieties planted in subsequent years allowed corn yields to rise above pre-1970 levels (Crosson and Rosenberg 1989).

The widespread cultivation of HYVs also favours an increase in pests and diseases, which in turn has led to increased pesticide use, contributing to increases in production costs, environmental pollution and human health hazards (Pingali *et al.* 1994). The heavy use of pesticides often causes severe problems such as increasing human morbidity and mortality, while at the same time pest populations become resistant and escape natural control measures (Pingali and Rosegrant 1998).

Although early green revolution varieties played an important role in raising crop yields, they were also associated with many of the natural resource degradation problems mentioned above. These studies provide a powerful message that agricultural research needs to be sensitive to the results of new technology and that evaluating the impacts of research should be an integral part of the research design process. Technology improvement, however, is not a one-time event that took place only under the green revolution. Agricultural research in the post-green revolution period (1980 onwards) has responded to these sustainability concerns by developing technologies and resource-management practices that are both productivity enhancing and environmentally friendly. In the following section we review some of the products of agricultural research since the early green revolution varieties.

Modern varieties and the environment: response of agricultural research in the post-green revolution era

Breeding research has continued to produce new varieties that respond better to environmental constraints. Byerlee (1996) provides a comprehensive overview of how modern varieties in the post-green revolution era have contributed to input efficiency and sustainability. The following examples substantiate this point.

Resistance to biotic stresses and maintenance research

A major criticism of green revolution varieties was that they were not very resistant to pests and diseases. However, Byerlee (1996) contends that neither were the traditional cultivars they replaced. The green revolution rice varieties were resistant to only one kind of insect pest and required substantial chemical sprays to control others. By comparison, the modern varieties developed subsequently are resistant to six or seven pests and no longer require pesticide application. New rice varieties, developed by the International Rice Research Institute in partnership with national programmes, now incorporate tolerance to an increasing array of pests, diseases and other stresses. Reduced susceptibility to pests has made yields of both rice and wheat far more stable than at the time of the green revolution.

The spread of modern varieties to marginal areas

Evidence suggests that the adoption of modern varieties is no longer closely associated with the availability of irrigation. Recent breeding improvements have enabled modern varieties to spread to rainfed areas. Byerlee (1996) estimates that three-quarters of the more recent adoption (20 million ha) in India took place on rainfed land and much of this was on semi-arid or even arid land.

Modern varieties and biodiversity

Byerlee (1996) cites several examples that show that the role of modern varieties in reducing genetic diversity in farmers' fields is greatly overstated. Traditional systems enjoyed neither spatial nor temporal diversity. Today's modern varieties offer three genetic diversity advantages: (i) they contain genetic material from numerous sources so each modern variety represents significant diversity; (ii) they are more narrowly targeted to specific ecosystems, raising spatial diversity; and, (iii) they are replaced by completely new varieties with increasing frequency, thus raising temporal diversity.

The spread of modern varieties into rainfed areas has increased the erosion of genetic diversity since this is where indigenous landraces are grown, but recent analysis has shown that landraces have surprisingly narrow diversity for some traits. New modern varieties are often more genetically diverse and have greater resistance to important pests and diseases.

Modern varieties and NRM

Agricultural research is also responding by developing varieties that promote sustainable resource use. Promising examples cited by Byerlee (1996) include: the possibility of developing new wheat varieties with increased ability for nutrient uptake, varieties with improved root systems that reduce leaching of nitrates thus reducing ground water pollution, a 'super' rice variety with drastically altered plant architecture that is expected to raise yields by 30%, disease-resistant pigeon pea that will reduce production costs by 42% and short-duration pigeon pea varieties that will enable farmers to grow the crop after the rice harvest, without delaying wheat planting (thus contributing to restoring soil nutrients).

In addition to the above examples, which link varietal technology with sustainability, agricultural research has increased its attention to developing management practices that have a direct impact on the use of RNR. Opportunities are explored of managing soil fertility, reducing losses due to pests and diseases, and cutting back on the use of pesticides through better application of NRM and integrated pest-management techniques.

From identification of consequences to impact assessment: methods and data needs

The literature reviewed thus far provides empirical evidence that establishes the relationship between research and changes in the use of RNR. In order to assess environmental impacts of research, one needs to link the changes in RNR to consequent changes in crop yield or agricultural production costs, and then link these to resulting changes in consumption, market supply, farm income, food security and economic growth. Environmental economics aids in this process by introducing environmental values into the equation. These include the costs and benefits of maintaining natural resource stocks for future use, and the various benefits that can be derived from natural resources and the environment. Identifying and assessing the environmental costs and benefits involved in research projects illuminates the tradeoffs which are being made among different sets of values, among different users, and between private and public interests.

Impact assessment in the context of agriculture

There is a sizeable amount of literature on assessing the environmental impact of changes in RNR in general. Methodologies found in the literature include contingent valuation, assessing the costs incurred to enjoy environmental benefits, and willingness to pay varying amounts for the improvement of some aspect of the environment. Most of these techniques have been used to estimate the effects of surface- and coastal-water pollution and industrial pollution (e.g. Dixon *et al.* 1993). But there are very few studies that use these techniques to specifically assess the impact of agricultural research on the environment.

Environmental costs and benefits are typically not included in conventional economic evaluation studies of agricultural research. The now familiar ground of ex-post economic assessment in research evaluation features explicit attention to efficiency related developmental impacts. Economic impacts of agricultural research are measured by changes in the partial factor productivity indicators, such as the observed crop yields. A recent meta-analysis of the returns to agricultural research by Alston *et al.* (1998) found that out of more than 1100 research evaluation observations, only 11 included environmental variables in the rate of return analysis. The effect of allowing for environmental impact on the rate of return was both positive and significant. According to the authors, this reflects bias in the selection of the research evaluation studies, i.e. where environmental impacts were measured they were overwhelmingly positive.

However, there are growing concerns that past assessments of research performance, based on measures of efficiency, have been too narrow. A major criticism of past approaches is that they ignore the fact that the improved technologies produced by agricultural research may often have favourable and unfavourable consequences for the natural resource base and the environment. The review of impacts presented earlier confirms this claim. Critics contend that these consequences must be taken into account in any evaluation of agricultural research and in the setting of research priorities.

Environmental impact assessment: state of the art

Methodologically, one way of addressing the concerns of sustainability, as suggested by Crosson and Anderson (1993), is to extend the concept of productivity to a 'total productivity' measure. This will include all inputs (including natural resources) and outputs of an agricultural activity (including impacts on the use of RNR). However, this approach is hard to put into operation because of the difficulties in measuring environmental inputs and outputs (Anderson 1999).

A much-cited reason for the lack of EIA in agriculture is that it is data intensive and requires highly developed skills in collecting and statistically manipulating large quantities of data, which are sparse in developing countries (Crosson and Anderson 1993). For example, an assessment of the economic effects of soil degradation requires estimates of changes over time in the type, scale and rate of physical soil quality at a subregional or higher scale. No developing country has in place a national monitoring system to assess the use of RNR. Studies that try to assess changes in the use of RNR have, therefore, used approximate measures. Scherr (1999) lists the following methods and examples of studies that use them (in the specific area of soil degradation).

- Consultation with experts who provide a ranking or qualitative assessment of the scale and process of degradation within the region, according to agreed-upon criteria (e.g. Oldeman *et al.* 1990).
- Review and comparative evaluation of published studies on similar natural resource problems from many different sites within a region (e.g. Dregne and Chou 1992; Lal 1995).
- Extrapolation of the results of case studies, field experiments and other micro-level or watershed-level data to the national level (e.g. cases in Bojo 1991).
- Estimates constructed from examination of secondary data on land-use change, representative ecological conditions and so on (e.g. Rozanov *et al.* 1990).

Assessing environmental costs and benefits in economic terms

There are four steps involved in assessing the economic costs and benefits:

- Firstly, understand the causes and impact of changes in the use of RNR. These include deforestation, rangeland degradation due to overgrazing, soil erosion, the decline in the fertility of arable land, the salinization of soil and water sources, loss in biodiversity, etc.

- Secondly, identify the main types of economic costs (and benefits, if any) involved, such as damage to natural resource stocks and loss of species, and identify who bears these costs.
- Thirdly, establish whether or not the costs and benefits can be expressed in monetary terms.
- Fourthly, assess the extent of changes in the use of RNR and the environmental effects that have taken place, and gather data to allow measurement of the impacts on development indicators such as productivity, income and consumption lost (or gained), human health and morbidity.
- Finally, it is necessary to assess the level of costs involved by using economic techniques to value the changes that have taken place.

A number of techniques are available to place economic values on environmental changes (Pearce and Turner 1990; Winpenny 1991). Winpenny (1991), for example, describes in more detail the methods of assessing the economic impact of land degradation. The principal technique used is the 'effect-on-production' approach, which costs losses in yield or income resulting from degradation by using market prices for goods involved or their nearest available substitutes traded on the market. Studies by Bishop and Allen (1989), and Magrath and Arens (1989) illustrate the use of this technique to estimate cropland erosion in Mali and Indonesia, respectively.

A second technique is to assess the value of capital assets or natural resources lost as a result of the degradation of natural resources by establishing their replacement costs at market prices (e.g. Cruz *et al.* 1988; Quan *et al.* 1994). Where markets do not exist for natural resource goods or services the market price for commercially available substitutes can be used, or the costs of rehabilitating or restoring a damaged environment can be assessed. A third and related approach is the preventive expenditure method which estimates the economic value of environmental resources by assessing what it would cost to prevent damage to them, e.g. value of inputs needed to compensate for lost nutrients, or current or discounted future income streams to farm income (see Tolba and El-Kholy 1992, pp.145-146, for an example of such estimates).

It should be remembered that in addition to the use-value of resources, their total economic value has other components. It can be very difficult to place monetary values on many environmental goods, such as the cultural or spiritual importance of natural environments, the possible future option value of natural resources to future generations and the unique existence value of living species and habitats. Economists have attempted to develop methods of measuring such values, generally based on the principle of willingness to pay, but these are of only limited applicability to most developing country situations. This does not mean, however, that they do not have economic values or that these should be discounted in decision-making.

There are a number of methods that can be used for appraising possible courses of action in NRM and the implication of environmental projects. Perhaps the most common is the economic appraisal technique known as cost-benefit analysis, where costs and benefits of a course of action or of a number of alternatives, are estimated and compared. There are other related techniques, such as cost-effectiveness analysis and least-cost approaches, where the desirability of certain objectives is assumed and the most cost-effective or least costly means of reaching them is then assessed (Winpenny 1991). Where environmental costs and benefits are involved, these must be somehow measured and valued in monetary terms for incorporation in these calculations.

Until recently, cost-benefit analysis had made little headway in treating the environmental impacts of research projects and programmes, mainly because of difficulties in quantifying biological processes and in valuing the changes which may ensue. The difficulty also stems from assessing environmental benefits, which are mostly the on-site and off-site damages avoided by adopting the technology. This requires an assessment of the likely changes in the use of RNR in the absence of research and is the topic of review for the next section.

Technology and environmental consequences: tracing the links in a 'without research' scenario

So far, the focus of the overview has been on the documented impacts of research on RNR and the environment. The literature does provide empirical evidence that links new agricultural technology (the green revolution type) with intensification and monoculture that have quantitative and qualitative impacts on natural resources. These, in turn, have had environmental impacts in some areas by affecting crop productivity, incomes and human health. However, in order to assess the environmental costs and benefits of past research, a valid question to ask is: what are the environmental costs avoided due to research?

In order to assess what would be the impact on RNR and the environment if research had not produced a technology, one needs to examine the feasible alternatives available to an economy prior to the introduction of a new technology. Thus, prior to the introduction of the yield-increasing green revolution-type technology, the world could have addressed the food crisis and met the subsequent demands for food, feed and fibre in two ways: via technological change to increase the productivity of land currently in production and via expansion of the total amount of land in agricultural production. The latter option leads to deforestation and other forms of environmental degradation that affect human wellbeing. One of the major impacts on natural resources of the yield-increasing technologies (associated with the CGIAR) is, therefore, the land-resource savings (both the quantity and quality) and the avoidance of deforestation.

Norman Borlaug (1997) made a compelling point when he calculated that if the USA attempted to produce the 1990 harvest of the 17 most important crops with the technology and yields that prevailed in 1940, it would have required an additional 188 million ha of land of similar quality. This, theoretically, could have been achieved either by ploughing up 73% of the nation's permanent pastures and rangelands or by converting 61% of the forest and woodland to cropland (Borlaug 1997). Finn (1986) also makes a similar argument for Canada by estimating the additional land base required in 1983 to maintain the same level of production of wheat, barley and rapeseed in the absence of new varieties (i.e. those introduced after 1971). According to Finn's (1986) estimates, the additional land requirement, if the older, pre-1972 varieties had been produced in 1983, would have been approximately 2.1 million ha with the same pattern of fertilizer use and crop management practice prevailing in 1983. This, the author contends, corresponds to an equivalent bread-wheat yield advantage of the new varieties of 3.5 million tons.

The estimates of Borlaug and Finn may be too simplistic as they ignore the causal link between factors other than technology, such as population, policies and infrastructure, and the land-use decision. Nonetheless, on a global scale it seems that yield-increasing technological change does reduce deforestation. Thus, one of the major impacts on RNR of new technology has been the land-saving impact. To date, this indirect effect of yield-increasing research has not been sufficiently recognized in the debate on sustainability.

The question is how much and under what circumstances does a yield-increasing technology lead to land savings (or reduce deforestation and expansion of cultivation in marginal lands)? This is not an easy question to answer. The Panel did not find any studies that addressed this issue with sufficient rigour or analysis to enable an assessment of the global land-saving impacts and environmental benefits of past research. The literature, however, is replete with micro- and regional-level case studies that examine the following questions:

- Do yield-increasing technological changes reduce or augment deforestation?
- Under what conditioning factors does technological change in agriculture promote deforestation?

These questions have important implications for establishing the linkage between research that leads to yield-increasing technologies and land saving. The major themes/viewpoints emerging from the review are summarized in the following sections.

Empirical evidence linking technology to land-use transformation

The Forest Resources Assessment 1990 Report (1990) estimated the deforestation rate (across 62 countries lying mostly in the humid tropic zone) for the period 1976 to 1980 as 9.2 million ha per year. It increased 83% to 16.8 million ha per year for the period 1981 to 1990.[1] In many areas of the humid tropics, agricultural land expansion is one of the most important direct causes of forest conversion (Buringh and Dudal 1987). Thus, despite the introduction of yield-increasing technologies in developing countries, deforestation has continued at an increased pace. Therefore, the question that arises is whether land transformation is occurring because of yield-increasing technology or because of the lack of it? Empirical evidence on this question can be grouped as supporting the following interrelated arguments.

Increasing the productivity of agriculture on the best land can help control deforestation by reducing demand for new farmland

This is known in the literature as the Borlaug hypothesis and is named after its most famous exponent (World Resources Institute 1986; Rudel and Horowitz 1993; Southgate 1998). The hypothesis is based on the relationship between increased production of a commodity and its world price, and how the price affects farmers' land-use decisions. It suggests that increased productivity would lower the price of tropical commodities on the world market. Under pressures created by lower prices, some producers would stop cultivating the crop, and in some instances land might be left fallow and eventually revert to forest. Low prices would also persuade other cultivators not to carve a new farm out of the forest or expand the amount of cultivated land on their farms at the expense of forested land. By implication, the path to tropical forest conservation lies through increments in the land productivity of crops grown in the tropics.

Rudel (1999) examines the forest-cover dynamics in the southern USA to test the Borlaug hypothesis. In a comparison of 800 counties, based on their dominant cash crops, he finds a distinct pattern in forest-cover change that supports the Borlaug hypothesis. Those counties that saw the largest increases in the yields of their dominant crops (more than 120% over the 40-year period) showed greater gains in forest cover than counties that had lower increases in yields per acre. Counties where yields increased the most had the largest decline in acreage planted.

At a theoretical level, the Borlaug hypothesis is supportable. By and large, commodity demands are inelastic, accordingly, technological innovations that augment supply tend to drive down market prices. Along agricultural frontiers, price declines outweigh whatever farmers gain from lower costs. Deforestation is thereby discouraged (Southgate 1998). This is not just a theoretical conjecture. Tweeten (1998) points out that since the 1960s, global demand growth has been matched by yield increases. As a result, real commodity prices have been remarkably stable. However, the possibility exists that agricultural intensification can coincide with accelerated deforestation. For instance, in a small open economy that enjoys a comparative advantage in agriculture, such as in Central America for example, demand is fairly elastic. As productivity increases do not lead to major price declines they represent a stimulus for forest loss.

[1] The report cautions that the 1980 estimates may have been underestimated, thus resulting in a significant increase in deforestation over the next decade.

When labour is not a constraint and other employment opportunities are not created then a new profitable technology could lead to more deforestation

The Borlaug hypothesis claims that yield-improving technological change will discourage land clearing because the declining commodity price would not be sufficient to generate profits on marginal land. However, a counter argument (or qualification) to this claim (as illustrated above by the example of Central America) is that by making agriculture more profitable, production is just as likely to expand at the extensive frontier as in the intensive areas (Pagiola and Holden 1998; Pichon *et al.* 1999). Even if agricultural technologies that create a more productive resource base are available, this may not necessarily reduce land clearing. Settlers with more productive resource bases may simply use their higher economic returns to invest in more extensive land-use forms such as cattle raising if labour is not a constraint and other employment opportunities are not available.

Yanggen *et al.* (1999) contend that much of the history of US agriculture has been one of increasing yields via the application of productivity-enhancing technologies such as fertilizers, hybrid seeds, pesticides and herbicides, while at the same time the expanding total land area is cultivated via the adoption of tractors, combines and other machinery. Indeed, if a yield-increasing technology change makes a particular crop more profitable, this may both encourage land expansion to benefit more from increased returns and permit land expansion by providing financial capital to purchase labour and/or capital inputs needed to bring more land into production.

Finn (1986) consulted expert opinion to ascertain the possible impact of the introduction of new varieties of wheat, barley and rapeseed during 1971-81 on new marginal land utilization in Canada. While more than half the expert group felt there had been virtually no impact, the remainder felt the introduction of new crop varieties had had an effect on marginal land use, but that this was very small compared with the influence of other factors. According to the latter group, the introduction of HYVs augmented the use of marginal land by only 3%. More important considerations in increasing marginal land use were factors such as market prices, shipment quotas, the farmer's financial position, and the ability and desire to expand the farm.

Effects of yield-increasing technological changes in agriculture on long-term land transformation can be positive or negative and are often ambiguous

At a micro or regional level, there is not necessarily a direct correlation between yield-increasing technological changes and a slowing down in the rate of deforestation. Thus, many have argued that intensification and extensification of land use are not mutually exclusive options (Yanggen *et al.* 1999). The Borlaug hypothesis and 'intensification myth' suggests the decision to intensify or extensify depends on factors such as price elasticities (and thus the commodity market), off-farm employment opportunities (and thus the labour market) and the type of technology (labour-intensive or capital-intensive). Factors that lead to extensive rather than intensive growth are still not fully understood. The magnitude, and sometimes even the direction, of the effect of certain factors are likely to vary with site-specific conditions. Therefore, the review feels that it makes little sense to talk in general terms about the effect of technological change in agriculture on deforestation.

Kaimowitz and Smith (1999) provide a very good case study illustrating the negative effect of new soybean technology on land expansion. They trace the impact of new crop technology in the presence of other conditioning factors, namely high international prices, government subsidies and market infrastructure, to the loss of vegetation in Brazil and Bolivia. Soybean yields from 1960 to 1970 increased 15% on average. By the 1970s, yields were 36-63% higher than in the previous decade. The main source of increased yields was improved soybean varieties developed and adapted locally. Kaimowitz and Smith (1999) report that the cultivated area in south Brazil jumped from 1.2 million ha in 1970 to 5.1 million ha in 1975, and 6.9 million ha in 1980. Simoes (1985, cited by Kaimowitz and Smith 1999) calculated that for each percent of increase in expenditure on soybean research between 1973 and 1983, the soybean area grew by 0.28% (mostly at the expense of destruction in natural vegetation).

Studies that try to quantify the relationship between productivity increments and land saving are rare in the literature. Godoy and Sandals (1999) cite a study by Foster *et al.* (1998) on the relation between farm yields and forest clearance in India. Using panel information from 1970 to 1982 from about 250 villages, Foster and his colleagues found that doubling crop yields increased deforestation by 6% (direct effect). But they also found that the presence of a factory in a village reduced deforestation by 19% (indirect effect). Improvements in agricultural productivity lower the price of food and enhance real wages while nominal wages remain constant. In so doing, it encourages the growth of economic activities outside the farm. One could argue, even in this study, that technological progress in agriculture enhances land saving by a net 13%, provided one takes into account both the direct and indirect effects of improved farm productivity on deforestation and not simply the direct effect of yields on land saving.

Another study by Barbier (1999) estimates the price and population 'elasticities' of land saving in the context of pre- and post-NAFTA in Mexico. The author estimates that in the short run, a 10% increase in the maize-price ratio in Mexico caused a 4.4% increase in the demand for land, whereas a 10% increase in the long run caused demand to rise by 5.1%. Similarly, a 10% increase in population led to a 0.8% rise in the short run and a 1% rise in the long run.

Angelsen and Kaimowitz (1998) use analytical models and illustrative empirical examples to analyze the conditions under which technological progress in agriculture can be expected to reduce or increase deforestation. Technological progress is more likely to encourage deforestation when: (i) farmers behave as profit maximizers rather than subsistence-oriented producers, (ii) the new technology displaces labour, (iii) the technology can be applied in agricultural frontier contexts, and (iv) labour supply and the demand for agricultural products are both elastic (i.e. prices and wages do not change much).

The authors systematically discuss some of the analytical arguments and empirical evidence regarding the impact of technological progress in agriculture on deforestation. They highlight three factors that are important for the outcome: the type of technological change, the sub-sector of agriculture in which it occurs, and the market conditions. The answer to the question as to whether technological progress in agriculture leads to more deforestation depends upon these factors. From the theoretical and empirical review, three broad conclusions emerge (Angelsen and Kaimowitz 1998).

- Technological progress in the intensive sector is generally good for land saving unless it substitutes labour with capital and expels the displaced labour to the agricultural frontier.
- Labour-intensive technological progress will tend to increase land saving, while labour-saving technologies have the opposite effect.
- The effect of pure yield-increasing and labour-saving technological progress in the extensive sector (marginal, frontier regions) is sensitive to market assumptions. Technological change, accompanied by subsistence type behaviour, imperfect labour markets, endogenous prices and inelastic demand, may reduce deforestation, otherwise they tend to encourage it.

From a land-saving perspective, the 'worst' type of technological progress at the frontier is labour saving (capital intensive) with an elastic demand for the output (typically export crops with a fixed world market price). The 'best' type of technological change is labour intensive and utilized in contexts where there are limited opportunities for in-migration and an inelastic demand for agricultural products.

Assessing the environmental impacts of agricultural research: conceptual and empirical issues emerging from the literature review

The overview of the major themes encountered in the literature presented above indicates that tracing the link between agricultural research and changes in the use of RNR, specifically land use, is a difficult task. As illustrated in Figure 4, there are many contributing factors and inter-relationships between these factors that complicate the pathway from research to environmental impacts. The forces and links identified in Figure 4 are an illustrative representation of the major points and issues discussed in this chapter and summarized below.

Evidence of the link between research, the use of RNR and environmental impacts

Agricultural research creates new technologies that change the use of RNR either by intensification or extensification (Fig. 4). This, in turn, impacts on the development and environment variables that result in developmental and environmental impacts by affecting human welfare. The literature provides clear evidence in tracing the link between past agricultural research that resulted in HYVs and changes in the use of RNR, typically the intensive use of resources accompanied by the practice of monoculture. The pathway that further links changes in the use of RNR with developmental impacts is well researched. There are many empirical estimates of these developmental impacts of yield-increasing technologies and most conclude that these impacts have been overwhelmingly positive.

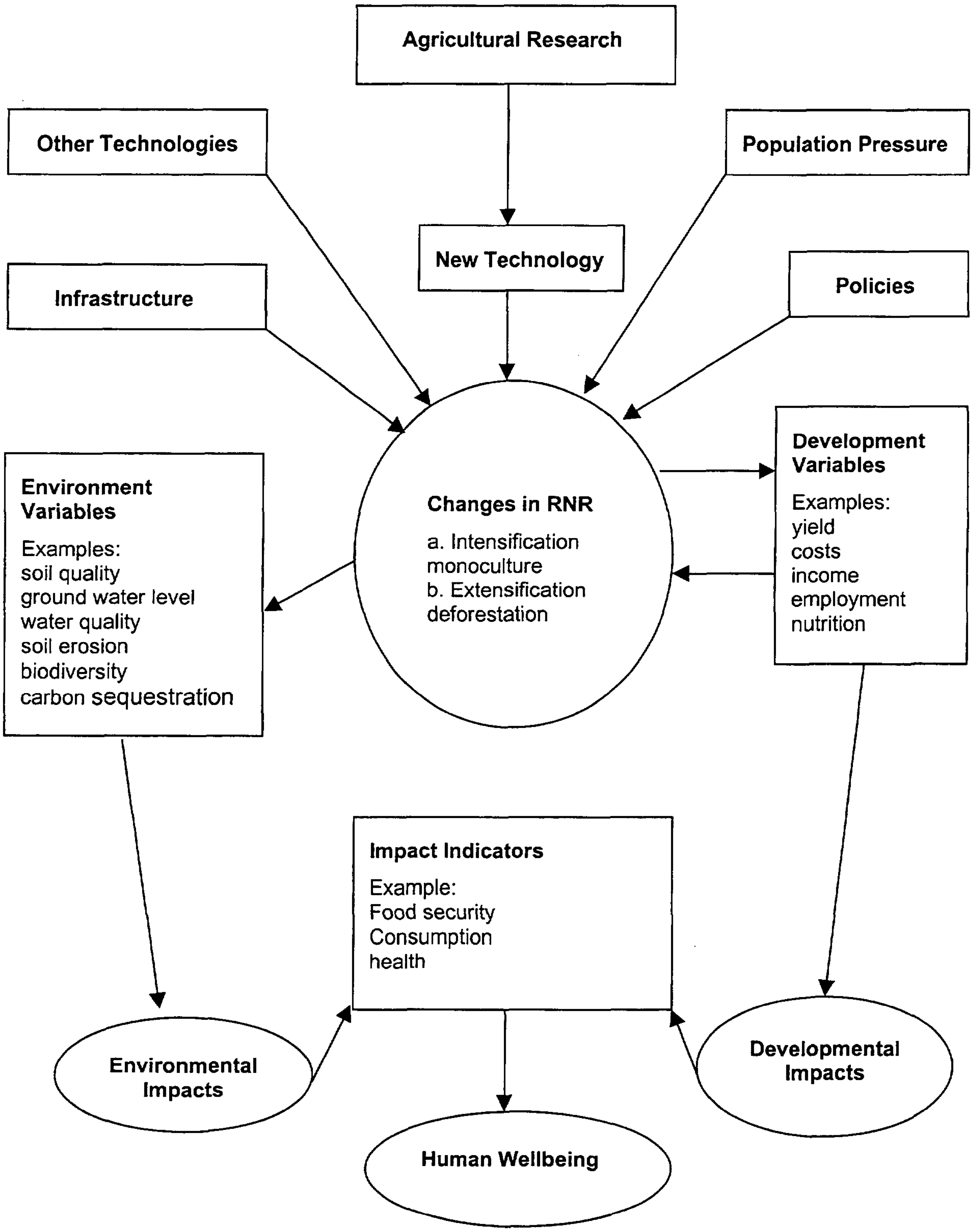
The pathway linking changes in the use of RNR and environmental impacts is a less researched one, although empirical evidence linking and assessing the impact of changes in the use of RNR on the quality and characteristics of natural resources does exist. The empirical evidence mostly points to the degradation of natural resources due to intensification and monoculture, which is linked to negative environmental impacts in the form of reduced agricultural productivity and human health. The new generation technologies emerging from the research system have responded to these concerns of negative impacts on the environment with improved crop varieties that impact positively on the quality of natural resources. Empirical assessment of the environmental impacts of these technologies is, however, not found in the literature.

Evidence linking research with changes in the RNR base and the environment

Studies reviewed either examine or measure the effect of changes in the use of RNR on environment indicators (e.g. effect of intensive cultivation on salinity build-up) or they start with an observed change in the indicator and measure its impact on the environment (e.g. impact of soil erosion on crop yields). Quantitative assessments linking the environmental impacts to agricultural research were not found (although the search was not exhaustive).

Lack of empirical studies linking research with environmental impact is due to: (i) lack of data to measure changes in natural resource variables in a consistent manner over time and across places; (ii) lack of research identifying and measuring the links between changes in the use of natural resources and improved technology; and (iii) lack of understanding on how agricultural development, along with other forces, impact on the use of RNR.

Fig. 4. Agricultural Research and Environmental Impacts: Tracing the Link from the Literature



The lack of studies on EIA of agricultural research, despite the heightened concerns on sustainability issues, indicates that tracing this link in the real world is a complex matter. Isolating the effect of agricultural research on RNR and environment from myriad other influences (Fig. 4), means that any EIA will have to be based on assumptions regarding the direction and scale of the relationship between the use of RNR and other factors. In the absence of data and information on such relationships, EIA exercises may not render meaningful results.

Technology is not the only cause of environmental impacts

The review points to the role of other factors that condition the change in the use of RNR. According to Pingali and Rosegrant (1998) intensification *per se* is not the root cause of the lowland resource-base degradation observed in rice and wheat, but rather the policy environment (trade policies, price policies and input subsidies) that encouraged monoculture systems and injudicious input use.

The literature also points to the poverty-environment trap that makes it difficult to trace the link between research and environmental consequences, and between research and poverty (Quan *et al.* 1994; Anderson 1999; Kerr and Kolavalli 1999). The poor are often unable to finance agricultural inputs such as fertilizer, to use 'green manure' or to undertake soil conservation. As a result, they generally face declining soil fertility and lower crop yields, further exacerbating their poverty and increasing their dependence upon the land. In fact, the existence of this poverty-environment trap suggests that often it is not the technology, but the lack of it, which is the cause of environmental degradation.

Agricultural technology affects the use of RNR in a very different manner and is dependent upon population pressure, incidence of poverty, policies, infrastructure, and the type of technology, commodity, labour market and input market. There are, therefore, no generalizations that can be made concerning relationships and linkages between yield-increasing technology and agricultural intensification and extensification, and the resulting environmental impacts.

Tracing the links between new technology and environmental impacts is also difficult because the resulting developmental impacts can have contradictory effects on the use of RNR, off-setting the impacts on the environment, for example, increased income from yield-increasing and intensive agriculture may encourage further land clearing and deforestation.

Because so many factors influence land-use decisions, there is not necessarily a direct correlation between yield-increasing technological change and a variable for RNR, such as rate of deforestation. Intensification and extensification of land use are not mutually exclusive options. Much of the history of agriculture in the USA, for example, has been one of increasing yields via the application of productivity-enhancing technologies such as fertilizers, hybrid seeds, pesticides and herbicides. At the same time, the total land area cultivated has expanded via the adoption of tractors, combines and other machinery. Indeed, if a yield-increasing technology change makes a particular crop more profitable, this may encourage land expansion to benefit more from increased returns, and permit land expansion by providing financial capital to purchase labour and/or capital inputs needed to bring more land into production.

Issues for further empirical research

The development of yield-increasing technologies, such as the modern varieties developed by the CGIAR, is an essential element of sustainable cropping systems. Their contribution to land saving, through increases in productivity, is often the most important contribution. However, to date these impacts of research are not sufficiently recognized in the literature. Studies to assess the land-saving impacts of research are, therefore, much needed, both at the aggregate global level and at the commodity specific micro level. Any complex analysis of environmental impacts linked to agricultural research that can provide policy-relevant results at an aggregate level will need to incorporate the following:

- estimates of land-saving and land-augmenting impacts of technology by type of land;
- estimates of changes in land productivity due to modified cropping intensity or cropping patterns;
- an assessment of the dynamics of land-use change, in terms of geographic location and moves towards the intensive or extensive margins, in response to the availability of new technology.

Case studies that develop empirical evidence of the types of relationship illustrated in Figure 4 would provide necessary data for aggregate analysis. However, any meaningful generalization on land-saving impacts will require a critical mass of such studies. Until such information is generated from detailed case studies there is no alternative but to take a simplistic view of the causal links between the different elements described in Figure 4 and assess the land-saving impacts of past agricultural research. To date, these important environmental impacts have been ignored in the literature. The analysis presented in Chapter 3 is a preliminary attempt towards filling this gap. Assumptions, qualifications and caveats are appropriately noted in describing the method and results of this analysis.

CHAPTER 3. Estimating land savings from research on agricultural productivity

Introduction

This chapter examines the question of what might have been the extent of global RNR degradation and its long-term socioeconomic consequences in the absence of CGIAR research, that is to say the negative environmental impacts which otherwise would have occurred.

In this phase of the study, the main thrust is on the scenario of resource degradation that might have occurred without the CGIAR's productivity research category, which accounted for 56% of the budget over the period 1972-1998. Within that category the principal focus is on environmental damage avoidance associated with the System's innovations in the seven key food crops[1] and in forage/livestock genetic and management research affecting productivity of cattle, sheep and goats. Environmental implications in the categories of NRM and policy, which over 25 years have increased from 7% to 40% of the budget, will be addressed in Phase 2. Positive and negative impacts stemming from productivity research on all 29 mandated commodities in the commodity sector will also be dealt with in Phase 2.

The point of departure for the evaluation is the available evidence on the degradation in RNR over the past 30-40 years, with particular attention to developing countries. These, with the exception of the arid regions of West Asia and North Africa (WANA), China and the Southern Cone of South America, are concentrated in tropical zones. The discussion then moves to consideration of how the rate of RNR degradation might have accelerated if yields had remained stagnant or even declined in the absence of agricultural research leading to new technology, and considers the constraints to inferring simplistic land saving from this relationship. For the seven principal mandated commodities four scenarios of land-use change are presented. In addition, there is discussion of issues of potential land savings derivable from livestock research, and research which increases the quality and quantity of food available to consumers from any given level of gross harvested production. With respect to the precise source of technological innovations and the question of attribution to the CGIAR, national agricultural research systems (NARS), the private sector, etc., it is assumed that in the mandated commodities (particularly the seven listed in footnote 1) the System has played a considerable role in all cases through research on germplasm, management packages and IPM. The final section assesses what the environmental impacts might have been as a consequence of accelerated RNR degradation.

Framework for examining land-saving impacts of the CGIAR's research efforts over the 1970s to 1990s

As a point of departure it is critical to have a plausible scenario of the rate of RNR degradation: first, over the period of the 1960s and 1970s before CGIAR research findings were adopted on a large scale; and second, over the period of the 1980s and 1990s. Available global estimates suggest that over the past 40 years, forests have been degraded at an average annual rate of 18 million ha, pasture at 17 million ha and crop lands at 14 million ha. About two-thirds of this degradation occurred in developing countries – 20% in Latin America, 50% in Asia and 30% in Africa (Tables 1 and 2). It is

[1] Barley, cassava, maize, pulses, rice, sorghum and wheat.

widely accepted that the rate has generally been accelerating, so in more recent years the annual degradation should be significantly higher than the above averages.

What might have been the rate of degradation without the increase in yields attributable to agricultural research? The answer amounts to the land-saving benefits of research. Maximum possible global saving can be approximated from the additional area required to produce the output of the 1990s with 1970s yields. For the seven principal CGIAR mandated crops, the saving in harvested area could have been as high as 278 million ha, assuming 100% cropping intensity (Table 3). Clearly these figures require substantial qualification. For the purpose of this analysis only these seven crops, which account for 90% of total area in 21 mandated food crops, are considered when illustrating the issues to be addressed in the endeavour to derive a credible range of estimates for land savings attributable to agricultural research in general, and CGIAR research in particular.

The principal qualifications are:

1. The estimates of rate of increase in gross product harvested do not account for research results that may have increased effective net consumption, e.g. reduced post-harvest losses or higher nutrition value. Field production required to meet the same level of consumption would be less. Taking these aspects into consideration would increase land savings.
2. Research not only changes yields, it also changes the productivity of all factors of production. Thus, one would expect the changes in TFP in an equilibrium situation to force substitution of crops. This has been documented in India, where HYVs of rice and wheat have displaced pearl millet and sorghum. One might expect this process to reduce the land-saving impact.
3. The assumption of 100% cropping intensity may understate or overstate the total area that would have had to be brought into production to make available the necessary harvested area. This index will vary widely by country, region and rainfed versus irrigated cropping. Among regions, the estimated 1988/90 cropping intensity varied from 55% in Sub-Saharan Africa to 112% in South Asia. The average for all Less Developed Countries (LDCs) in rainfed crops was 70% compared with 110% for irrigated lands (Alexandratos 1996). Also, the introduction of management packages with HYVs and increased cropping intensity will exert greater leverage on the land-saving outcome.
4. The above land-saving estimates depend on an assumption that the 1990s demand by crop will remain unchanged. It is evident that with the modification in TFPs and associated supply and prices, the demand for any given crop will change. If prices were to be higher the likely situation in the absence of research is that consumption, poverty-alleviation impacts and land savings would all be less.
5. The estimates also depend on an assumption that in the absence of improvements in yield, post-harvest loss and nutrition effects attributable to research, new lands would be brought into production at constant costs that do not change the 1990s prevailing consumer price. In practice, one would expect sharply increasing marginal costs of production to be associated with progressively bringing into production land that is more inaccessible and less suited to agriculture. Yields would be lower, and unit production and transport costs higher. Thus, prices would rise, restricting both demand and the land-saving impact. Further, this translates into reduced socioeconomic impact, i.e. new technology generates a 'win-win' situation.
6. The latter point introduces a further complication. Where would the additional lands have been brought into production? The primary concern of the CGIAR is with agriculture and poverty in LDCs. However, changes in TFPs and differential marginal costs of bringing new lands into production may well have changed trade patterns and the locus of land expansion in developed countries. There would still be a global environmental impact, but since yields in the Organisation

for Economic Co-operation and Development (OECD) and other temperate countries were 70% higher for the five crops grown in both tropical and temperate zones than in the LDCs, land saving would have been 12%[1] more than that which would have resulted if the current geographic distribution of production had been maintained (Table 3). In addition, from a comparison of Tables 3 and 7 it is evident that Asia simply did not have enough forest area to clear to make up the shortfall. Thus, aside from a change in North/South trade there would have been a change in intra-LDC trade. The major land-saving impact would be in Latin America and the Caribbean (LAC).

7. For the purpose of estimating the environmental impacts on land saving, qualification (6) above is crucial. It is not only whether, in the absence of yield-increasing or net consumption-increasing technology, land expansion would have taken place in developed rather than in developing countries, but also what land in any country or region would have been developed, through the conversion of forests and range, to annual crops or the expansion of irrigation. Externalities, in the form of unplanned changes in long-term human welfare from these conversions of RNR will be highly site-specific. Thus, one may expect the aggregate physical land savings to be essentially unchanged. But the aggregate environmental impacts of these savings (obtained by summing the various site impacts) would bear no particular relationship to the physical area.

In order to refine land-saving estimates one could develop country, region and global equilibrium models to handle the commodity substitution, increasing marginal costs and trade issues. One could also superimpose agroecological zones at country and regional levels to obtain an indicator of where the area in any particular crop would have been likely to expand in the event yields had not increased by 2-3% annually. Since this study is restricted to seven commodities, no effort has been made to develop an equilibrium model. Even if all 29 mandated commodities were to be addressed, such a model would have to encompass a wider range of substitutable agricultural, forest and fishery products.

Scenarios of land-use change

To develop some regional and agroecological bases for assessing land savings from research-induced changes in productivity of the seven mandated commodities, four base scenarios are considered.

1. The additional lands that would have been required to meet the 1990s production levels would be derived exclusively through expansion of rainfed agriculture in humid, sub-humid and semi-arid tropical zones. It is assumed that expansion would have been in forested areas. As shown in Table 5, the type of forest and its state of degradation vary widely. Biomass may vary from over 300 tons per ha in closed tropical rainforest to less than 50 tons per ha in semi-arid savanna bush land or in forests severely degraded by slash-and-burn agriculture. The incremental area would have to compensate for an assumed non-expansion in temperate zones (approximated by OECD countries) where yields are higher than in LDCs. *Gross land savings through reduced deforestation – 460 million ha.*
2. The source of all additional land is assumed to be tropical forest areas but in contrast to scenario 1, there would have been no requirement to make up a shortfall in production from the temperate zone. *Gross land saving through reduced deforestation – 340 million ha.*

[1] Yields in barley in the 1990s were 140% higher than in LDCs, maize 80%, pulses 90%, sorghum 80% and wheat 15%, with a weighted average 70% higher. Thus, in order to cover the shortfall in production from the 50 million ha saved in OECD and other temperate countries would have required an expansion of 84 million ha in LDCs, i.e. 34 million ha, a level approximately 12% higher than the 287 million ha shown in Table 3.

3. The shortfall in production in LDCs would have been covered by a combination of deforestation and irrigation development in non-forested semi-arid and arid areas. Temperate zone production is assumed to be as in Scenario 2. *Gross land saving through reduced deforestation – 350 million ha.*
4. It is assumed that productivity in temperate zones would have been less in the 1990s without research by the CGIAR and its partners and that half the 1990s shortfall in LDCs would have been made up by imports from temperate countries. The other half of the LDC shortfall would be covered by deforestation in tropical areas. *Gross land saving through reduced deforestation – 170 million ha.*

A fifth scenario was considered under which countries would be broadly grouped into six subregions as an approximation of five ecological zones[1], with estimates for three types of land-use change (non-forested arid and semi-arid areas to irrigation, conversion of rangeland to arable farming, and deforestation) for each commodity (Table 4). This exercise was abandoned as being excessively speculative without substantial additional work to disaggregate agroecological zones for major producing countries such as India, China and Brazil, and to assess more precisely the extent to which there may be links between the CGIAR and other tropical agricultural research entities operating in temperate zones.

Scenario 1: Land-use change in tropical areas

FAO has undertaken a detailed study of changes in tropical land use from 1980 to 1990, basically focused on the conversion (and reversion) of native vegetation (closed and open forest) to degraded vegetation usually associated with shifting agriculture, and to permanent annual cropping, tree crops and forest plantations (FA0 1996). Data available from this study (Tables 5 and 6) provide the basis for a more in-depth assessment of the extent to which agricultural research on the seven commodities might have influenced the pattern of changes in land use during the 1980s in three tropical ecological zones within the Asian, African and LAC regions.

Gross conversion of closed forest to agriculture in the 1980s was 35 million ha; adding conversions from open and degraded forests, total deforestation amounted to 85 million ha. Assuming the same rate to hold over the two decades covered by this scenario suggests around 170 million ha could have been transformed from forest to permanent agriculture and pasture over this period.

The world's supply of land to cover the shortfall in production which would have occurred if yields had stagnated from the 1970s to 1990s lies largely within the tropics (Table 7). At one extreme it may be assumed that the shortfall from the seven commodities considered here would have been 100% covered by clearing these lands for rainfed production. This scenario would have called for deforestation of approximately 15% of this 2.5 billion ha area (Table 8). The estimate is based on the following assumptions:

- no increase in yields in OECD countries, China or WANA; implicit here is that the absence of research by the CGIAR, NARS and others in tropical countries would largely explain this stagnation;
- distribution of deforestation among regions will be in proportion to the share of tropical lands in 1980 (Table 7). Gross deforestation for conversion to permanent agriculture, including pasture, during the decade of the 1980s (85 million ha) was 60% in LAC, 21% in Africa and 19% in Asia;
- distribution of deforestation among ecological zones will be in proportion to the area of each zone in each region (Table 7);
- distribution among commodities within ecological zones within each region is based on a judgement that wheat, barley, sorghum and pulses will be

[1] Temperate zone plus four tropical zones – humid, sub-humid, semi-arid and arid.

concentrated in subhumid and semi-arid zones, and rice, maize and cassava will be concentrated in humid and semi-humid areas;

- average cropping intensity will be 70% - that prevailing in the 1988/90 period for rainfed crops in LDCs (Alexandratos 1996).

In this base case the land savings would have approached 460 million ha (Table 8).[1] Thus, the incremental rate of deforestation over the two decades would have averaged 23 million ha per year, i.e., a rate about two and a half times that recorded in the 1980s (Table 5). For reasons outlined above, this is likely to be a substantial overstatement. Reducing this rate estimate by 50% results in land savings (reduced deforestation) of 230 million ha attributable to the effect of agricultural research on yields.

Scenario 2: Limited land-use changes in tropical areas

This is substantially less extreme and more plausible than Scenario 1 and is based on the following assumptions:

- There is no linkage between research undertaken by the CGIAR, NARS and others in tropical countries and the productivity of the seven crops grown in the temperate zone; thus, there would have been no shortfall in the 1990s production in this zone in the absence of research on tropical agriculture.
- The LDCs (including China as part of the Asian region) would make up their own cumulative shortfall through the clearing of forest land for rainfed cropping.
- Distribution among commodities and ecological zones and regions follows the same framework applied in Scenario 1.

Gross incremental area at 100% cropping intensity in Asia, Africa and LAC would have been 237 million ha (Table 3) which, with adjustment for 70% cropping intensity, becomes approximately 340 million ha, i.e. 80% of Scenario 1.

Scenario 3: Land-use change in tropical areas - with irrigation

As in Scenario 2, the constraint that land expansion could only have occurred for rainfed agriculture in tropical zones is relaxed. It is assumed that temperate zone agriculture[2] (in the seven mandated commodities) would have met its 1990s production level regardless of the research effort in the tropics. Further, it is assumed that in the absence of CGIAR and other research in tropical countries between the 1970s and 1990s, irrigated cropping would have continued to expand. Between the 1960s and 1970s, irrigation development in LDCs was 13 million ha; the expansion between the 1970s and 1990s was 57 million ha. It is assumed that 25 million ha of this (i.e. about the same absolute expansion as in the 1960s) would have occurred without research. On the assumption of cropping intensity of 110% on these lands, plus irrigated yields of 30% above the average of those obtained in rainfed agriculture, the land savings (reduced deforestation) due to this irrigation amount to 50 million ha at a 70% cropping intensity. However, part of this irrigation would have been on forest land. In 1988/90, 30% of irrigation in LDCs was developed in arid lands. Assuming another 20% was in non-forest semi-arid areas, then 13 million ha of irrigated crops would have been converted from forest. Thus **net** land savings would be 37 million ha.

With this assumption, the level of deforestation in Scenario 2 is reduced to about 300 million ha or 70% of Scenario 1. However, implicit in the foregoing assumption is that the additional 32 million ha of irrigation developed between the 1970s and 1990s

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[1] Total incremental area harvested would be 287 million ha (Table 3), adjusted by 12% to compensate for the higher yields which would otherwise have been generated in temperate zones, i.e. total = 322 million ha; with 70% cropping intensity, the additional land required in LDCs would have been 460 million ha.

[2] Temperate zones are calculated by subtracting the Asia (including China), Africa and LAC totals from the World total, see Annex 1.

is attributable to research in tropical countries. This represents a gross reduction of 65 million ha of potential deforestation, where the net reduction (on the same assumptions as above) would be around 50 million. Total land savings would be 350 million ha.

This scenario illustrates the sensitivity of deforestation savings to irrigation expansion, a significant part of which may be attributable to agricultural research. Attributing irrigation expansion to research carried out by the System and its partners clearly carries potential positive and negative environmental implications beyond the deforestation land savings discussed here.

Scenario 4: Expansion of production in temperate zones

Scenario 1 represents a massive shift in production from temperate to tropical zones. This scenario postulates a reverse shift, i.e. in the absence of agricultural research by the CGIAR and its partners, much of the shortfall in tropical areas would have been covered by imports from temperate countries, resulting firstly in a corresponding expansion of area in the latter countries and secondly in a reduction in the rate of tropical deforestation suggested in the first three scenarios.

The following assumptions are applied:

- the LDCs will cover half of the shortfall (Table 3) from expansion of cropping through deforestation in tropical zones;
- the remaining 50% (primarily in wheat, maize, sorghum and barley, where the OECD alone accounted for 54% of global production in the 1990s) would be produced in temperate zones;
- in the absence of research by the CGIAR and its partners the productivity increase of these four crops in temperate zones would have been half that realized in the 1990s.

With these assumptions, deforestation in tropical areas becomes 120 million ha, i.e. 35% of Scenario 2. The major impact is in temperate zones where expansion of area in the seven crops is 118 million ha[1] beyond that estimated for Scenarios 2 and 3 (Table 9).[2] Aside from the potential environmental impacts of this latter expansion, the trade implications of this scenario are clearly prejudicial to development among LDCs.

Land savings from livestock and forage research

Yield for livestock may be approximated from carcass weights. Calculating 1990s production at 1970 carcass weights suggests that in Asia and Latin America an additional 25.6 million head of cattle would have had to be slaughtered. In the case of Africa, carcass weights declined, with the result that if 1970s carcass weights had been maintained, 0.8 million **less** cattle would have been slaughtered to meet the 1990s production level. For sheep and goats, yields in the LAC remained unchanged over the two decades. From yield increases in Asia and Africa it may be concluded that an additional 50 million head of small ruminants would have had to be slaughtered in the 1990s.

It could be implied from these figures that there have been land savings in terms of additional permanent pastures or expansion on to unoccupied rangelands. However, unlike crops, there is no ready means of equating the number of head of livestock with land use. The exponential annual growth rate in cattle stocks in the three developing regions over the past three decades has been in the order of 1-2%; for sheep and goats growth rate has been between 1.5 and 3% in Africa and Asia, with a 0.5% decline in LAC. In part, this growth has been supported by expansion of improved pastures, often through deforestation, as discussed. Between the 1960s and 1980s there was no change in permanent pasture area in Africa, and in Asia and LAC

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[1] Cropping intensity assumed at 100%.

[2] In scenarios 2 and 3 it was assumed that there would be no land savings in temperate zones attributable to research by the Centres and their partners.

expansion amounted to 170 million ha. If the increased livestock production outlined above had been derived from expansion of permanent pastures, this would have required conversion in the order of 50 million ha from rangeland or forest. Alternatively, supposing that half this production had been derived from expansion of grazing onto marginal rangelands, the area involved would be between 100-150 million ha.

From the point of view of the environment, a key question is to what extent agricultural research has slowed the rate of degradation of the rangelands that account for most of the 670 million ha estimated to have been degraded between 1950 and 1990 (Table 1). At this stage, without being able to establish a relationship between the stocking rates and efficiency with which range is converted to animal output, the answer to this question must remain open. To the extent that research has created employment opportunities in non-range agriculture, and thus reduced stocking pressure which otherwise would have accelerated the degradation process, there are clear savings in RNR. Any estimate of such an impact would require evaluation of the role of all types of research, e.g. policy and NRM, and is beyond the scope of this phase of the study.

Land saving attributable to research which reduces losses beyond farmers' fields

On the assumption that research which reduces post-harvest losses or increases nutritional values will reduce the volume of gross production required to satisfy a given demand, these approaches will be as important as yield increases in contributing to land saving. However, estimates of post-harvest losses are notoriously unreliable and data available for the seven mandated commodities addressed in this study show no significant trend over the past three decades. Further, in the case of nutritional value, there are no consistent time series from which one might infer that germplasm research has generated changes in calorie or protein content since the 1970s. The fact that there is no evidence of change in either of these indicators does not necessarily mean that research has had no impact – losses could have been higher and nutrition quality lower without research. Given this data situation, no attempt has been made to speculate on what additional land savings may be credited to these two consumption-related sources of research.

Water savings attributable to agricultural research

The CGIAR's productivity research cuts both ways in increasing or decreasing the supply of water downstream from the area where new technologies are applied. For example, in rainfed agriculture water-conservation practices or an increase in crops requiring water upstream may reduce availability downstream. This will have a negative impact only if there is an existing or potential demand for the water that has been withdrawn from the system. Alternatively, the development of drought-resistant or less water-demanding varieties may indeed release more water downstream (i.e. true water saving), which again will only have a beneficial impact if there is an existing or potential demand for the additional water.

In the case of irrigated agriculture, similar water-related costs and benefits may arise from adoption of new technology. Less water-demanding varieties or crop rotations, plus improved efficiency in irrigation distribution systems, will release water downstream for expanded irrigation or other uses (hydroelectricity, urban supply, etc.). In contrast, new profitable technologies may encourage increased upstream use and draw-down of water tables. Also, there is the question of irrigated land lost or degraded due to salinization or waterlogging. This is linked more to land than water saving, and is basically a question of NRM research, which is beyond the scope of this phase of the study.

Regardless of whether water is saved through new technology applied to rainfed or irrigated agriculture, this water can only be used in the same watershed or basin. Thus, the issue of quantification of savings is highly site specific with respect to water quantity and quality. Regional and global estimates of savings attributable to research or land loss to salinization, etc., would have to be built up from a comprehensive survey of cases within a structured typology. This was the conclusion drawn from the recent TAC Email network consultation on soil and water degradation. Under these circumstances the question of quantification of water savings is not pursued further in this phase of the study.

The issue of attribution of yield change to the CGIAR Centres

One approximation may be obtained by a comparison of exponential yield growth rates in LDCs in the 1965/75 period before the CGIAR technologies were adopted, with the subsequent two decades 1975/95. Weighted average yield change for wheat, rice and maize over these three decades show:

- wheat increased from 3.6% to 4% in 1975/85 and declined to 1.2% in 1985/90;
- rice increased from 1.9% to 2.8% in 1975/85 and declined to 1.5% in 1985/95;
- maize remained unchanged at 2.6% in 1975/85 and declined to 2.4% in 1985/95.

The increased yield growth rates in rice and wheat in the 1980s could be interpreted as being due to the CGIAR. However, the decline in growth rates in all three crops in the 1990s weakens this inference. From the figures one might conclude that the CGIAR was running out of steam by the mid 1980s. An alternative inference is that the rates would have declined even more without the System's research contribution. The decline in rates of increase in yields are likely to be related to factors other than the traditional ones that have been addressed by the CGIAR. Once these factors have been identified, it is hoped that research could reverse the trend. Among other things, the rapid expansion of NRM research in the CGIAR is related to the preliminary conclusion that in many areas inadequate resource management and consequent deterioration in the production environment are responsible for the decline in rates of productivity.

From the calculations of Lopez-Pereira and Morris (1994) a critical question arises on how far one can go in assigning productivity and total production to one source of research, e.g. CGIAR *vis a vis* NARS, or to one type of research, e.g. productivity *vis a vis* the management of RNR. They establish that in the case of maize:

- 43% of the area sown in 1990 was in modified varieties with average yields 30% higher than traditional varieties;
- 55% of the area in modified varieties was planted with types which contained CGIAR germplasm;

- the average CGIAR germplasm content in these types was 45%; therefore,
- the production increase attributable to CGIAR germplasm was 55 x 45 = 25%.

However, it appears one could equally justify 55% as attributable to CGIAR research. From this, it is concluded that there is little point in attempting to calculate (in this study) the percentage change in yield and production that is specifically attributable to the Centres' research in productivity in the mandated commodities. For the purpose of examining the potential environmental impact of changes in land use deriving from yield increases, it is assumed that all changes attributable to agricultural research on the seven commodities will be indivisible from the System's contribution.

Environmental impacts of CGIAR research

From the foregoing discussion, the following aspects set the framework for this evaluation.

- The only land-saving impacts considered are those attributable to productivity research on the seven key mandated food commodities and three livestock classes[1] that have accounted, on average, for two-thirds of the 85% increase in gross physical output in LDCs between the 1960s and 1990s.
- Over the past three decades it is assumed that the CGIAR has been a significant player in global research on the seven commodities, in direct association with its NARS partners, and in indirect association with the other public and private sector actors. Accordingly, no attempt is made to credit the System with some fraction of the overall land savings that could be attributed to agricultural research in general.
- Scenario 2 is used to illustrate the process. It is based on the assumptions that the concern is only with land saving in LDCs, and that without the results and adoption of yield-increasing research all the additional land brought into production in LDCs would have been in the humid, subhumid and semi-arid tropics.
- Total maximum land savings in the seven mandated crops are estimated at 340 million ha, all of which would have to be derived from deforestation, recognizing the wide diversity of vegetative cover encompassed in the definition of 'forest' (Table 5). For purposes of environmental assessment the above area is reduced by 50%, i.e. 170 million ha, as an adjustment for potential over-statement. To this area is added the 50 million ha converted to pasture, therefore, total deforestation likely to have occurred is placed at 220 million ha.

The likely environmental consequences would have been:

- Loss of biodiversity with the potential to benefit long-term human welfare.
- Reduction in carbon-storage capacity with the potential to accelerate climate change, which on net balance is considered to be prejudicial to long-term human welfare.
- On-site damage to soil through erosion, fertility decline and loss of water-holding capacity, which will reduce or eliminate the productive potential of forests and agriculture over the short and long term.
- Downstream changes in RNR and their use (siltation, flooding, increased water stress during the dry season, chemical pollution, turbidity) due to modification of water flows and quality.

[1] Livestock production measured by output of beef and goat meat, mutton and milk.

As in the case of water-saving benefits, these consequences are site specific. For example, in the case of biodiversity the potential value of loss will depend on the relative scarcity of the species destroyed in the deforestation process. The logical range of values is from one approaching infinity for the last few surviving plant or animal species to one approaching zero where the type of forest remaining is in the tens or hundreds of millions of hectares. David Simpson of Resources for the Future (RFF) has estimated that in the case of a biodiversity 'hot spot' - the Valdivian temperate rain forest in Chile - 'willingness to pay' would probably not exceed US$1 per ha. In the case of extremely high endemism in isolated forest areas of western Ecuador, he estimated biodiversity value could reach US$20 per ha.[1] On the assumption that 40% of the deforestation to permanent agriculture would have been from closed forest (Table 6) with a relatively high value of biodiversity, e.g. US$5 per ha, total savings may be estimated at US$440 million for 88 million ha. The remaining 132 million ha of degraded forest cleared may be assumed to have zero biodiversity value.

Estimates for the value of carbon sequestration vary widely – at the high end a value of US$1700 per ha has been placed on dense tropical rainforest with a biomass of 300 tons per ha. However, most studies place the value in the range of US$0.30 to US$45 per ton where, depending on the type of forest cleared for agriculture, the carbon released may be in the range of 50 to 300 tons per ha. Assuming that about 60% of the forest converted to agriculture would have been in some stage of degradation reducing canopy cover and biomass (Table 6), values of US$1 per ton and 100 tons of carbon per ha may be justified. This would yield a total value of US$22 billion for the 220 million ha deforested.

In the case of environmental savings through avoidance of on-site damage and negative downstream socioeconomic consequences, estimates would have to be derived from the type of breakdown suggested in Table 4. There can be little doubt that in the event of upstream deforestation, particularly where hillsides are involved, the negative environmental consequences in virtually all cases will be significant. Any quantitative estimate of how significant will depend on successive approximations derived from geographical information systems (GIS) and other means of establishing a typology of situations and case studies to match the types that demonstrate the biophysical and socioeconomic cause/effect relationships in play.

[1] Simpson, D. RFF. Personal communication.

CHAPTER 4. Conclusions and recommendations for the future

The Panel is of the opinion that there has been a degree of confusion over the exact nature of negative and positive environmental impacts of research associated with increasing production in agriculture, forestry or fisheries. In order to move forward systematically and accumulate experience on the question of how environmental issues should be incorporated into research policy and project design within the System, it is felt that a consensus on definitions is needed to specify the objectives and the information required to verify performance through M&E.

All changes in technology alter the state of natural resources, the purpose being to increase sustainable productivity, i.e. planned change in water availability, vegetative cover or soil characteristics. Some hold the view that these biophysical impacts, whether they involve positive socioeconomic changes (e.g. irrigation in arid zones) or take the form of modifying vegetative cover and other characteristics of natural resources, are all environmental impacts. It is proposed here that *environmental impacts* be defined as ***externalities****, which are the unplanned and unforeseen changes in the system of natural resources (biophysical impacts) that have had, or are forecast to have, consequences for long-term human welfare (environmental impacts) as a result of the* ***adoption*** *of past or ongoing CGIAR research results.*

In adopting this definition it is recognized that much of the research undertaken by the Centres is directly focused on conservation or rehabilitation of the environment. Since these are explicit planned objectives, the results are considered to be development impacts. The challenge in measuring the latter is essentially the same as that confronted for EIA; the difference being that in the ex post situation addressed in this study, by definition, potential environmental impacts were not specified in research project design. In the ex ante situation, EIA is designed to forecast impacts for all projects and in the case of management of natural resources or other environmental projects, justification rests on the specification of changes in the state of natural resources as a development impact. In 1996, it was estimated that over one sixth of CGIAR research related directly or indirectly to the category of soil and water related research (TAC Soil and Water Study 1996).

As a great deal of assessment and evaluation has been devoted to the negative impacts of modern agricultural technology on the biophysical environment and its socioeconomic consequences, in this initial phase of the assessment the Panel focused on the potential positive environmental impacts of CGIAR research since the 1970s. Examples include the large volume of work related to sources of agricultural pollution associated with use of chemical fertilizers, pesticides and herbicides. In contrast, there has been little rigorous investigation and evaluation of the positive environmental impacts of agricultural research. Such evaluation involves linking research, adoption of results, resulting biophysical changes and then environmental impacts, as defined above.

Given the complexity of tracing these links, the Panel decided to focus initially on the land-saving implications of productivity-enhancing innovations in agriculture resulting from CGIAR research. This fully recognizes that the overall IAEG programme of assessment eventually will need to cover the whole range of positive and negative impacts on the environment of other kinds of CGIAR research in agriculture, livestock, forestry and fisheries. The purpose was to clarify the issues that must be addressed in the overall assessment.

As the Panel commenced its work, a number of complications became immediately evident. First was the challenge of establishing a credible link between the availability of new yield-increasing technology and the nature, extent and spatial distribution of the development impacts over the period from the 1970s to 1990s. Clearly such impacts are related to many factors, such as other complementary types of research, policy and institutional change, and so forth. Second was the problem of establishing the increase in arable land that would have been required to compensate for the lower yields prevailing in the absence of research. Both these aspects were addressed through scenario analysis, due to lack of data and time to do anything else. Third was the difficulty in attributing impacts to the CGIAR in isolation from its various partners in research. The general conclusion emerged that attempting attribution of environmental impacts, or parts of such impacts to the CGIAR alone, was an exercise in futility and would involve a great deal of arbitrariness that could easily be disputed. Thus, it was decided to assess impacts in the context of work done jointly by the CGIAR and its partners. This procedure is in keeping with the more general approach adopted by the IAEG in its other assessments.

Preliminary conclusions: CGIAR impacts on the use of land resources

This initial assessment has focused on the unplanned positive externalities – basically land savings – associated with research aimed at increasing productivity of key commodities. The question of planned positive improvement in environmental quality deriving from research specifically aimed at NRM and policy has not been addressed. It is evident that there are many pitfalls in attempting to generate estimates of positive environmental benefits that could be attributable to research by the CGIAR and its partners. Not least of these is the fact that yield increases are not only a response to agricultural research. Issues concerning changes in TFP, crop substitution, and trade and institutions (markets and policy) also influence land-use decisions. In addition, there are absolute constraints on the availability of RNR if one adopts a self-sufficiency approach by country or region to meeting production shortfalls in the absence of yield-increasing research, as for example in Asia.

The scenarios could be refined by introducing country-level analysis assessing potential critical agroecological zones and, within these, distinguishing between rainfed and irrigated lands, crops and pasture, and annual versus perennial crops. One may superimpose such a data set within equilibrium modelling to trace the path of changes resulting from the introduction of new technology. Despite the shortcomings, it may be concluded that the favourable impact on the environment from adoption of agricultural research results has been impressive.

The four scenarios examined in Chapter 3 suggest land savings from productivity research in the seven key mandated food crops to be in the range of 170 to 460 million ha. Another 50 million ha in reduced requirements for permanent pasture may also be attributed to forage/livestock research. Thus, even if these figures represent an overstatement of 100%, land savings would still be in the 100-250 million ha range. The environmental benefits associated with a reduction of deforestation of this magnitude – biodiversity, carbon-storage erosion or downstream damage – can reasonably be expected to be highly significant and important from a global perspective. On the assumption of average carbon storage of 100 tons per ha valued at US$1 per ton on this area, the environmental savings may be placed in the order of US$10-25 billion over two decades. Also, assuming 40% of lands developed would have been for clearing closed forest with an average value in biodiversity of US$5 per ha, additional savings amount to US$200-500 million. Estimates of benefits from reduced on-site and downstream socioeconomic damage attributed to these land savings would require a great deal of location-specific evaluation. One can, however, assert with some confidence that deforestation in the order of 100 million ha is likely to have substantial negative impacts on long-term human welfare, particularly in the case of hillside areas.

Even if only 25% of the potential land-saving estimates were to have been achieved, the figure would be in the order of 100 million ha. The environmental benefits associated with a reduction of deforestation of this magnitude – biodiversity, carbon storage, erosion or downstream damage – can reasonably be expected to be highly significant and important from a global perspective.

Issues for further empirical assessment

For purposes of research policy, the CGIAR needs aggregate estimates of environmental impacts, both positive and negative, which can be attributed to research on mandated commodities by type of research, or by some relevant combination of these. Figure 4 is a graphic representation of the complex inter-relationships involved in tracing the pathway from a research finding to the planned and unplanned (in ex post assessment) long-term socioeconomic consequences of its adoption. Even at the micro level, obtaining empirical evidence of the cause/effect elements in play and estimating their social or economic outcomes, constitutes a major challenge.

Drawing on this preliminary examination of issues associated with land saving, it is concluded that any comprehensive evaluation of the impact of this type of environmental research capable of yielding meaningful results at an aggregate level, will be a complex modelling exercise taking into consideration the following.

- Estimate the land-saving and/or land-augmenting impacts of a technology by type of land (e.g. high-potential irrigated land, extensively managed marginal regions, high-quality rainfed land, densely populated marginal land)
- Account for changes in cropping intensities (multiple cropping) and cropping patterns (crop-substitution effects) to estimate changes in land productivity.
- Account for direct impacts beyond what could be expected from the net cultivated-area figures. This should include the 'consumptive' transient land-use changes in response to technological change. For example, it is typical in the land-extensive frontier regions to leave behind degraded arable lands (where the new technology was used for some years) and move on to other regions by clearing more forests (Wunder 1999). Similarly, the variable requirements of different varieties and technology packages may induce frequent shifts in geographical location of agriculture. The abandoned areas may then be used for other crops or pastures, and are not converted back to forests. The geographical shifts in crop production that occur due to the changing characteristics of a technology, or the dynamic and unpredictable institutional context within which new technologies are applied, can be an independent factor in promoting deforestation. This needs to be accounted for in the aggregate land-saving estimates.
- Account for the demand and supply elasticities of a commodity (in a global trade setting) and their effect on the production and area-expansion decisions in developing countries.

Case studies assessing and quantifying the relationships between various variables highlighted in Figure 4 can assist in providing the data required to carry out aggregate-level analysis on land-saving impacts. These include quantitative and qualitative assessment studies of impacts of improved technology on the use of RNR and biodiversity, and studies that quantify environmental impacts of changes in the use of RNR. Because the effects of technology on land use depend on many factors, case studies that clearly delineate the relative role of these factors are needed. Indicators of how to measure and judge land-use change need to be developed. Only when there is a much larger number of sophisticated case studies will we be able to generalize about how current and future technological changes are likely to change land use.

Questions on next steps

In considering the way forward there appear to be three crucial aspects that should be borne in mind.

- Research projects are different from standard development investment projects in terms of what can be expected from EIA. The attribution of development impacts as a prerequisite for estimating past and forecasting future environmental impacts is much more diffuse and indirect in the case of research. Accordingly application of the same degree of rigour in EIA is probably unwarranted.

- The great majority of research undertaken by the Centres, *a priori*, can be said to be either neutral or favourable to the quality of the environment, with the obvious exception of contamination of water and soil through increased use of agrochemicals, where there are equally obvious tradeoffs in productivity and poverty alleviation that must be evaluated. This is particularly true of NRM and policy research. Thus, a question arises as to the marginal benefit of investing in evaluation of externalities in the latter two types of research.
- The evaluation of global environmental costs and benefits deriving from CGIAR or other sources of research faces three obstacles. First, these impacts tend to be site-specific; this poses a serious constraint in terms of the time and cost of assembling a critical mass of case studies in a context that is highly dynamic (evolving technologies, institutions and society's perceptions of environmental issues). Second, there are very little relevant data available with a consistent degree of detail worldwide to enable extrapolation from case studies to a credible aggregate impact. Third, there appear to be few case studies providing empirical evidence attributable to research that would allow meaningful aggregation even if a global database existed for mapping a geographically referenced typology of situations to which the respective cases could be applied.
- In the balance of Phase 1 it is proposed to include exploration, in more detail, of the opportunities and constraints for dealing with the above questions, with a view to identifying viable options.

Recommendations for further activity

Based on the Panel's work to date, a number of preliminary and perhaps obvious recommendations for the IAEG and the CGIAR as a whole emerge. These include the following.

There is a virtual vacuum in empirical evidence on the sorts of linkages and chain reactions addressed in this phase of the IAEG's overall assessment, and no GIS or other framework exists that would enable empirical case studies and M&E experience to be accumulated towards global or regional estimates. Accordingly, the Panel recommends that the CGIAR System consider creating a longer term, System-wide research programme to investigate the linkages between agricultural research and the goal of the CGIAR related to sustaining the environments within which the rural poor reside and agricultural development takes place.

Centres need to continue their efforts to establish useful M&E systems that can track environmental impacts over time and within the context of their normal planning activities. Such systems can be created in the context of the logframe approach that is being adopted by the System.

Further thought needs to be given to the question of how to expand IAEG's programme on environmental assessment beyond productivity-enhancing research; NRM research should be addressed and possibly also policy research. NRM will bring in water-related and health impacts, as well as programmes related to irrigation, soil management, biodiversity, forestry, agroforestry and fisheries. Thus, the Panel also recommends that the CGIAR System pursue further the work started at the meeting held at the International Centre for Research on Agroforestry on the impacts of NRM research (Izac 1998). Most impacts of this type of research can be labelled as developmental, i.e. aimed directly at improving the sustainability of production and other environmental services. However, such research may also involve positive or negative externalities – impacts related to the environment that were not foreseen in the original design.

This further assessment activity will be neither short-term nor low cost. Thus, a fuller discussion of the implications and the Group's needs is required. The Panel believes that the Group must give guidance to the IAEG in terms of the depth and breadth of future EIA and evaluation that is desired.

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STATISTICAL TABLES

Table 1. Estimated global land degradation 1950–1990

Type of land use	Area (million ha)					
	Under-graded (1950)	Degree of degradation (1950/90)				Under-graded (1990)
		Severe	Medium	Light	Total	
Forest	4,000	NA	NA	NA	720	3,280
Pasture	3,200	NA	NA	NA	670	2,530
Crop	1,500	NA	NA	NA	565	935
Total	**8,700**	**305**	**870**	**780**	**1,955**	**6,745**

NA = not available

Source: Oldeman, L. *et al.* 1990. World Map of the States of Human-Induced Soil Degradation, Wageningen, 1990. Oldeman, L. 1992. Global extent of soil degradation. Biannual Report. International Soil Reference and Information Centre, Wageningen, the Netherlands.

Table 2. Estimated land degradation in developing regions, 1990

Type of land use	Area of degraded land (million ha)			
	Region			
	Latin America	Asia	Africa	Total
Forest	137	344	130	**611**
Pasture	78	197	243	**518**
Crop	92	206	121	**419**
Total	**307**	**747**	**494**	**1548**

Source: Oldeman, op.cit.

Table 3. Incremental area in seven mandated commodities required to meet the 1990s production levels with 1970s yields, by region

Mandated commodity	Total harvested area 1990s and incremental area[1] by region (million ha)									
	Asia		Africa		Latin America		Rest of the world		Total	
	Total	Incremental	Total	Incremental	Total	Incremental	Total	Incremental	Total	Incremental
Wheat	102.1	74.2	9.0	6.9	9.3	6.2	106.1	31.5	**226.5**	**118.8**
Rice	134.9	69.0	7.3	6.3	6.5	4.5	1.9	4.5	**150.6**	**84.3**
Maize	42.1	35.1	25.7	2.0	29.1	18.2	43.0	0.6	**139.9**	**55.9**
Cassava	3.6	0.7	10.3	2.4	2.7	0.6	0.0	-1.6	**16.6**	**2.1**
Barley	16.4	0.6	4.7	1.0	1.1	0.5	44.6	10.9	**66.8**	**13.0**
Sorghum	13.9	2.9	22.7	0.9	3.4	0.4	4.8	-2.5	**44.8**	**1.7**
Pulses	36.7	4.2	14.4	-0.7	8.7	1.6	9.4	6.5	**69.2**	**11.6**
Total	**349.7**	**186.7**	**94.1**	**18.8**	**60.8**	**32.0**	**209.8**	**49.9**	**714.4**	**287.4[2]**

Source: Annex 1

[1] Assumes 100% cropping intensity.
[2] Incremental area calculated with 1980s yields is reduced to 70 million ha.

Table 4. Model for base scenario of additional lands that would have been brought into production by the 1990s, by region, in the absence of productivity research for seven mandated commodities, over the period 1970-98

Region, ecological zone and type of change in land-use	Commodity by area change (million ha)							
	Wheat	Rice	Maize	Cassava	Barley	Sorghum	Pulses	Total
WANA								
(arid sub-tropical)								
Irrigation								
Range conversion								
Sub-Saharan Africa[1]								
(tropical–humid & sub-humid)								
Irrigation								
Deforestation								
Range conversion								
Asia [1]								
(tropical-humid and sub-humid)								
Irrigation								
Deforestation								
China								
(temperate)								
Irrigation								
Range conversion								
LAC[1]								
(tropical-humid & sub-humid)								
Irrigation								
Deforestation								
Range conversion								
Rest of world[2]								
(temperate)								
Irrigation								
Deforestation								
Pasture/range conversion								
Total								
Irrigation								
Deforestation								
Pasture/range conversion								

[1] Excludes temperate countries.
[2] Includes temperate countries normally grouped within the Africa, Asia and LAC regions.

Table 5. Global transformations in land use in tropical areas by ecological zone, 1980–1990

Land-use transformations[1]	**Area changes by ecological zone (million ha)**			
	Humid	**Semi-Humid**	**Semi-Arid**	**Total**
Closed forest to:				
- agriculture[2]	10.1	22.9	1.8	**34.8**
- transitional forest[3] &/or shifting agriculture	18.2	29.8	3.5	**51.5**
- plantations	3.7	0.2	0.1	**4.0**
Total net conversion[4]	-31.3	-51.5	-5.1	**-87.9**
Open forest to:				
- agriculture	0.2	7.6	2.4	**10.2**
- transitional forest [5]&/or shifting agriculture	0.5	7.0	2.9	**10.4**
- plantations	ns	0.2	ns	**0.2**
Total net conversion	+0.3	-8.3	-2.6	**-10.6**
Transitional forest[5] to:				
- agriculture	7.2	28.5	4.5	**40.1**
- intensified shifting agriculture				
- plantations	2.8	3.4	0.2	**6.4**
Total net conversion	0.3	0.4	0.1	**0.8**
	+10.6	+2.4	+0.2	**+13.2**
Agriculture to:				
- closed, open and transitional forest[5]	1.5	3.9	1.6	**7.0**
- plantations	0.1	0.3	0.1	**0.5**
Total net conversion	+16.0	+54.5	+7.2	**+77.7**

ns = not significant

Source: FAO. 1996. Forest resource assessment 1990: Survey of tropical forest cover and study of change processes. Annexes 17, 18 and 19. Forestry Paper No. 120. FAO, Rome.

[1] Figures show gross transformation from one land use to another, plus the net conversion for each land use between 1980 and 1990.
[2] This is classed by FAO as 'other land cover' excluding tree crops and forestry plantations. For purposes of this analysis this category is considered as land in permanent agriculture (annual crops and pasture).
[3] In the particular case of closed forest conversion, transitional forest includes open forest as well as the other four classes of land use (long fallow, fragmented forest, shrubs and short fallow) assumed to be within this category.
[4] Net conversion represents the gross additions minus gross subtractions from the land-use category between 1980 and 1990.
[5] Transitional forest is defined by the four land-use classes listed in footnote 3.

Table 6. Global transformations in land use in tropical areas by region 1980–1990

Land-use transformations[1]	Area changes by region (million ha)			
	Asia	Africa	Latin America	Total
Closed forest to:				
- agriculture[2]	7.2	3.3	24.3	**34.8**
- transitional forest[3] /or shifting agriculture	15.8	18.7	17.0	**51.5**
- plantations	2.9	1.0	0.1	**4.0**
Total net conversion[4]	-24.1	-21.7	-42.1	**-87.9**
Open forest to:				
- agriculture	0.8	5.9	3.5	**10.2**
- transitional forest[5] &/or shifting agriculture	1.8	6.7	1.9	**10.4**
- plantations	0.1	ns	0.1	**0.2**
Total net conversion	-0.7	-7.2	-2.7	**-10.6**
Transitional forest[5] to:				
- agriculture	7.8	7.3	25.0	**40.1**
- intensified shifting agriculture				
- plantations	3.4	0.9	2.1	**6.4**
Total net conversion	0.3	0.1	0.4	**0.8**
	+6.7	+15.4	-8.9	**+13.2**
Agriculture to:				
- closed, open and transitional forest[5]	1.6	4.1	1.3	**7.0**
- plantations	0.2	0.2	0.1	**0.5**
Total net conversion	+14.0	+12.6	+51.1	**+77.7**

ns = not significant

Source: FAO. 1996. Forest resource assessment 1990: Survey of tropical forest cover and study of change processes. Annexes 17, 18 and 19. Forestry Paper No.120. FAO, Rome.

1 Figures show gross transformation from one land use to another, plus the net conversion for each land use between 1980 and 1990.
2 This is classed by FAO as 'other land cover' excluding tree crops and forestry plantations. For purposes of this analysis this category is considered as land in permanent agriculture (annual crops and pasture).
3 In the particular case of closed forest conversion, 'transitional forest' includes open forest as well as the other four classes of land use (long fallow, fragmented forest, shrubs and short fallow) assumed to be within this category.
4 Net conversion represents the gross additions minus gross subtractions from the land-use category between 1980 and 1990.
5 Transitional forest is defined by the four land-use classes listed in footnote 3.

Table 7. Forest land[1] in tropical areas by region and ecological zone – 1980

Region	Ecological zone (million ha)			
	Humid	Subhumid	Semi-Arid	Total
Asia	167	101	43	**311**
Africa	91	363	129	**583**
Latin America	500	307	86	**893**
Total	**758**	**771**	**258**	**2587**

Source: FAO, op.cit. Annex 20.

[1] Defined as: closed forest, open forest, long fallow and fragmented forest, most of which are assumed to be available for conversion to permanent agriculture or pasture.

Table 8 Base scenario 1 – Deforestation in tropical zones between the 1970s and 1990s in the absence of yield-increasing research: seven mandated commodities by region and ecological zone

Region and ecological zone	Deforested for mandated commodities (million ha)							
	Wheat	Rice	Maize	Cassava	Barley	Sorghum	Pulses	Total
Asia								
Humid	-	17	8	-	-	-	-	**25**
Subhumid	16	-	-	-	-	-	4	**20**
Semi-arid	10	-	-	-	-	-	-	**10**
Total	26	17	8	-	-	-	4	**55**
Africa								
Humid	-	6	2	3	-	-	-	**11**
Subhumid	32	28	-	-	-	2	-	**62**
Semi-arid	25	-	-	-	21	-	-	**46**
Total	57	34	2	3	22	1	-	**119**
LAC								
Humid	-	69	67	1	-	-	4	**145**
Subhumid	83	-	164	-	-	2	4	**109**
Semi-arid	28	-	4	-	-	-	-	**32**
Total	111	69	87	1	-	2	8	**286**
Total three regions								
Humid	-	92	77	4	-	-	8	**181**
Subhumid	131	28	16	-	-	4	12	**191**
Semi-arid	63	-	4	-	21	-	-	**88**
Total	194	120	97	4	21	4	20	**460**

Source: Annex 1, Tables 3, 5 and 6 and Panel estimates.

Table 9. Base scenario 4 – Land use change in temperate and tropical zones between 1970 and 1990 in the absence of yield-increasing research: seven mandated commodities by region

Mandated crop	Land saving by region (million ha)				
	Asia	Africa	LAC	Temperate zone	Total
Wheat	14.2	1.0	2.0	78.2	**95.4**
Rice	69.0	6.3	4.5	4.0	**83.8**
Maize	6.0	0.3	7.5	21.4	**35.2**
Cassava	0.7	2.4	0.6	-1.6	**2.1**
Barley	-	-	-	10.2	**10.2**
Sorghum	1.5	0.4	0.4	-	**2.3**
Pulses	2.0	-1.3	1.0	5.5	**7.2**
Total	**93.4**	**9.1**	**16.0**	**117.7**	**236.2**

Source: Annex 1 and Panel estimates

Annex 1.

Incremental area of the seven major CGIAR mandated crops required to produce the 1990s output level at 1960s, 1970s and 1980s yields

Crop	Region						
	Africa	SSA	Asia	LAC	Oceania	LDC	World
				Thousand ha			
1960 yields							
Barley	2,701.6	234.9	3,341.7	949.5	–	161.9	25,387.2
Cassava	4,130.5	4,130.5	1,983.7	-188.1	1.5	1,739.6	4,011.0
Maize	8,637.6	7,620.2	63,300.0	26,298.0	3.3	3,487.8	109,843.7
Pulses	1,591.3	1,898.6	7,158.2	722.8	2.8	-966.1	17,636.3
Rice	2,032.8	1,673.3	112,712.3	5,324.8	1.9	15,892.6	120,265.8
Sorghum	2,429.7	3,191.2	7,974.2	2,296.6	1.0	-247.3	13,862.6
Wheat	11,453.0	1,362.9	149,730.5	7,181.4	0.0	2,928.5	212,104.0
1970 yields							
Barley	1,011.9	-28.2	597.9	519.3	–	-34.7	12,959.1
Cassava	2,370.6	2,370.6	649.4	136.0	1.4	686.3	2,077.5
Maize	2.003.2	1,647.7	35,087.0	18,186.5	4.6	1,001.8	55,911.5
Pulses	-700.3	-495.4	4,248.3	1,611.9	2.3	-1,368.7	11,617.0
Rice	6,251.5	1,234.5	69,027.9	4,469.9	-0.2	10,749.0	75,344.4
Sorghum	922.3	1,518.0	2,929.1	362.9	1.4	-853.8	1,737.3
Wheat	6,925.0	511.1	74,204.5	6,241.2	0.0	1,334.4	118,752.6
1980 yields							
Barley	944.3	-54.1	-510.6	166.8	–	-230.2	954.1
Cassava	709.5	709.5	161.2	74.1	1.3	-230.8	286.7
Maize	2,134.7	1,172.3	13,327.1	8,129.8	2.5	1,827.5	15,846.5
Pulses	-767.0	-419.6	1,336.4	2,368.1	1.2	-500.9	2,007.9
Rice	1,112.0	284.5	20,423.8	2,295.2	0.5	3,636,5	23,169.2
Sorghum	296.7	430.9	3,543.9	70.9	0.5	1555.1	-1,767.8
Wheat	2,953.7	192.3	11,247.4	1,748.2	0.0	411.4	29,733.0

Annex 2

Growth rates in area, yield and production for major CGIAR Mandate Commodities - 1960s to 1990s

A: Barley			1960s	1970s	1980s	1990s	Exponential growth rates per decade		
							1960s/1970s	1970s/1980s	1980s/1990s
Africa	Area harvested	ha	4,211,318	4,474,155	5,527,158	4,715,562	0.6%	2.1%	-1.6%
	Yield	hg/ha	6,488	8,402	10,005	9,707	2.6%	1.8%	-0.3%
	Production	mt	2,732,586	3,775,741	5,535,534	4,812,238	3.3%	3.9%	-1.4%
Sub-Saharan Africa	Area harvested	ha	988,832	721,193	911,319	1,112,281	-3.1%	2.4%	2.0%
	Yield	hg/ha	8,350	10,377	10,631	10,171	2.2%	0.2%	-0.4%
	Production	mt	825,661	748,269	968,942	1,124,935	-1.0%	2.6%	1.5%
Asia	Area harvested	ha	13,300,080	11,450,950	11,619,623	16,430,533	-1.5%	0.1%	3.5%
	Yield	hg/ha	12,195	14,160	15,146	14,736	1.5%	0.7%	-0.3%
	Production	mt	16,229,803	16,238,427	17,599,017	24,112,283	0.0%	0.8%	3.2%
Latin America & Caribbean	Area harvested	ha	1,251,735	1,276,949	854,928	1,050,449	0.2%	-3.9%	2.1%
	Yield	hg/ha	9,824	12,519	16,144	18,648	2.5%	2.6%	1.5%
	Production	mt	1,231,113	1,604,665	1,383,679	1,965,124	2.7%	-1.5%	3.6%
Least Developed Countries	Area harvested	ha	1,485,285	1,098,148	1,212,050	1,361,366	-3.0%	1.0%	1.2%
	Yield	hg/ha	9,149	10,505	10,232	10,287	1.4%	-0.3%	0.1%
	Production	mt	1,358,631	1,149,161	1,240,212	1,393,624	-1.7%	0.8%	1.2%
OECD	Area harvested	ha	24,729,533	31,362,087	32,801,270	28,492,567	2.4%	0.4%	-1.4%
	Yield	hg/ha	24,056	26,569	31,387	33,515	1.0%	1.7%	0.7%
	Production	mt	59,518,090	83,368,270	102,950,220	95,585,567	3.4%	2.1%	-0.7%
World	Area harvested	ha	60,471,807	80,958,470	78,818,877	66,819,043	3.0%	-0.3%	-1.6%
	Yield	hg/ha	16,324	18,867	22,209	22,570	1.5%	1.6%	0.2%
	Production	mt	98,740,037	152,825,000	175,041,133	150,517,467	4.5%	1.4%	-1.5%

B: Cassava			1960s	1970s	1980s	1990s	Exponential growth rates per decade		
							1960/1970s	1970s/1980s	1980s/1990s
Africa	Area harvested	ha	6,057,256	6,994,769	7,629,173	10,296,520	1.4%	0.9%	3.0%
	Yield	hg/ha	58,739	66,902	76,997	82,309	1.3%	1.4%	0.7%
	Production	mt	35,578,457	46,783,190	58,735,437	84,742,997	2.8%	2.3%	3.7%
Sub-Saharan Africa	Area harvested	ha	6,057,256	6,994,769	7,629,173	10,296,520	1.4%	0.9%	3.0%
	Yield	hg/ha	58,739	66,902	76,997	82,309	1.3%	1.4%	0.7%
	Production	mt	35,578,457	46,783,190	58,735,437	84,742,997	2.8%	2.3%	3.7%
Asia	Area harvested	ha	2,416,752	3,207,427	3,699,620	3,623,226	2.9%	1.4%	-0.2%
	Yield	hg/ha	84,349	110,694	124,971	130,596	2.8%	1.2%	0.4%
	Production	mt	20,373,383	35,543,280	46,258,080	47,294,117	5.7%	2.7%	0.2%
Latin America & Caribbean	Area harvested	ha	2,340,594	2,779,647	2,648,397	2,677,789	1.7%	-0.5%	0.1%
	Yield	hg/ha	128,844	114,391	116,564	119,790	-1.2%	0.2%	0.3%
	Production	mt	30,164,073	31,786,127	30,871,677	32,077,713	0.5%	-0.3%	0.4%
Oceania Developing Countries	Area harvested	ha	16,910	13,051	18,433	16,517	-2.6%	3.5%	-1.1%
	Yield	hg/ha	102,342	102,775	103,349	111,593	0.0%	0.1%	0.8%
	Production	mt	173,058	134,138	190,439	184,132	-2.5%	3.6%	-0.3%
Least Developed Countries	Area harvested	ha	4,443,763	5,146,688	5,664,777	6,238,937	1.5%	1.0%	1.0%
	Yield	hg/ha	52,552	60,545	69,787	67,204	1.4%	1.4%	-0.4%
	Production	mt	23,353,380	31,146,930	39,533,827	41,928,890	2.9%	2.4%	0.6%
OECD	Area harvested	ha	1,800	3,649	142	148	7.3%	-27.7%	0.4%
	Yield	hg/ha	200,000	175,073	92,947	87,555	-1.3%	-6.1%	-0.6%
	Production	mt	36,000	63,277	1,318	1,305	5.8%	-32.1%	-0.1%
World	Area harvested	ha	10,831,510	12,994,897	13,995,623	16,614,050	1.8%	0.7%	1.7%
	Yield	hg/ha	79,660	87,900	97,214	98,904	1.0%	1.0%	0.2%
	Production	mt	86,288,973	114,246,733	136,055,633	164,298,967	2.8%	1.8%	1.9%

C: Maize			1960s	1970s	1980s	1990s	Exponential growth rates per decade		
							1960/1970s	1970s/1980s	1980s/1990s
Africa	Area harvested	ha	16,886,333	18,706,237	22,219,707	25,656,033	1.0%	1.7%	1.4%
	Yield	hg/ha	11,590	14,370	14,302	15,499	2.2%	0.0%	0.8%
	Production	mt	19,622,150	26,860,247	31,701,767	39,746,363	3.2%	1.7%	2.3%
Sub-Saharan Africa	Area harvested	ha	11,412,053	12,656,120	16,275,037	20,685,243	1.0%	2.5%	2.4%
	Yield	hg/ha	9,251	11,725	11,980	12,665	2.4%	0.2%	0.6%
	Production	mt	10,563,281	14,838,660	19,461,057	26,185,377	3.5%	2.7%	3.0%
Asia	Area harvested	ha	30,480,247	35,347,460	36,785,640	42,123,257	1.5%	0.4%	1.4%
	Yield	hg/ha	14,436	19,711	27,446	36,112	3.2%	3.4%	2.8%
	Production	mt	44,048,467	69,670,760	101,039,947	152,189,067	4.7%	3.8%	4.2%
Latin America & Caribbean	Area harvested	ha	24,643,983	25,392,143	27,329,517	29,109,440	0.3%	0.7%	0.6%
	Yield	hg/ha	13,364	15,656	19,884	25,431	1.6%	2.4%	2.5%
	Production	mt	32,952,717	39,796,683	54,339,363	74,046,550	1.9%	3.2%	3.1%
Oceania Developing Countries	Area harvested	ha	1,872	1,910	2,860	3,677	0.2%	4.1%	2.5%
	Yield	hg/ha	13,544	11,523	15,404	25,930	-1.6%	2.9%	5.3%
	Production	mt	2,557	2,202	4,353	9,514	-1.5%	7.1%	8.1%
Least Developed Countries	Area harvested	ha	8,566,907	9,134,713	10,976,840	12,836,793	0.6%	1.9%	1.6%
	Yield	hg/ha	9,636	11,367	10,727	12,249	1.7%	-0.6%	1.3%
	Production	mt	8,257,063	10,386,467	11,767,877	15,730,373	2.3%	1.3%	2.9%
OECD	Area harvested	ha	36,764,973	42,023,713	41,421,223	43,368,997	1.3%	-0.1%	0.5%
	Yield	hg/ha	37,178	46,625	63,249	66,288	2.3%	3.1%	0.5%
	Production	mt	136,802,000	196,020,933	261,952,433	288,090,167	3.7%	2.9%	1.0%
World	Area harvested	ha	110,120,633	123,595,967	130,687,100	139,919,000	1.2%	0.6%	0.7%
	Yield	hg/ha	22,527	28,731	36,121	40,183	2.5%	2.3%	1.1%
	Production	mt	248,327,333	355,196,400	472,090,700	562,640,500	3.6%	2.9%	1.8%

D: Pulses			1960s	1970s	1980s	1990s	Exponential growth rates per decade		
							1960/1970s	1970s/1980s	1980s/1990s
Africa	Area harvested	ha	9,521,013	9,728,464	10,364,247	14,425,497	0.2%	0.6%	3.4%
	Yield	hg/ha	4,558	5,319	5,345	5,067	1.6%	0.0%	-0.5%
	Production	mt	4,313,931	5,170,161	5,535,713	7,300,441	1.8%	0.7%	2.8%
Sub-Saharan Africa	Area harvested	ha	8,406,358	8,639,771	9,243,452	13,605,300	0.3%	0.7%	3.9%
	Yield	hg/ha	4,118	4,871	4,842	4,697	1.7%	-0.1%	-0.3%
	Production	mt	3,442,755	4,197,810	4,473,422	6,384,510	2.0%	0.6%	3.6%
Asia	Area harvested	ha	36,631,253	35,380,333	35,732,643	36,662,367	-0.3%	0.1%	0.3%
	Yield	hg/ha	5,933	6,355	6,842	7,093	0.7%	0.7%	0.4%
	Production	mt	21,784,243	22,494,607	24,451,797	25,998,727	0.3%	0.8%	0.6%
Latin America & Caribbean	Area harvested	ha	7,327,426	7,838,342	9,233,623	8,721,289	0.7%	1.7%	-0.6%
	Yield	hg/ha	6,113	5,587	5,206	6,621	-0.9%	-0.7%	2.4%
	Production	mt	4,480,642	4,384,437	4,807,114	5,773,155	-0.2%	0.9%	1.8%
Oceania Developing Countries	Area harvested	ha	4,261	5,180	6,390	7,525	2.0%	2.1%	1.6%
	Yield	hg/ha	5,739	6,059	6,822	7,883	0.5%	1.2%	1.5%
	Production	mt	2,447	3,138	4,360	5,932	2.5%	3.3%	3.1%
Least Developed Countries	Area harvested	ha	5,658,277	7,234,220	8,661,060	12,068,600	2.5%	1.8%	3.4%
	Yield	hg/ha	5,768	5,985	5,536	5,309	0.4%	-0.8%	-0.4%
	Production	mt	3,262,281	4,330,837	4,792,069	6,403,906	2.9%	1.0%	2.9%
OECD	Area harvested	ha	7,437,431	5,510,139	8,538,639	10,416,763	-3.0%	4.5%	2.0%
	Yield	hg/ha	8,309	9,326	13,164	14,567	1.2%	3.5%	1.0%
	Production	mt	6,170,099	5,142,268	11,279,119	15,171,573	-1.8%	8.2%	3.0%
World	Area harvested	ha	66,414,530	62,384,723	67,278,707	69,183,153	-0.6%	0.8%	0.3%
	Yield	hg/ha	6,309	6,779	7,694	7,918	0.7%	1.3%	0.3%
	Production	mt	41,926,620	42,295,117	51,773,320	54,774,423	0.1%	2.0%	0.6%

E: Rice (paddy)			1960s	1970s	1980s	1990s	Exponential growth rates per decade		
							1960/1970s	1970s/1980s	1980s/1990s
Africa	Area harvested	ha	3,470,288	4,585,700	5,195,125	7,340,955	2.8%	1.3%	3.5%
	Yield	hg/ha	17,028	17,430	18,883	21,733	0.2%	0.8%	1.4%
	Production	mt	5,920,911	7,989,871	9,811,185	15,961,677	3.0%	2.1%	5.0%
Sub-Saharan Africa	Area harvested	ha	3,074,178	4,133,985	4,780,381	6,722,736	3.0%	1.5%	3.5%
	Yield	hg/ha	12,911	13,623	15,470	16,121	0.5%	1.3%	0.4%
	Production	mt	3,974,265	5,629,856	7,395,785	10,840,120	3.5%	2.8%	3.9%
Asia	Area harvested	ha	115,479,667	128,095,767	128,208,800	134,790,700	1.0%	0.0%	0.5%
	Yield	hg/ha	20,949	25,439	33,405	38,463	2.0%	2.8%	1.4%
	Production	mt	241,972,167	325,909,300	428,252,500	518,494,033	3.0%	2.8%	1.9%
Latin America & Caribbean	Area harvested	ha	5,836,641	7,947,170	7,611,190	6,518,175	3.1%	-0.4%	-1.5%
	Yield	hg/ha	17,376	18,728	23,349	31,597	0.8%	2.2%	3.1%
	Production	mt	10,153,948	14,862,637	17,738,080	20,578,433	3.9%	1.8%	1.5%
Oceania Developing Countries	Area harvested	ha	9,059	11,440	13,674	8,242	2.4%	1.8%	-4.9%
	Yield	hg/ha	17,920	22,669	20,814	22,364	2.4%	-0.9%	0.7%
	Production	mt	16,222	25,911	28,550	18,255	4.8%	1.0%	-4.4%
Least Developed Countries	Area harvested	ha	21,091,103	21,407,893	22,023,917	23,962,313	0.1%	0.3%	0.8%
	Yield	hg/ha	15,218	17,473	21,976	25,312	1.4%	2.3%	1.4%
	Production	mt	32,117,457	37,408,847	48,392,827	60,651,133	1.5%	2.6%	2.3%
OECD	Area harvested	ha	5,797,889	5,671,874	5,157,627	4,965,589	-0.2%	-0.9%	-0.4%
	Yield	hg/ha	48,670	56,112	61,083	64,630	1.4%	0.9%	0.6%
	Production	mt	28,230,687	31,820,240	31,508,410	32,083,000	1.2%	-0.1%	0.2%
World	Area harvested	ha	126,180,133	142,643,167	143,162,867	150,611,867	1.2%	0.0%	0.5%
	Yield	hg/ha	20,935	25,097	32,632	37,649	1.8%	2.7%	1.4%
	Production	mt	264,221,733	358,024,233	467,161,167	567,082,367	3.1%	2.7%	2.0%

F: Sorghum			1960s	1970s	1980s	1990s	Exponential growth rates per decade		
							1960/1970s	1970s/1980s	1980s/1990s
Africa	Area harvested	ha	14,292,873	14,140,340	18,215,850	22,627,503	-0.1%	2.6%	2.2%
	Yield	hg/ha	7,577	8,062	8,282	8,380	0.6%	0.3%	0.1%
	Production	mt	10,845,554	11,361,580	15,100,850	18,985,840	0.5%	2.9%	2.3%
Sub-Saharan Africa	Area harvested	ha	13,450,410	13,633,663	17,642,280	22,265,880	0.1%	2.6%	2.4%
	Yield	hg/ha	7,022	7,516	7,876	8,018	0.7%	0.5%	0.2%
	Production	mt	9,456,647	10,213,779	13,912,263	17,875,993	0.8%	3.1%	2.5%
Asia	Area harvested	ha	26,258,330	22,186,790	19,175,520	13,872,940	-1.7%	-1.4%	-3.2%
	Yield	hg/ha	7,100	9,223	8,906	11,168	2.7%	-0.3%	2.3%
	Production	mt	18,665,240	20,452,187	17,073,683	15,511,457	0.9%	-1.8%	-1.0%
Latin America & Caribbean	Area harvested	ha	2,051,349	4,414,974	4,755,899	3,443,354	8.0%	0.7%	-3.2%
	Yield	hg/ha	16,958	25,573	27,698	28,186	4.2%	0.8%	0.2%
	Production	mt	3,531,765	11,291,133	13,181,323	9,733,779	12.3%	1.6%	-3.0%
Oceania Developing Countries	Area harvested	ha	456	1,535	540	973	12.9%	-9.9%	6.1%
	Yield	hg/ha	13,333	11,340	17,770	26,933	-1.6%	4.6%	4.2%
	Production	mt	602	1,748	951	2,637	11.3%	-5.9%	10.7%
Least Developed Countries	Area harvested	ha	8,474,740	9,836,446	12,090,857	15,085,760	1.5%	2.1%	2.2%
	Yield	hg/ha	6,969	7,266	6,785	6,846	0.4%	-0.7%	0.1%
	Production	mt	5,917,862	7,146,203	8,229,857	10,340,931	1.9%	1.4%	2.3%
OECD	Area harvested	ha	6,298,820	7,924,804	8,361,875	6,573,693	2.3%	0.5%	-2.4%
	Yield	hg/ha	31,587	31,198	37,857	35,977	-0.1%	2.0%	-0.5%
	Production	mt	19,857,237	24,689,577	31,674,143	23,828,210	2.2%	2.5%	-2.8%
World	Area harvested	ha	48,469,387	47,475,930	48,748,413	44,751,257	-0.2%	0.3%	-0.9%
	Yield	hg/ha	10,670	13,453	14,550	13,931	2.3%	0.8%	-0.4%
	Production	mt	51,759,870	63,861,440	71,009,220	62,540,993	2.1%	1.1%	-1.3%

G: Wheat			1960s	1970s	1980s	1990s	Exponential growth rates per decade		
							1960/1970s	1970s/1980s	1980s/1990s
Africa	Area harvested	ha	7,916,738	8,852,376	8,353,744	8,962,362	1.1%	-0.6%	0.7%
	Yield	hg/ha	8,105	10,415	13,886	18,238	2.5%	2.9%	2.8%
	Production	mt	6,430,080	9,241,712	11,604,447	16,546,690	3.7%	2.3%	3.6%
Sub-Saharan Africa	Area harvested	ha	1,333,829	1,193,715	1,180,777	1,575,990	-1.1%	-0.1%	2.9%
	Yield	hg/ha	8,343	11,748	13,866	15,547	3.5%	1.7%	1.2%
	Production	mt	1,113,007	1,396,186	1,637,122	2,451,885	2.3%	1.6%	4.1%
Asia	Area harvested	ha	62,476,090	75,752,823	82,554,630	102,105,700	1.9%	0.9%	2.1%
	Yield	hg/ha	9,919	14,567	22,037	24,460	3.9%	4.2%	1.0%
	Production	mt	61,980,607	110,396,167	181,915,567	249,796,300	5.9%	5.1%	3.2%
Latin America & Caribbean	Area harvested	ha	8,328,949	10,675,168	10,697,663	9,305,077	2.5%	0.0%	-1.4%
	Yield	hg/ha	13,360	14,168	19,927	23,582	0.6%	3.5%	1.7%
	Production	mt	11,124,613	15,282,303	21,305,490	22,025,930	3.2%	3.4%	0.3%
Oceania Developing Countries	Area harvested	ha	43	25	224	53	-5.2%	24.3%	-13.4%
	Yield	hg/ha	26,667	23,333	17,247	19,667	-1.3%	-3.0%	1.3%
	Production	mt	117	59	393	105	-6.6%	20.9%	-12.4%
Least Developed Countries	Area harvested	ha	3,790,369	4,015,859	3,924,388	4,901,614	0.6%	-0.2%	2.2%
	Yield	hg/ha	9,095	11,420	13,404	14,523	2.3%	1.6%	0.8%
	Production	mt	3,440,922	4,585,092	5,261,495	7,121,528	2.9%	1.4%	3.1%
OECD	Area harvested	ha	72,197,313	77,146,577	80,306,317	79,076,113	0.7%	0.4%	-0.2%
	Yield	hg/ha	18,091	22,048	27,366	30,676	2.0%	2.2%	1.1%
	Production	mt	130,584,367	170,142,333	219,673,467	242,676,700	2.7%	2.6%	1.0%
World	Area harvested	ha	217,498,733	229,687,567	226,072,333	226,498,333	0.5%	-0.2%	0.0%
	Yield	hg/ha	13,207	16,778	22,607	25,564	2.4%	3.0%	1.2%
	Production	mt	287,242,467	385,643,367	510,935,933	579,262,067	3.0%	2.9%	1.3%

H: Beef			1960s	1970s	1980s	1990s	Exponential growth rates per decade		
							1960/1970s	1970s/1980s	1980s/1990s
Africa	Stocks	head	135,769,100	158,034,933	176,686,000	209,230,533	1.5%	1.1%	1.7%
	Slaughtered	head	15,177,560	18,445,020	22,477,970	25,921,100	2.0%	2.0%	1.4%
	Carcass weight	hg/an	1,454	1,458	1,472	1,413	0.0%	0.1%	-0.4%
	Production	mt	2,206,049	2,689,902	3,306,989	3,662,591	2.0%	2.1%	1.0%
Sub-Saharan Africa	Stocks	head	118,332,100	137,434,700	157,448,467	188,275,933	1.5%	1.4%	1.8%
	Slaughtered	head	10,699,357	12,717,250	16,350,970	18,917,353	1.7%	2.5%	1.5%
	Carcass weight	hg/an	1,380	1,380	1,341	1,278	0.0%	-0.3%	-0.5%
	Production	mt	1,476,512	1,755,054	2,192,485	2,417,916	1.7%	2.3%	1.0%
Asia	Stocks	head	331,817,200	344,236,200	381,007,333	452,408,367	0.4%	1.0%	1.7%
	Slaughtered	head	28,450,827	36,302,407	47,519,797	84,000,607	2.5%	2.7%	5.9%
	Carcass weight	hg/an	1,077	1,129	1,280	1,429	0.5%	1.3%	1.1%
	Production	mt	3,062,644	4,099,870	6,085,579	12,007,633	3.0%	4.0%	7.0%
Latin America & Caribbean	Stocks	head	201,817,733	267,389,900	306,650,933	347,079,700	2.9%	1.4%	1.2%
	Slaughtered	head	31,131,720	42,617,977	51,327,327	58,602,847	3.2%	1.9%	1.3%
	Carcass weight	hg/an	1,913	1,873	1,935	1,978	-0.2%	0.3%	0.2%
	Production	mt	5,953,562	7,981,517	9,932,669	11,588,217	3.0%	2.2%	1.6%
Oceania Developing Countries	Stocks	head	390,070	607,853	670,367	768,490	4.5%	1.0%	1.4%
	Slaughtered	head	61,268	87,218	107,387	109,728	3.6%	2.1%	0.2%
	Carcass weight	hg/an	1,709	1,712	1,772	1,853	0.0%	0.3%	0.4%
	Production	mt	10,466	14,909	19,022	20,333	3.6%	2.5%	0.7%
Least Developed Countries	Stocks	head	133,922,367	146,181,967	157,727,000	184,873,367	0.9%	0.8%	1.6%
	Slaughtered	head	12,109,053	13,850,870	16,352,747	19,560,840	1.4%	1.7%	1.8%
	Carcass weight	hg/an	1,103	1,102	1,163	1,108	0.0%	0.5%	-0.5%
	Production	mt	1,335,363	1,526,283	1,901,054	2,166,857	1.3%	2.2%	1.3%
OECD	Stocks	head	287,639,667	342,101,867	309,795,700	297,297,833	1.7%	-1.0%	-0.4%
	Slaughtered	head	98,041,633	117,207,300	107,515,533	97,492,860	1.8%	-0.9%	-1.0%
	Carcass weight	hg/an	1,943	2,174	2,452	2,714	1.1%	1.2%	1.0%
	Production	mt	19,052,277	25,486,530	26,359,540	26,456,050	3.0%	0.3%	0.0%
World	Stocks	head	1,028,606,667	1,196,595,667	1,263,915,333	1,332,608,667	1.5%	0.5%	0.5%
	Slaughtered	head	206,064,833	250,719,600	264,380,067	288,650,200	2.0%	0.5%	0.9%
	Carcass weight	hg/an	1,682	1,866	1,980	1,940	1.0%	0.6%	-0.2%
	Production	mt	34,679,607	46,791,437	52,344,417	55,988,780	3.0%	1.1%	0.7%

I: Sheep and Goats			1960s	1970s	1980s	1990s	Exponential growth rates per decade		
							1960/1970s	1970s/1980s	1980s/1990s
Africa	Stocks	head	252,899,367	285,463,833	341,947,600	421,503,600	1.2%	1.8%	2.1%
	Production	head	74,062,933	85,487,300	105,456,400	144,418,700	1.4%	2.1%	3.2%
	Carcass weight	hg/an	120	122	126	129	0.2%	0.3%	0.3%
	Production	mt	891,693	1,045,466	1,324,005	1,865,792	1.6%	2.4%	3.5%
Sub-Saharan Africa	Stocks	head	169,100,233	200,039,033	250,137,000	325,424,367	1.7%	2.3%	2.7%
	Production	head	48,634,397	58,111,990	73,536,503	101,123,953	1.8%	2.4%	3.2%
	Carcass weight	hg/an	117	117	117	121	0.0%	0.0%	0.3%
	Production	mt	570,688	679,694	858,483	1,220,973	1.8%	2.4%	3.6%
Asia	Stocks	head	467,529,933	531,165,667	608,281,867	832,868,000	1.3%	1.4%	3.2%
	Production	head	134,225,200	171,209,333	237,277,233	400,652,800	2.5%	3.3%	5.4%
	Carcass weight	hg/an	122	121	126	134	-0.1%	0.4%	0.6%
	Production	mt	1,636,523	2,070,409	2,987,398	5,366,529	2.4%	3.7%	6.0%
Latin America & Caribbean	Stocks	head	158,380,233	139,952,900	142,624,967	132,068,167	-1.2%	0.2%	-0.8%
	Production	head	31,364,850	29,530,210	29,380,627	31,192,030	-0.6%	-0.1%	0.6%
	Carcass weight	hg/an	147	138	136	138	-0.6%	-0.1%	0.1%
	Production	mt	459,663	407,380	400,871	430,451	-1.2%	-0.2%	0.7%
Oceania Developing Countries	Stocks	head	234,114	180,779	272,039	300,945	-2.6%	4.2%	1.0%
	Production	head	65,008	52,602	86,558	102,162	-2.1%	5.1%	1.7%
	Carcass weight	hg/an	109	112	114	119	0.2%	0.2%	0.4%
	Production	mt	708	586	989	1,215	-1.9%	5.4%	2.1%
Least Developed Countries	Stocks	head	183,915,667	205,750,600	228,210,033	308,618,133	1.1%	1.0%	3.1%
	Production	head	55,867,380	64,954,297	73,984,897	102,399,187	1.5%	1.3%	3.3%
	Carcass weight	hg/an	115	117	114	115	0.1%	-0.2%	0.1%
	Production	mt	643,896	757,369	842,359	1,180,947	1.6%	1.1%	3.4%
OECD	Stocks	head	427,959,833	391,236,800	420,027,700	369,126,233	-0.9%	0.7%	-1.3%
	Production	head	159,529,433	170,113,467	203,350,700	186,530,333	0.6%	1.8%	-0.9%
	Carcass weight	hg/an	159	154	153	163	-0.3%	-0.1%	0.7%
	Production	mt	2,536,317	2,623,882	3,101,913	3,042,063	0.3%	1.7%	-0.2%
World	Stocks	head	1,410,582,667	1,455,741,333	1,629,459,333	1,755,829,333	0.3%	1.1%	0.7%
	Production	head	461,465,167	499,762,633	618,323,400	772,376,633	0.8%	2.2%	2.2%
	Carcass weight	hg/an	139	137	137	139	-0.1%	0.0%	0.1%
	Production	mt	6,410,595	6,849,840	8,481,904	10,744,223	0.7%	2.2%	2.4%

J: Milk			1960s	1970s	1980s	1990s	Exponential growth rates per decade		
							1960/1970s	1970s/1980s	1980s/1990s
Africa	Production	mt	11,989,750	14,650,770	19,131,320	24,050,590	2.0%	2.7%	2.3%
Sub-Sahara	Production	mt	7,238,719	8,702,224	12,326,437	15,412,673	1.9%	3.5%	2.3%
Asia	Production	mt	45,805,060	60,893,573	91,113,000	143,531,933	2.9%	4.1%	4.6%
Latin America & Caribbean	Production	mt	22,534,700	32,613,523	38,780,357	52,962,580	3.8%	1.7%	3.2%
Oceania Developing Countries	Production	mt	46,271	63,899	57,968	71,234	3.3%	-1.0%	2.1%
Least Developed Countries	Production	mt	8,316,540	9,871,296	12,706,330	16,013,777	1.7%	2.6%	2.3%
OECD	Production	mt	218,793,400	239,383,867	273,238,433	274,393,433	0.9%	1.3%	0.0%
World	Production	mt	373,230,833	434,681,567	517,596,000	539,781,100	1.5%	1.8%	0.4%

Acronyms

CGIAR	Consultative Group on International Agricultural Research
EIA	Environmental Impact Assessment
GIS	Geographical information systems
HYV	High-yielding variety
IAEG	Impact Assessment and Evaluation Group
IFAD	International Fund for Agricultural Development
IPM	Integrated pest management
LAC	Latin America and the Caribbean
LDC	Less Developed Country
M&E	Monitoring and evaluation
NARS	National agricultural research systems
NRM	Natural resource management
OECD	Organisation of Economic Cooperation and Development
RFF	Resources for the Future
RNR	Renewable natural resource
SSA	Sub-Saharan Africa
TAC	Technical Advisory Committee
TFP	Total factor productivity
WANA	West Asia and North Africa