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Towards a natural resource management paradigm for international agriculture: the example of agroforestry research

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Abstract

This paper presents the basis of a new research paradigm, integrated natural resource management, which aims to increase agricultural production in tropical countries in a sustainable manner. Integrated natural resource management (NRM) combines traditional germplasm improvement approaches with NRM concerns. The theoretical framework underlying this approach is based on concepts of natural capital and ecosystem hierarchy, and highlights the role of natural capital in providing ecosystem services such as nutrient and water cycling and C sequestration, which may be lost or reduced in intensive agricultural systems. The main components of an integrated NRM agenda are explored, and the need for research to be carried out by interdisciplinary teams including ecologists, social scientists and economists at a range of spatial and temporal scales is discussed. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Agricultural sustainability; Natural capital; Agricultural development; Ecosystem hierarchy; Ecosystem services

Agriculture is:

a science which teaches us what crops are to be planted in each kind of soil, and what operations are to be carried on, in order that the land may produce the highest yields in **perpetuity**

(Varro [Roman landowner], first century BC, our emphasis)

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Soils become infertile because:

the trees, cut down by the axe, cease to nourish their mother with their foliage

(Columella, one century later, our emphasis).

1. Introduction: research challenges for international agricultural research over the next 20 years

Some 30 years after the Consultative Group on International Agricultural Research (CGIAR) was created, new research challenges confront the system and will continue to do so over the next couple of decades (FAO, 1997). Persistent food insecurity and a widening gap between the poor and the rich, both within tropical countries and between rich and poor countries, are two dimensions of this challenge. This is in spite of previous gains in agricultural productivity and in spite of the success of the green revolution, which was largely initiated by the CGIAR. Crop yields in some of the high potential and high input areas of the tropics have now started to decrease, while at the same time, reserves of unused lands are decreasing, and the resource base of agriculture continues to be depleted (FAO, 1997). Yields of rice in the most favourable environments in South East Asia, for example, are falling. The International Rice Research Institute analyses the problem thus,

> The problem of sustaining productivity growth comes about because of inadequate attention to understanding and responding to the physical, biological and ecological consequences of agricultural intensification (Ranganathan et al., 1996).

In addition to these various trends, which provide the context within which future gains in agricultural productivity must take place, a number of complicating factors must be considered. The emerging global concerns of biodiversity loss and global climate change have to be factored into whichever characteristics and whatever directions tropical agriculture will take over the next decades. Furthermore, rates of change seem to be accelerating for a number of variables, such as climate and economic policy. For example, in the analysis of the Intergovernmental Panel on Climate Change, global warming has been accelerating during the past 50–60 years (Bolin, 1998, p. 349). Likewise, the International Geosphere — Biosphere Programme's research shows accelerating changes in environmental and human-driven parameters (Walker and Steffen, 1997, p. 6). As a consequence, crises (e.g. economic crashes such as those which recently occurred in South East Asia or Brazil; extreme environmental events such as El Niño) occur more often and uncertainty is increasing.

In such a context, further gains in agricultural productivity through germplasm improvement alone are unlikely to be sustainable because the resource base of agriculture is limited. International agricultural research, which has been relying on gains in germplasm improvement to increase agricultural productivity since the green revolution, thus needs to develop new approaches to fulfil its mandate of increasing agricultural productivity in tropical countries in a sustainable manner. Moreover, the negative and positive impacts of agricultural development need to be measured with more than an improved germplasm yardstick.

This was explicitly recognised by the recent systemwide review of the CGIAR (CGIAR System Review Secretariat, 1998). The review concludes that two relatively distinct thrusts in the CGIAR research agenda, genetic improvement research and natural resource management research, must now be brought together and integrated. The reviewers consider that the CGIAR's specific contribution to international agricultural research depends upon its ability and willingness to develop a natural resource management (NRM) $\times$ genetic improvement (or integrated NRM) paradigm. The basic assumption underlying the review panel's recommendation is that future increases in productivity will occur and will be sustainable, only if the research community is able to integrate natural resource management concerns with genetic improvement concerns (CGIAR System Review Secretariat, 1998).

The objective in this paper is to present and discuss the dimensions of such an integrated paradigm, illustrating the discussions with examples drawn from the agenda which the International Centre for Research in Agroforestry (ICRAF) has been developing and with which the authors are most familiar (Sanchez et al., 1997). This new approach builds upon the results of the green revolution but differs from it in three principal ways. First, the group of farmers whose needs are primarily addressed in this approach are the poorest of the poor (who do not have access to the resources needed to benefit from green revolution technologies). Furthermore, other kinds of stakeholders and beneficiaries whose interests are considered are local, national and international policy-makers, as well as community-level land users and managers (e.g. community-level management of forest and forest-buffers). Second, this approach focuses on heterogeneous environments, which require a range of NRM practices and where green revolution technologies cannot be successfully applied in a blanket fashion. Thirdly, it builds upon the functions which natural capital fulfils in agriculture in order to further increase productivity while ensuring the sustainability and stability of these increases.

This paradigm should be of relevance to international and national research institutions dealing with natural resources as well as to those agricultural institutions interested in setting their germplasm improvement research within an appropriate NRM context.

In what follows, the concepts of natural capital and ecosystem hierarchies are first discussed, as they form the backbone of the theoretical framework of the proposed integrated NRM agenda. Second, the principal components of this agenda are discussed, and are illustrated, using examples from agroforestry research. Lastly, the main differences between this integrated NRM paradigm and the more traditional genetic improvement paradigm are highlighted. The dimensions of this agenda which are still unresolved and require methodological breakthroughs to be made are also identified.

2. Theoretical framework: natural capital and systems hierarchies

The tropical agroecosystems which are the focus of the interventions of the international and national agricultural research community are highly complex, both from an economic and an ecological perspective. Traditional scientific approaches to agriculture (e.g. plant breeding, agronomy, soil science, agricultural economics) are reductionist in nature, and as such, fail to account for the substantial number of interactions which prevail in such complex ecosystems. Examples of these interactions are upstream–downstream effects in a watershed, or the farm level trade-offs between profitability, stability and biodiversity, or pest–soil relations at the plot level. Two concepts, one from ecological economics viz., natural capital, and one from ecology, viz., hierarchies of systems, are particularly relevant to the analysis of these interactions and the development of an integrated NRM agenda.

NRM is defined here as the sustainable use of the resource base of agriculture, in order to meet the production goals of farmers (e.g. profitability) as well as the goals of the rest of the community (e.g. welfare of future generations, poverty alleviation, environmental preservation). The resource base of agriculture, in turn, consists of all the natural resources essential to agricultural production, such as soil, water, solar energy and plant, tree and animal germplasm. Agroforestry has recently been defined as: 'an integrated landuse that, through the capture of intra-specific diversity and the diversification of species on farm, combines increases in productivity and income generation with environmental rehabilitation and the creation of biodiverse agroecosystems' (Leakey, 1998, p. 143). It is clearly an example of NRM and a branch of agriculture (Spedding, 1996).

The understanding of the linkages between agriculture, natural resources and the environment and the concept of natural capital have evolved over time. The Physiocrats (a school of economic thought in eighteenth century France) argued that agriculture is the only true source of economic surplus in a nation, because it is based upon the free gifts of nature. Later, Ricardo (an English economist from the nineteenth century) spoke eloquently about the 'original and indestructible powers of the soil'. These authors initiated a tradition in economics in which natural resources (natural capital) are viewed as boundless inputs to agriculture. Many economists still consider that increases in agricultural production are limited only by technical progress (and appropriate policies) and definitely not by the resource base of agroecosystems. One of the basic assumptions of traditional economic theory is that of total substitutability of all inputs for one another, including natural resources. Barnett and Morse (1993, p. 11), for example, wrote:

> Nature imposes particular scarcities, not an inescapable general scarcity. Man is therefore able, and free, to choose among an indefinitely large number of alternatives... In a neo-Ricardian world, it seems, the particular resources with which one starts increasingly become a matter of indifference.

About 30 years ago, a few writers started to argue that the use of natural resources in agriculture could entail some irreversible losses in these resources (e.g. Georgescu-

Roegen, 1971). Their writings have recently been built into a school of thought, ecological economics, which resurrected the concept of natural capital in the mid 1990s by identifying the optimal level of natural resources necessary to ensure sustainability of production (Whitby and Adger, 1996).

Whilst a number of authors have written about the different types of natural capital (Costanza and Daly, 1992; Daly, 1994), its optimal rate of use (e.g. Barbier, 1987; Odum, 1994) and its various ecosystem functions (e.g. Costanza et al., 1997), relatively few writers have articulated a definition of the concept (the exceptions are Cleveland, 1991; Daly, 1994). In this paper, natural capital is defined as 'stocks of resources generated by natural biogeochemical processes and solar energy that yield useful flows of services and amenities into the future' (Izac, 1997). Within a given ecosystem, stocks of soil nutrients, secondary minerals and organic matter held in the soil, or stocks of germplasm in plant and animal communities are instances of natural capital. Examples of flows of services and amenities (i.e. ecological functions useful to mankind) associated with stocks of natural capital include nutrient cycling, water cycling and carbon sequestration.

The second concept crucial to the development of an integrated NRM paradigm is that of ecosystem hierarchy. The ecosystem concept dates from the 1920s and ecologists quickly recognised the hierarchical relations between ecosystem components (see O'Neill, 1989 for references). The application of ecological concepts to agriculture, however, is much more recent (e.g. Odum, 1971).

Interest in analysing complex systems led ecologists to recognise that these systems have different process rates which can be organised over a hierarchy of levels. Each level in the hierarchy is driven by a few processes, operating at similar rates. Lower levels have relatively rapid rates of processes whereas higher levels have relatively slow rates (O'Neill, 1989; Beeby, 1993). For example, at the scale of a stand of trees, processes of competition between trees, nutrient uptake and impacts of human interventions operate at about the same temporal scale (around 1 year). These processes are influenced by factors at a higher level (e.g. climate change, land use change) which have a much longer rate (many decades). At the same time, the tree stand scale in the hierarchy is determined by processes at lower levels (photosynthesis, nutrient mineralisation) which have a quicker turnover rate (days). This is illustrated in Fig. 1.

Dynamics at any one level or scale (e.g. tree stand) are thus constrained and controlled by the next higher level and at the same time, they are based upon the limitations embodied in the components of the next lower level (Allen and Starr, 1982; O'Neill, 1989). It follows that the analysis and subsequent understanding of processes and their dynamics at one specific scale (e.g. farm level) implies, at a minimum, analysis of processes at the next higher and lower scales. Systems, their components and their interactions, can be defined differently, depending upon the problem being addressed and the objective of the research. As aptly noted by O'Neill (1989, p. 145), such a hierarchical approach to agroecosystems constitutes a theoretical framework or '...a new way of looking at systems rather than a set of equations and theorems'.

The concepts of ecological hierarchy and natural capital can be combined in a framework which is useful for analysing the complexity of ecosystem services

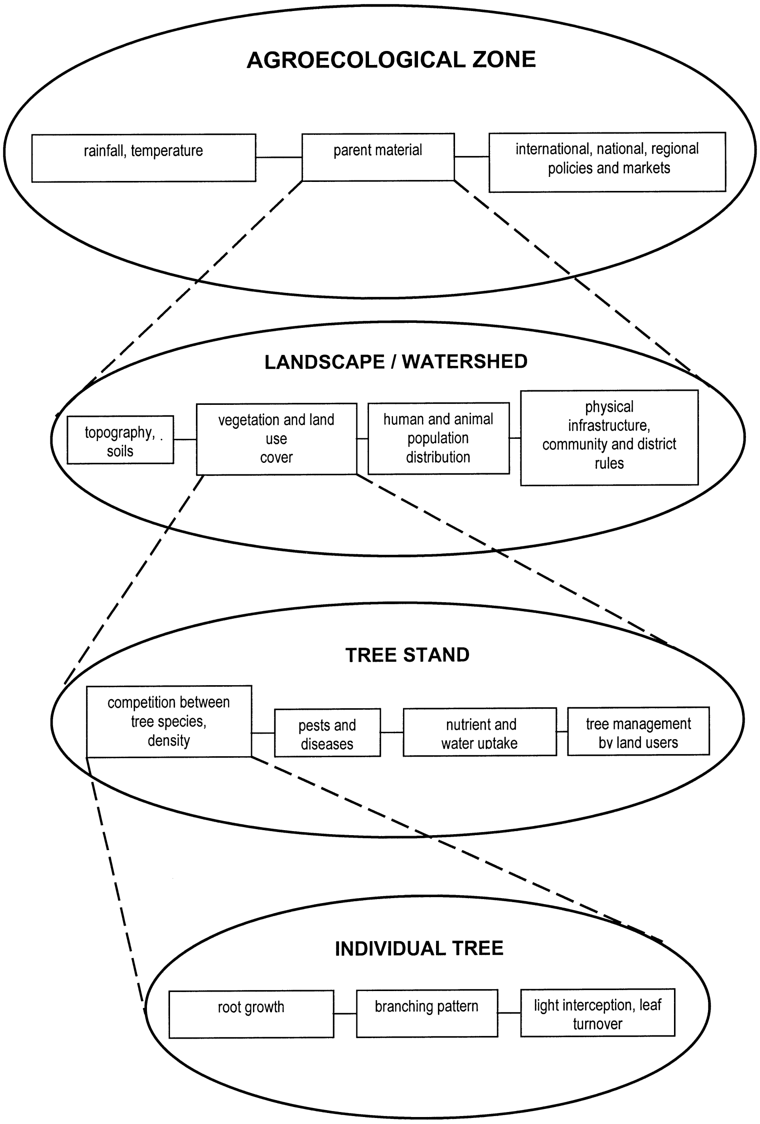


Fig. 1. Example of a hierarchy: factors influencing the composition and productivity of a tree stand (adapted from Holling [1992] and Izac [1993]).

generated by natural capital. Natural capital (such as trees) generates a number of ecosystem flows and services, and does so at different scales. In other words, it has a number of useful ecological functions at different spatial and temporal scales. This is illustrated in Figs. 2 and 3, using agroforestry trees and systems as an example.

At the farm level for instance, agroforestry trees (trees planted or retained by farmers) yield a number of ecosystem services or functions, represented in Fig. 2.

1. **Food and raw materials**
   The harvested part of net primary plant production (e.g. fruits, leaves, fuelwood, poles...) directly results in products that generate income (e.g. tea, coffee, resin of damar trees, bark of *Prunus africana,* medicinals).

2. **Nutrient cycling**
   Atmospheric N fixation, mobilisation of stored organic and inorganic soil reserves, increasing the quality and quantity of nutrient uptake and return (e.g. improved fallows).

3. **Erosion control and sediment retention**
   Trapping sediments, binding soil through tree roots and mycohriza (e.g. trees on contours, ...)

4. **Water cycling**
   Increasing infiltration capacity of soils, accessing subsurface water flows, increasing water cycling and uptake by transpiration, reducing risks of rising water tables and salt intrusion

5. **Microclimate regulation**
   Providing a buffered environment at ground level with smaller daily variations in temperature and humidity (e.g. shade trees,...)

6. **Habitats for other biota**
   Habitats for pollinators and biological control agents of pest and disease organisms.

Fig. 2. Ecosystem services of trees at the farm scale.

These flows of services fall into two categories. First are the functions that are of direct and immediate interest to farmers. They consist of all the food, raw materials and income generating functions of the trees (e.g. fruits, medicinal products, and timber). Second are the functions which may or may not be of direct and immediate interest to farmers, but which are nevertheless essential biological functions for ecosystem maintenance and health (e.g. nutrient and water cycling).

Fig. 3 shows the range of functions that agroforestry systems fulfil at different spatial scales, from the farm to the globe. At the global scale, for instance, maintenance of biodiversity, greenhouse gas regulation and climate regulation are probably the best-known functions of such systems (Sanchez, 1995). A number of the functions represented in Figs. 2 and 3 are of course not unique to agroforestry trees. Other examples of natural capital (e.g. wild animal populations) share some of these functions (e.g. biodiversity enhancement).

Since natural capital generates different ecosystem services at different spatial and temporal scales, its use or management has potential impacts on different categories of stakeholders, at these different spatial scales. This is also illustrated, to continue with the case of agroforestry trees, in Fig. 3. It must be kept in mind that the international scientific community is also one category of stakeholders in the sense that it has a germane interest in the understanding of the impacts of trees at each of the scales shown in Fig. 3. It should also be noted that different stakeholders often have different perspectives and will therefore value the different impacts of agroforestry systems differently. For example, while an individual farmer may value the income generated by a land use incorporating high value trees such as *Prunus africana*, the

Scale	Ecosystem functions
Farm	food production nutrient cycling erosion control water cycling genetic diversity micro-climate regulation *farmers, extensionists*
Watershed / Village / Landscape	decreased poverty erosion and sedimentation control water cycling refugia, pollination, biological control (landscape patches) *land managers, policy makers, project managers, local planners*
Region	decreased poverty decreased deforestation and desertification biodiversity water cycle *public, politicians, donors in Northern and Southern countries, national / regional decision-makers*
Global	greenhouse gas regulation climate regulation biodiversity rural poverty alleviation *public, politicians, donors in Northern and Southern countries*

Fig. 3. Principal ecosystem services and stakeholders (in italics) of agroforestry trees at different scales.

general public in the North may consider that the biodiversity value of such land uses is higher than its income value.

Natural capital plays a central role in the process of agricultural intensification. Indeed, intensification can be defined as a process of deliberate simplification of natural ecosystems through a decrease of biological diversity in order to enable one species to become dominant and higher yielding. This simplification is managed over time by replacing various ecosystem functions of renewable natural capital (e.g. nutrient cycling, biodiversity, water cycling) by manufactured capital (e.g. machinery) and non-renewable natural capital (e.g. petro-chemicals). The long-term environmental costs of such a substitution may be significant. It is, therefore, essential to take natural capital into consideration when developing sustainable agricultural intensification pathways in tropical countries.

The relative significance of the food and income production functions of natural capital vis-à-vis its ecosystem support functions (non-food production) is difficult to appraise. One attempt at evaluating these functions has recently been made. Costanza et al. (1997) estimated that the global value of 17 ecosystem services for 16 biomes (desert, tundra, ice/rock excluded) is about \$33 trillion per year. This is excluding the worth of the stocks of natural capital in these biomes, as these are too difficult to assess. By comparison, world GNP is only worth some \$18 trillion per year while the food production function of croplands amounts to about \$0.13 trillion per year (Costanza et al., 1997). These estimates do indicate that the ecosystem support functions of natural capital are extremely significant for mankind, over and beyond their food and income production functions.

Another example concerns the value of the carbon sequestered by complex multistrata (or agroforestry) systems in the humid tropics. The Alternatives to Slash and Burn agriculture (ASB) systemwide programme has established that about 70 t ha^{-1} of carbon are sequestered by such systems (ASB, 1998). A tonne of sequestered carbon currently has a market value (established in joint implementation mechanisms) which fluctuates between \$5 and \$25. Therefore, the value of only one ecosystem function of complex agroforestry systems in the tropics, carbon sequestration, varies from around \$350 to \$1750 ha^{-1}. In countries such as Cameroon (site of one of the ASB benchmark areas), it is very doubtful that the market value of 1 ha of agricultural land comes anywhere close to these figures. Stakeholders in countries in the North, however, are interested in the carbon sequestration value of multistrata systems in the tropics.

In summary, natural capital generates a range of ecosystem services at different spatial and temporal scales, from the plot to the globe, from weeks to decades and centuries. As a consequence, the management of natural capital has impacts on a range of stakeholders, from farmers to international policy-making bodies. The process of agricultural intensification is one of substitution of natural capital for manufactured capital; it is essential to ensure that natural capital is appropriately managed in this process because manufactured capital cannot be a full substitute for natural capital (Daly, 1994 for a demonstration). Furthermore, there are indications that the ecosystem services of natural capital may be more significant than its food production services. Most of the interventions designed by international agricultural research centres are at the plot or farm scale. The foregoing analysis clearly indicates that consequences for other spatial scales can no longer be ignored by researchers.

3. Main components of an integrated natural resource management agenda

The framework just presented, and its associated concepts, form the basis of the integrated NRM agenda presented in this section. This agenda has six principal components, or sets of activities, which are shown in Fig. 4, and discussed in what follows.

3.1. Component 1: identification of key poverty and NRM problems

The first step consists of identifying and quantifying the extent of resource degradation and rural poverty problems to be addressed in a given region. These problems are analysed from the perspective of their relevant spatial and temporal scales

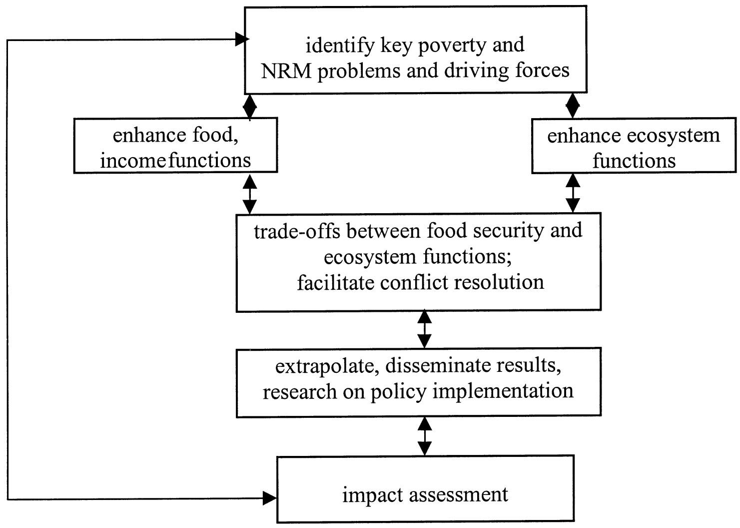


Fig. 4. Principal steps of a proposed integrated natural resource management (NRM) agenda.

and their driving forces are identified (Swift and Izac, 1993). This step goes beyond the traditional diagnosis and participatory rural appraisals in that it embodies an analysis of the root causes of the NRM and poverty problems to be addressed. Furthermore, it involves a quantification of patterns and trends in relevant parameters (Palm et al., 1995). Finally, it is essential to predict future trends in these driving forces, in order to build a dynamic dimension into the agenda from its inception. This ensures that the results produced are addressing problems which will emerge in the foreseeable future, instead of past problems (given the time lag in research dealing with trees, this is a particular danger in agroforestry research). The research questions to be answered are listed below.

1. What is the overall importance of the problem to be addressed relative to other problems within the domain of expertise, mandate or comparative advantage of the research institute implementing this agenda?
2. What are the spatial and temporal dimensions of the problem, what is its relative magnitude, and if and where is it likely to become a problem over the chosen planning horizon?
3. What are the foreseeable options/strategies/solutions (on offer by the research institute and partners) for solving the problem?
4. What would be the expected relative efficiencies and net benefits (including potential "spin-offs") should various options and strategies be implemented at specific locations and at specific points in time?

Addressing these questions leads to the identification of priority research themes (including priorities for policy research), priority geographical areas for the work and priority target groups of stakeholders for interventions.

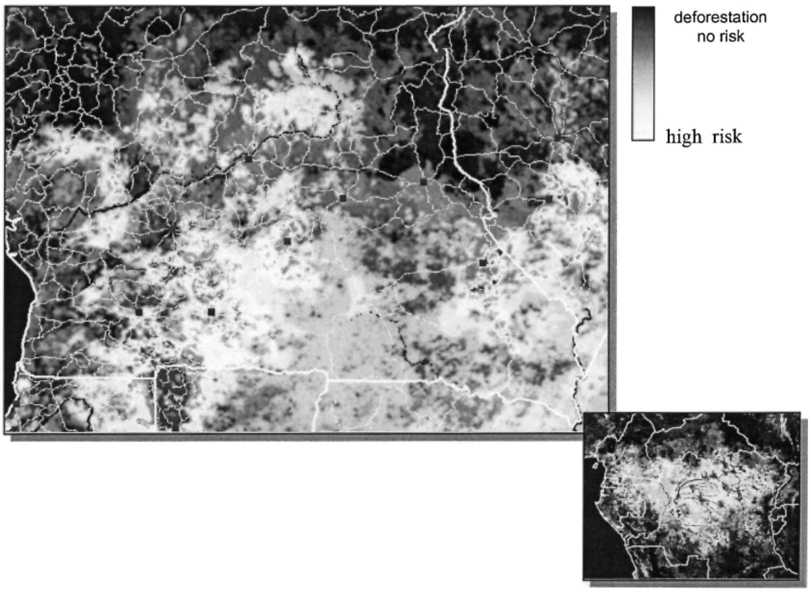
An illustration of the sort of intermediate results produced by this first step is shown in Fig. 5. This is a map of the Congo basin rainforest in which deforestation 'hot spots' (areas with a high risk of projected deforestation over the next few years) have been identified on the basis of an analysis of the driving forces of deforestation in the region. The analysis has enabled the ASB programme to assess how representative its benchmark site in the Cameroon is, at the scale of the Congo basin.

Depending upon the types of problems and driving forces identified, the agenda will focus more on component 2A or 2B, or both equally. Component 2A deals with the direct and immediate utilitarian value of natural capital (with the example of agroforestry trees and systems) whereas component 2B addresses their functional ecosystem values.

3.2. Component 2A: enhancing food and income utilitarian functions

Component 2A focuses on enhancing the direct utilitarian functions of natural capital, which consist of food, raw materials and income functions in the case of agroforestry systems. Examples of the basic research questions which are addressed in this component include the following.

1. Which tree species should be the focus of the work (and why)?
2. How should they be spatially organised through the farm, landscape and region to maximise their utilitarian value?



Source: ASB Consortium, 1998

Fig. 5. Risk of deforestation: Congo basin and Southern Cameroon.

3. What is the most effective way of 'improving' these trees, including manipulations of genotype, environment and management?
4. What are the prerequisites for successful adoption of these trees?

An example of the germplasm or tree domestication research involved in this step is that concerning *P. africana*. An extract from the bark of this wild tree, indigenous to the humid tropics of Africa at high elevations, is used to treat prostate gland disorders (Simons et al., 1998). There is a high demand for this bark from the international pharmaceutical industry and the species has been recognised as threatened by extinction. Consequently, *P. africana* is listed under Appendix II of the Convention on International Trade in Endangered Species of wild fauna and flora (CITES). Harvesters currently go and collect the bark in the wild by cutting trees down or debarking them in a manner such that the trees are killed. The bark of a mature wild tree is worth on average \$200 to \$2000 (Simons et al., 1998) to a collector. By comparison, this bark is worth \$6500 to \$65 000 to industry. Research on the performance and chemical quality of provenances, clones and different aged material is on-going (Dawson and Powell, 1999) and will hopefully lead to successful identification, production, management and adoption of desirable germplasm. This, in turn, will mean that farmers can capture and control a bigger part of the economic value of the bark while no longer over-exploiting the dwindling wild resource. Synthesis by industry of the active ingredients in the bark of *Prunus africana* is too complex to be an option at this point in time (Simons et al., 1998).

The objective in this component is to increase food and income production in specific agroecosystems. In the process, in an agroforestry context, wild tree germplasm, which may be under threat of over-exploitation, will be better protected, because farmers will be empowered to manage these now domesticated trees on their farms. This will also result in better on-farm management of biodiversity. In research institutions dealing with other resources than trees, this component includes the corresponding germplasm improvement work.

3.3. Component 2B: enhancing ecosystem functions

In component 2B of the integrated NRM paradigm, research activities aim at enhancing the non-utilitarian ecosystem functions of natural capital and natural resources, such as water cycling, erosion control and biodiversity. Examples of the principal research questions are as follows.

1. Which ecosystem functions of agroforestry systems are the most significant, from both an ecological and an economic perspective, at each scale?
2. Which kinds of agroforestry systems will improve internal ecological control mechanisms in existing land use systems?
3. Which ones will improve energetic efficiency?
4. Which ones will improve the regulation of the externalities generated by these systems?
5. What are the prerequisites for successful adoption of such systems?

An example of the type of results produced when addressing the first research question mentioned above is given in Fig. 6. The time-average carbon sequestration functions of different land uses were measured across a number of sites (in Cameroon, Indonesia and Brazil). Tree-based systems in the humid tropics sequester significantly more carbon in their biomass than crops, pastures and grasslands (ASB, 1998). Soil carbon sequestration, however, is slightly higher in agroforestry systems than in cropping or grazing systems (Fig. 6).

Another example of research focusing on enhancing ecosystem functions (nutrient cycling in this case) and which has led, in turn, to increases in food crop production, is provided by research on improved fallows in the sub-humid areas of Africa (Sanchez et al., 1997). Improved fallows of leguminous trees such as *Sesbania sesban, Tephrosia vogelii* and *Gliricidia sepium* are grown for 1 or 2 years. They contribute significant quantities of nitrogen to the soil through biological nitrogen fixation (Kwesiga and Coe, 1994). In sites in southern Zambia which have a strong nitrogen deficiency, and where farmers use natural fallows for 2 years before planting maize, these improved fallows have resulted in increases in maize yields of around 100% (Sanchez, 1999). Furthermore, the positive nutrient cycling effects of these fallows on maize yields can last up to 3 years after a two-year fallow, as shown in Fig. 7.

Research under this component of the integrated NRM agenda leads to the identification of a range of land use practices and land use management options which rehabilitate and/or strengthen the ecosystem functions of agroecosystems and thereby, boost their sustainability.

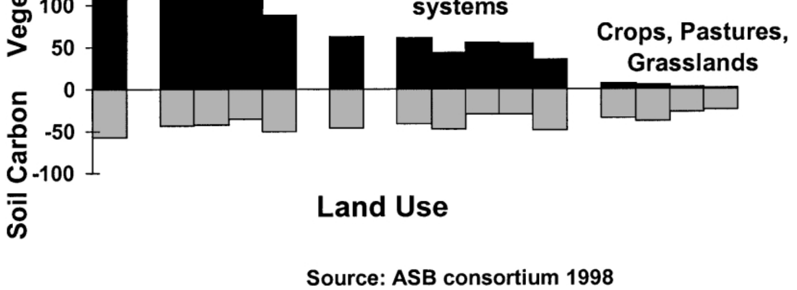


Fig. 6. Time-averaged carbon stocks by land uses across benchmark sites.

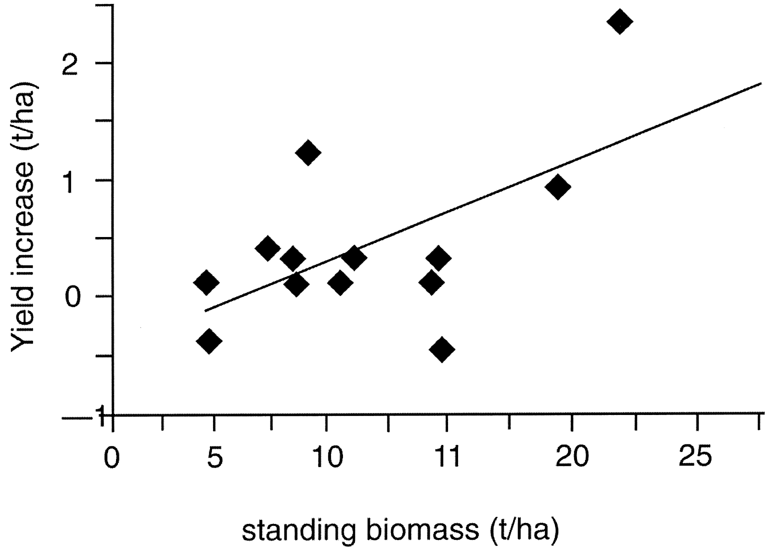


Fig. 7. Maize yield increases, 3 years after a 2-year *Sesbania* fallow, and by comparison with yields following a natural fallow system (source: Kwesiga et al., ICRAF unpublished data).

3.4. Component 3: assessment of trade-offs

The third component of this integrated NRM paradigm is the assessment of trade-offs between the two ranges of options arrived at in components 2A and 2B. That is, of trade-offs between the options which enhance the food and income functions of systems and those options which enhance the other ecosystem functions of systems. The objective is to identify the combinations of options which optimise these trade-offs from different perspectives. These perspectives are those of the major stakeholders who include farmers, community-level decision-makers, national and global policy-makers, depending upon the specific problems being addressed (Fig. 3). The policy work included in this step focuses on facilitating conflict resolution (e.g. between individual farmers and national society).

At the heart of these trade-offs lies the fact that the use and management of natural capital generates a number of positive and negative externalities. These are effects which are not priced by the market mechanism and which impinge on the welfare of different stakeholders. Because they are not priced and they affect various groups in society differently, externalities create discrepancies between private and social costs and benefits. The benefits of adoption of an improved NRM practice that are received by individual farmers are likely to be inferior to the (non-monetary) benefits received by society at large from this improved NRM. For example, in the absence of specific policies, farmers are unlikely to consider the carbon sequestration value of sustainable agroforestry practices in their decisions to adopt these practices. This implies that rates of adoption of such improved practices are likely to be suboptimal from society's viewpoint whilst optimal from individual farmers' perspectives (see Izac, 1993 for a full demonstration). These discrepancies are the reason why a policy dimension must be part and parcel of an integrated NRM agenda.

The trade-offs which are analysed in this third component of the agenda are thus trade-offs between the perspectives and interests of different stakeholders. For example, an assessment of different land uses has recently suggested that there are no land use management systems in Cameroon's humid zone that can generate high profits and at the same time have a high level of diversity; in other words, win-win situations are very rare indeed (ASB, 1998). As shown in Fig. 8, systems with high diversity levels (community forests) have a very low profitability. However Fig. 8 also demonstrates that there are systems which yield high profits while at the same time having a medium biodiversity level (intensive cocoa production with fruit trees). Such systems do optimise trade-offs between profitability and diversity, that is, between the interests of farmers and those of the community.

The outcome of component 3 is the identification of those improved NRM options which can meet the needs and objectives of various stakeholders and the identification of policy or institutional options which will facilitate the adoption of these systems by farmers.

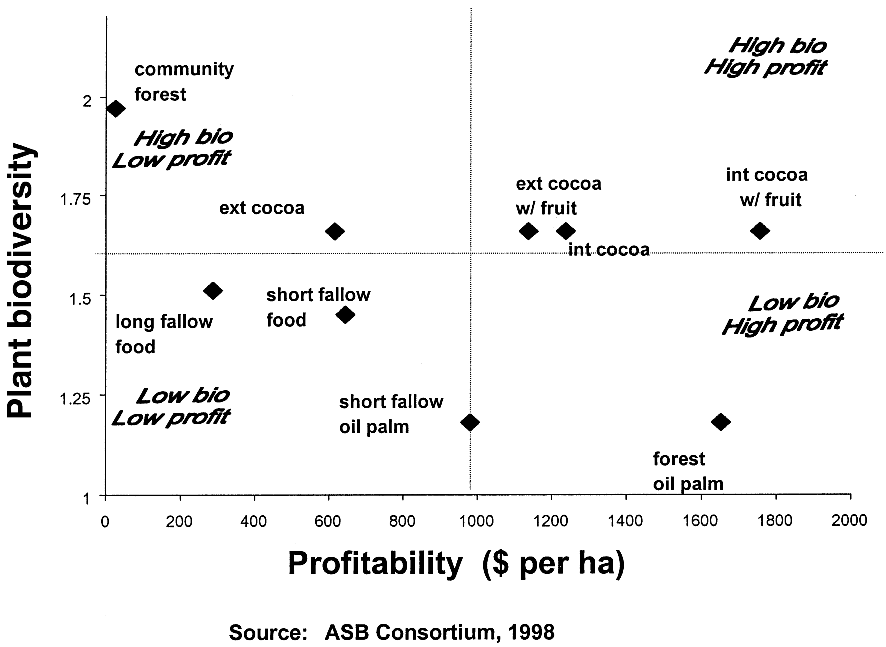


Fig. 8. Plant diversity and profitability of various land uses in Cameroon.

3.5. Component 4: extrapolation, dissemination and policy implementation

The fourth component of the NRM paradigm involves extrapolating and disseminating results through various means, including modelling, GIS and pilot projects in which NGOs, farmers' organisations and extension services are partners. Research on policy implementation, using participatory methods, also takes place in this component. The objectives, in this component, are, firstly, to determine under which conditions the results arrived at in the previous step can be extrapolated to larger areas than those areas where the research was physically undertaken. Secondly, once these extrapolation domains are identified (see Fig. 5 for an example of such a domain), the aim is to put in place mechanisms and linkages which ensure that adoption of improved NRM practices can indeed take place on a large geographical scale.

Through partnerships with development organisations, research institutions can assume a more pro-active role in catalysing and facilitating the adoption of improved NRM options by substantial numbers of farmers (Denning, 1998). For example, in the earlier example of improved fallows in Zambia, large-scale adoption is expected to occur through various mechanisms including farmer field schools, farmer-to-farmer dissemination and partnership with an international development NGO. The complexity of NRM and the heterogeneity of agroecosystems where those systems best fit, necessitate the use of such partnerships and approaches. This is most compelling in countries with poorly funded research and extension systems, often with an institutional separation of agriculture and the various ministries dealing with natural resources. In this approach a research institution and its partners accept joint responsibility and accountability for ensuring adoption and impact of NRM innovations. While retaining and continuing to strengthen strategic research functions, agricultural and NRM research institutions will now additionally serve as responsible and committed development partners.

Part of facilitation of adoption also involves the design of policy implementation instruments, with the full participation and collaboration of policy-makers at community and national levels. One instance of such policy implementation research is provided by a collaborative project implemented in Indonesia, that involves various international partners (two research institutions, an international NGO) as well as many national partners (in national and regional government, a national NGO, and the farmers; Fay et al., 1998). The work led to a new decree being passed by the Government of Indonesia. The decree gives some 7000 indigenous families economic rights over a resource they have been managing for about a century (Fay et al., 1998). This resource is the totally indigenous complex agroforests which these farmers have created over time (Michon and de Foresta, 1998). The rights to keep managing these agroforests and to receive the benefits of this management were questioned by one national governmental body, on the grounds that the farmers were degrading the natural forest. The new decree explicitly recognises the role of the local institutions set up by these indigenous farmers for managing their agroforests. The Government of Indonesia will 'extrapolate' this decree to other forest margins throughout the country if the current decree is successful in protecting the rights of the farmers vis-à-vis the rights of governmental institutions (i.e. if the conflict is successfully managed by the decree; Fay et al., 1998).

3.6. Component 5: impact assessment

The last step in this integrated NRM agenda is the assessment of the impacts of the adoption of the ranges of options thus devised. Impact assessment occurs within the natural capital and systems hierarchy framework used throughout the research agenda and is its logical output. It amounts to assessing the most significant functions of the improved NRM systems adopted by farmers at different spatial scales, from ecological, economic and social perspectives (Fig. 3). This is done by measuring a number of relevant indicators at different spatial and temporal scales. Izac and Swift (1994) provide an operational framework for doing so. The results of this step are fed back into the research agenda. Fig. 4 shows how the different components are related to each other in an iterative manner.

It is important to note that interdisciplinary teams of scientists are involved in each of the above steps, as ecological, social and economic parameters, and their interactions, are relevant at each step. Furthermore, each step also involves work at a minimum of three spatial scales (see above for a rationale). Finally, it must be noted that, operationally, the research undertaken is conducted for the most part in farmers' fields, rather than on research stations. This is to ensure that a representative range of biophysical and economic conditions are captured, as well as to facilitate the use of participatory research methods.

4. Conclusion

In conclusion, the integrated NRM paradigm described here differs notably from the traditional crop improvement paradigm, which has been so successful in bringing about the green revolution. It actually builds upon and integrates this crop improvement paradigm into a broader perspective which acknowledges the role played by natural capital in sustainable agricultural production. This is in line with the recommendations of the systemwide review of the CGIAR (CGIAR System Review Secretariat, 1998).

The principal ways in which these two approaches differ are summarised in Fig. 9. It must be stressed that 'genetic improvement' in this figure refers to the traditional genetic improvement approach, as it was developed some 30 years ago. A number of institutions currently undertaking research on crop improvement are relying on a paradigm which is more complex than this traditional approach.

The integrated NRM approach addresses problems as agroecosystem problems which are part of a larger whole, of which yields and profits are one component, but are by no means the only one. The objectives, in this paradigm, are multiple: to meet farmers' needs for welfare improvements while at the same time satisfying societal objectives for environmental protection.

Genetic improvement paradigm	Principal elements of paradigm	Integrated NRM paradigm
to maximise yields	**Objective**	to meet farmers' needs and those of society (enhance ecosystem health)
on plot and farm; participatory with farmers	**Focus**	cuts across spatial and temporal scales; participatory with range of stakeholders
simplified and 'homogeneised'	**Bio-complexity**	heterogeneity analysed as patterns in complex agroecosystems
variability is controlled, uncertainty largely ignored	**Uncertainty**	explicitly recognised so responses produced are adaptive, evolutionary
reductionist, experimental	**Methods**	reductionist + systems, integrative, interdisciplinary, chaos theory, non linear dynamics, systems hierarchy
one solution: improved crop variety, plus fertilizer, pesticide application, plus irrigation	**Outputs**	no single 'solution' but ranges of flexible, adaptive options

Fig. 9. Traditional crop improvement and integrated national resource management (NRM) paradigms.

Following principles from ecological hierarchy theory, this approach focuses on various spatial and temporal scales. It relies on participatory research methods, and applies these methods not only with farmers but also with a range of stakeholders, in particular, decision makers, at various levels. Whilst the original crop improvement paradigm dealt with biophysical heterogeneity by 'homogenising' cropping environments (e.g. through irrigation, control of soil fertility and pests through chemicals), heterogeneity is explicitly built into the agroforestry paradigm which attempts to capture patterns in the observed diversity and complexity of conditions. Likewise, uncertainty, for example that related to governmental policies, international prices, climate and pest infestation, is also explicitly taken into consideration, through the analysis of ranges of flexible options in terms of their risk reduction capabilities.

The methods used are those of the traditional crop paradigm and also include systems methods. In addition to principles from hierarchy theory and ecological economics, new methods and concepts from non-linear dynamics and thermodynamics (to address issues of uncertainty) and chaos theory (to address issues of complexity) need to be built in. Chaos theory, as it deals with the implications of instability for the irreversibility of basic processes in systems and for the dynamics of these systems (Prigogine, 1994), provides relevant insights for dealing with complex adaptive systems found in NRM. Scientists engaged in NRM research do work in interdisciplinary teams and know that no single science can identify, by itself, a solution for the complex agroecosystem and NRM problems which are being addressed. As a consequence, no single solution or '*optimum optimorum*' is arrived at, but ranges of flexible and adaptive options for different environments are identified.

There are a number of unresolved methodological issues, requiring research breakthroughs, with which a number of institutions engaged in NRM research are grappling. These concern, first of all, issues of scaling up and scaling down in the nested hierarchy of systems used in this paradigm. Since spatial scales are logically connected through process rate differentials it follows that 'addition' is not a relevant rule for aggregating processes across scales. For example, adding up biodiversity measures at the farm scale across a region does not produce a meaningful measure of biodiversity at the landscape or regional scale. Or adding up increases in farmers' income across individual farmers does not yield a legitimate assessment of the actual economic effects of these individual increases at the regional level. It is, however, important that we learn how to scale up and down hierarchical levels in order to develop models which cut across scales, and which can integrate a minimum of three scales, as was argued above. In this context, scaling up or down means capturing the constraints that level $X+1$ imposes on level X, as well as the way in which processes at level X are determined by those at level $X-1$.

Other issues which are unresolved include the specific ways in which risk and uncertainty about the future behaviour of key parameters are built into the analysis, how some ecosystem functions are actually measured (e.g. patch dynamics; resilience) and evaluated (e.g. value of biodiversity). We also need new and robust statistical methods to design and analyse the results of community level participatory approaches to improved NRM practices.

Finally, the implementation of the NRM paradigm discussed in this paper necessitates the establishment of partnerships with new stakeholders (e.g. policy-makers at different levels, from the village to the international sphere), as well as new collaborative modes with the other CGIAR centres, NGOs, NARS, ARIs. This paradigm brings about a significant shift in emphasis. Indeed, the emphasis is no longer on the large-scale adoption of a single solution (i.e. an improved crop variety) by one category of stakeholders (farmers). Rather, the research agenda is driven by the desire to ensure that a given problem, which occurs in a variety of environments, is resolved in a sustainable manner through the adoption of ranges of options (adapted to the different environments) by farmers, regional bodies (including NGOs), and policy-makers at national and international levels.

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