Increasing food production at the expense of tropical forests

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An attempt is made to estimate to what extent it is possible to increase food production by conversion of forest land to agricultural land. To accomplish this two different approaches have been explored. The first one represents the possibility of developing a comprehensive model capable of taking into account the various processes influencing the food production. It is judged that this approach cannot provide a realistic result due to insufficient knowledge of the processes involved, and lack of reliable data. Instead a simple, heuristic method has been applied. The main sources of information used include data representing the soil of the deforested land, the decline of the productivity of the land gained, and the length of time it can be used for agricultural production. Although this method also has its obvious limitations, there are reasons to believe it permits certain conclusions can be safely drawn: (a) even if each year the area of agricultural land is increased by a given amount through removal of forest, there will be no gain of the agricultural production after a few years; and (b) to achieve a constant annual increase of the food production will require that each year the area of forest removal is increased.

Keywords: deforestation, food production, environmental degradation

1. Introduction

Attempts to increase food production may not always lead to the desired result. This pessimistic statement results from copious evidence that to augment food production in the past has not produced the desired result. Such attempts often lead to complex interactive processes, and some of these can have negative effects. Consequently, the net result will not necessarily be as positive as expected. Actually, in some cases the net result can be negative. For example, excessive application of irrigation can lead to waterlogging, salinization, depressed crop yields and eventually loss of land for agriculture [10].

In a similar manner, there are several causes for the ongoing extensive overharvesting of tropical forests [50]. Examples include: the increasing need for fuelwood due to rapid population increase, consumer demands for wood in more developed countries, poor land use policies, debt burden and need for foreign exchange in less developed countries. However, conversion of forests to cropping and grazing is the prime cause of tropical forest disappearance [14].

So far it appears as if the planning and implementation of conversion of forests to increase agricultural production has been undertaken in haste and without making use of existent knowledge about the negative consequences. In some cases the clearing of forests in order to implement agricultural development schemes can only be characterized as being totally “bizarre” [8]. To this category belongs, for example, the development of agricultural land use in the Amazon beginning in the 1960s which was implemented by construction of the 5000 km Trans-Amazon highway.

The aim of this paper is limited to providing a reasonably realistic answer to the question: what is the net gain of food production for a given rate of expansion of agricultural land at the expense of tropical forests? For this purpose we will examine:

- The individual physical, chemical and biological factors that directly or indirectly impact food production.
- To what extent the removal of the forests is modifying these factors, and initiating other processes of importance.
- Alternative methods for estimating the increase of agricultural production that can be achieved through deforestation.

2. The extent of forests and deforestation in the tropics

The clearing of tropical rain forests for expansion of cropland is not a new phenomenon. According to Kirschbaum and Fischlin et al. [22], it began about 3000 BP in Africa and at about 7000 BP in India and Papua New Guinea. Since pre-agricultural times, the loss of forest areas has been highest in the temperate region (32–35%) while in the subtropics the loss has been somewhat less [14]. The tropical evergreen forest, which now exhibits the highest deforestation rate, has so far not lost more than about 4–6% of its area [29].

It deserves also to be emphasized that it is now more than hundred years ago it was recognized that the decline of forests and land degradation caused by human activities was a potential problem for which response action was required [28].

In tables 1(a) and (b) are presented estimates of the extent of the tropical forests in 1990 and the rate of defor-

Table 1(a)
FAO estimates of tropical forest cover area and rates of deforestation by main ecological zones. Source: Singh [43].

Ecological zone	Total land area 10^6 ha	Forest area 1990		Rate of change 1981–1990	
		Total 10^6 ha	% of land area	10^6 ha/y	% y
Total tropics	4778.3	1756.3	37	−15.4	−0.8
Forest zone	4186.4	1748.2	42	−15.3	−0.8
Lowland formations	3485.6	1543.9	44	−12.8	−0.8
Rainforest	947.2	718.3	76	−4.6	−0.6
Moist deciduous	1289.2	587.3	46	−6.1	−0.9
Dry deciduous	706.2	178.6	25	−1.8	−0.9
Very dry zone	543.0	59.7	11	−0.3	−0.5
Upland formations	700.9	204.3	29	−2.5	−1.1
Moist forests	528.0	178.1	34	−2.2	−1.1
Dry forests	172.8	26.2	15	−0.3	−1.1

Table 1(b)
FAO estimates of tropical forest cover area and rates of deforestation by region. Source: Faminow [8].

Region	Total land area 10^6 ha	Forest area 1990		Rate of change 1981–1990	
		Total 10^6 ha	% of land area	10^6 ha/y	% y
Total tropics	4778.3	1756.3	37	−15.4	−0.8
Africa	2236.1	527.6	24	−4.1	−0.7
Asia	8922.1	310.6	3.5	−3.9	−1.1
Latin America	1650.1	918.1	56	−7.4	−0.7
C. America/Mexico	239.6	68.1	28	−1.1	−1.4
Caribbean	69.0	47.1	68	−0.1	−0.3
South America	1341.6	802.9	60	−6.2	−0.7

estation during the decade 1980–1990 based on the World Forest Inventory carried out by the UN Food and Agriculture Organization [9].

In table 1(a) the data are presented for the main ecological zones [43], and in table 1(b) by regions [8]. As can be seen in table 1(b) the percentage change of the tropical forest area over this decade is about the same (∼7%) for Africa and Latin America, while it is higher in Asia (11%).

Although this FAO inventory of the world's forests represents a very comprehensive assessment, it must still be treated with caution. The estimates of the forest cover area and the rate of deforestation cannot be considered accurate. Some of the uncertainties are caused by differences in measurement technology, data limitations and many technical difficulties in estimating land cover. As expressed by Downton [6], the FAO inventory cannot be used to make comparisons of deforestation over time because of changes in data methodology that underlie the different inventories.

However, it can be expected that satellites with improved sensing capabilities may contribute substantially in developing more reliable inventories of the world's forests.

3. Use of forest land for agriculture

It is well known that in many regions soils of the tropical forests are not suitable for agriculture. Thus, the yield of the land gained from removal of forest is declining rapidly, and pest problems increase. Eventually, this will force the farmers to abandon the land, and move to new areas. In this way, due to the pressing need for increasing food production, and lack of other land available, extensive areas of forest are each year being converted to agricultural land.

Table 2
A continuum for shifting cultivation. Source: Dufour [7].

Stage	Time period	Crop
Newly planted field	0–3 months	None
New field	3–9 months	Fast-growing annual crops
Mature field	3/4–2 years	Fast-growing annual and perennial crops
Traditional field	1–5 years	Slower-growing perennial crops
Traditional fruit field	4–6 years	Slower-growing fruits and perennials
Orchard fallow	6–12 years	Fruit trees, smaller cultivars and natural vegetation
Forest fallow	12–30 years	Few economically useful plants
Old fallow	30+ years	Return to natural forest

However, little reliable information is available describing how this land is used for various types of agricultural production, such as "shifting" agriculture (cropping), "shifting" grazing, sedentary agriculture, cattle ranching and horticulture tree crops [14]. Traditionally "shifting" agriculture consists basically of three stages: conversion, cropping and fallow. It is much more sustainable than "the shiftless" agriculture when the farmer continues to crop until declining yields and increased pest problems force him to move to a new area.

An illustration of the "shifting" agriculture method is shown in table 2, indicating the lengths of the different stages and choice of crops, based on shifting agriculture practiced by Amerindians in the Amazonas. The periods of crop growing are considerably shorter than the periods of fallow. Because the degradation of the soil is much faster during the cropping stages than the soil regeneration during the fallow stages, the environmental potential for agriculture cannot be maintained even in this case.

Siiriäinen [42] studying environmental trends in sub-Saharan Africa illustrates schematically how the productivity of the land changes with time following the removal of forest in a given area applying three different types of land management (figure 1).

In the first case (curve (a)) short cropping periods are followed by considerably longer fallow periods. However, due to the comparatively fast degradation of the soil during the cropping periods, the productivity of the land is reduced successively until the productivity has reached a threshold value below which regeneration processes can no longer operate.

The second case (curve (b)) represents the "shiftless" type of agriculture. In this case the threshold level is reached considerably faster. In the third case (curve (c)) the cropping stage is followed by an extended fallow pe-

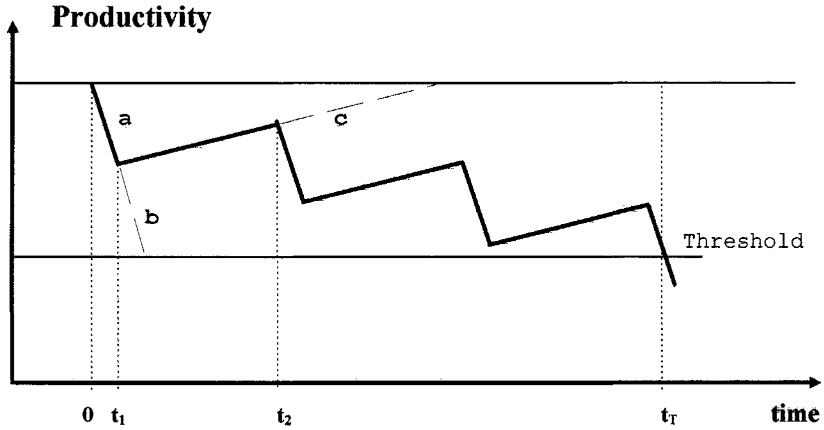

Figure 1. Schematic illustration of the decline of productivity applying different types of agriculture following the removal of forest for a given area. The thick solid line (a) represents the change of productivity of the deforested land during the cropping period (0 to t_1) and the subsequent fallow period (t_1 to t_2). Following repetitions of these periods, the productivity will eventually (t_T) fall below a threshold value. The dashed lines indicate the change of the productivity with time for the cases of (b) the non-sustainable "shiftless" agriculture, with no fallow period and (c) the traditional sustainable "shifting" agriculture with a short cropping period followed by an extended fallow period allowing time for forest regeneration. Source:[42].

riod during which the forest returns, although with great difficulty and much degraded in biological richness [14].

The least sustainable agricultural alternative is the use of deforested land for cattle production [11–13]. According to WRI [54] at least 20% of the Amazon rangeland have been abandoned.

A more optimistic view on this issue is taken by Faminow [8]. Based on studies in Brazil he believes the agricultural development in the Amazon should not be judged too harshly, and he does not exclude the existence of a potential for sustainable cattle production in the Amazon region.

4. Consequences of using forest land for food production

Undoubtedly, the gain of cropland and pasture land through deforestation directly increases food production. However, both the clearing of the forest land and its utilization for pasture and cropping may also initiate processes which can affect food production in a positive or negative way. It cannot a priori be excluded that their combined effect gradually may offset the enhancement of the food production achieved by the gain of cropland.

Figure 2 illustrates schematically (in a very simplified way) the various types of interactions and feedback processes that can play a role in expansion of agricultural land at the expense of forests. We are thus concerned with the following cause-effect processes:

4.1. Direct effects

Apart from the gain of agricultural land, clearing of forest land has a number of other consequences, for example:

Increased atmospheric concentration of carbon dioxide. The emission of carbon dioxide caused by deforestation on a regional scale has only a very minor effect on its atmospheric concentration. However, taking into account the total tropical deforestation, its contribution is of significance. The value (averaged over the years 1980–89) of the emission of carbon dioxide caused by changes in tropical land use is estimated to be 1.6 ± 1.0 Gigaton carbon per year, and the total anthropogenic emission to be 7.1 ± 1.1 Gigaton carbon per year [19].

Table 3
Characteristic albedo values for natural surfaces in lower latitudes (less than 40°). Source: Carson [4].

Surface	Albedo
Tropical rain forest	0.07
Deciduous forest	0.07
Coniferous forest	0.07
Fields, grasslands and steppes	0.10
Dry savannahs and semi-deserts	0.20
Deserts	0.30

Changes of land-surface characteristics. Removal of forest results in a less dark colour of the Earth's surface implying an enhancement of the reflection of the incident solar radiation, i.e., a higher value of the albedo (see table 3). This implies a reduction of the surface air temperature and a less warm soil.

Removal of forest also reduces land-surface roughness implying less surface friction and thereby influencing the atmospheric circulation in the boundary layer.

4.2. Secondary effects

As consequences of the direct impacts of deforestation the following effects may ensue:

4.2.1. Climatic change

The increase of the atmospheric carbon dioxide concentration will contribute to a global climatic change implying

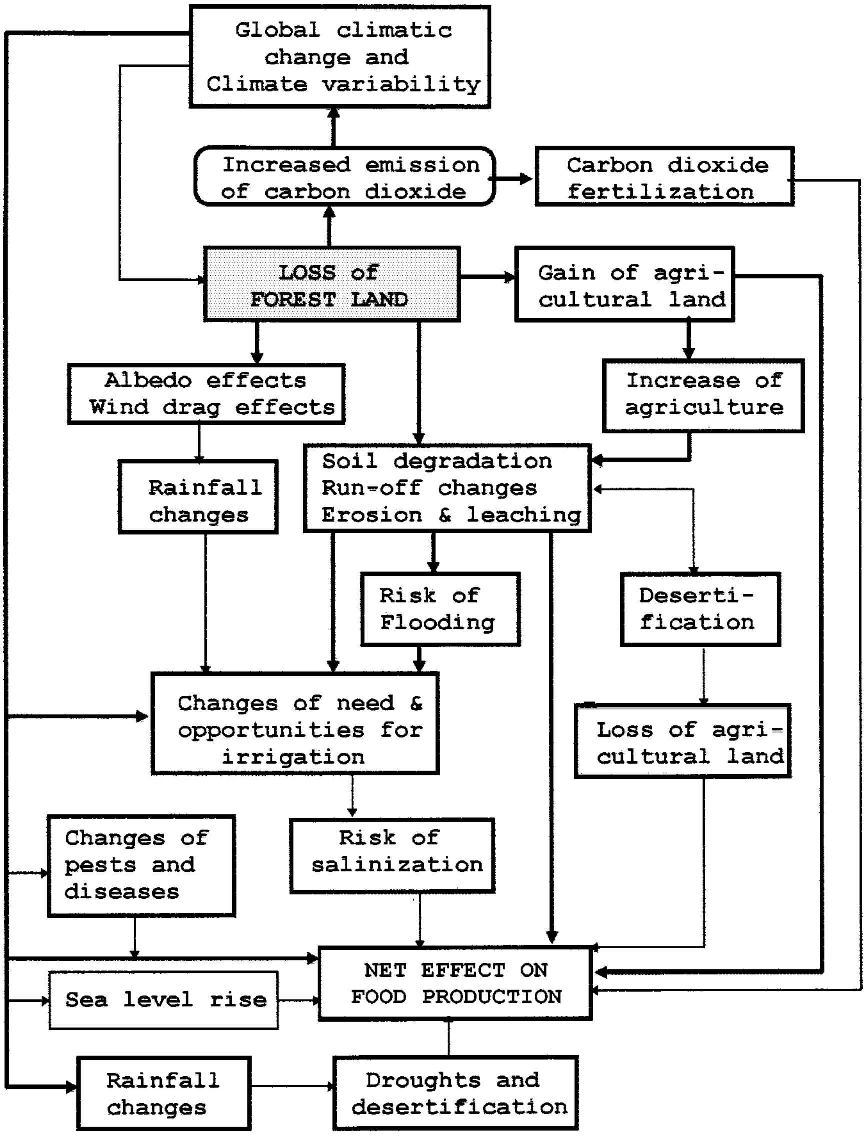

Figure 2. A schematic diagramme indicating some of the many processes that come into play following removal of forest in order to gain land for agricultural production. The effects of management and new technologies are not included. For a more detailed identification of the processes having an impact on the surface temperature and precipitation, reference is made to studies by Zhang et al. [59].

a gradual global warming and a change of the large-scale precipitation pattern, which in turn will have an impact on agricultural production (see table 4). It may also imply an increased climate variability. As an approximate estimation of this enhancement of the greenhouse effect we assume:

- That the present rate of deforestation in the tropics is not likely to decrease significantly in the near future. Actually, there exist concrete arguments for expecting that the rate may even increase before it eventually is bound to drop [10].
- That the rate of emission caused by deforestation in the tropics corresponds to about one fifth of the total anthropogenic emission of carbon dioxide.
- That the radiative forcing of the carbon dioxide is about 56% of the total radiative forcing taking into account all human induced greenhouse gases [41].

Thus, the emission of carbon dioxide caused by deforestation in the tropics is at present responsible for about 10% of the greenhouse gas induced global warming.

It should be emphasized here that according to recent studies [15] the forces that drive long-term climatic change cannot be considered to be known with accuracy sufficient to define future climatic change. Although we know quite well the forcing caused by the increasing atmospheric concentration of greenhouse gases, there are other anthropogenic forcings that are poorly measured, especially changes of atmospheric aerosols, clouds and land-use patterns that tend to offset greenhouse warming.

4.2.2. Carbon dioxide "fertilization" effect

Numerous controlled experiments with optimum environmental conditions have demonstrated a significant improvement in yield for C_3 plants (for example wheat, rice,

Table 4
Change in cereals production in 2060 using three general circulation models (GCMs) for simulation of a greenhouse gas induced climatic change. The changes are expressed in per cent from a base estimated for 2060 without climatic change. Sources: Rosenzweig and Parry [40], and Reilly [36].

Region	GISS[a]	GFDL[b]	UKMO[c]
World total			
Climate effects only	−10.9	−12.1	−19.6
Plus physiological effect of CO_2	−1.2	−2.8	−7.6
Plus adaptation level 1[d]	0.0	−1.6	−5.2
Plus adaptation level 2[e]	1.1	−0.1	−2.4
Developed countries			
Climate effects only	−3.9	−10.1	−23.9
Plus physiological effect of CO_2	11.3	5.2	−3.6
Plus adaptation level 1[d]	14.2	7.9	3.8
Plus adaptation level 2[e]	11.0	3.0	1.8
Developing countries			
Climate effects only	−16.2	−13.7	−16.3
Plus physiological effect of CO_2	−11.0	−9.2	−10.9
Plus adaptation level 1[d]	−11.2	−9.2	−12.5
Plus adaptation level 2[e]	−6.6	−5.6	−5.8

[a] GISS – Goddard Institute for Space Studies.
[b] GFDL – Geophysical Fluid Dynamics Laboratory.
[c] UKMO – United Kingdom Meteorological Office.
[d] Level 1 adaptation included changes in crop variety but not the crop, the planting date less than 1 month, and the amount of water applied for areas already irrigated.
[e] Level 2 adaptation additionally included changes in the type of crop grown, changes in fertilizer use, changes in the planting date of more than 1 month; and extension of irrigation to previously unirrigated areas.

soybean and some weeds) with an increased atmospheric concentration of carbon dioxide, while the yield for C_4 plants (for example maize, millet, sorghum and many of the major weeds) exhibit relatively little effect (see for example: Wolfe and Erickson [53] and Melillo et al. [30]).

However, results of field experiments indicate that the benefits of carbon dioxide enrichment are seldom, if ever, maintained when plants grow in a field situation. It should also be pointed out that predictions of growth of biomass due to CO_2 enrichment are impossible unless responses of other growth determinants are known [2,23]. According to Melillo et al. [30] there have been no comparable field experiments of forests.

Given the assumed rate of deforestation, we obtain 20% as an approximate value for the percentage contribution of the deforestation to the carbon dioxide "fertilization" effect.

4.2.3. *Effects of changes of land-surface*

Using general circulation models (GCMs), numerical experiments have been carried out to study the effects of (a) changes of the surface albedo, (b) reduction of waterholding capacity causing decreased interception of precipitation and reduced transpiration and (c) reduced surface friction following deforestation (see, for example, Wan Azli et al. [52] and Melillo et al. [30]).

Such studies indicate that extensive deforestation can have an impact not only on local and regional climate, but also produce global-scale impacts [59].

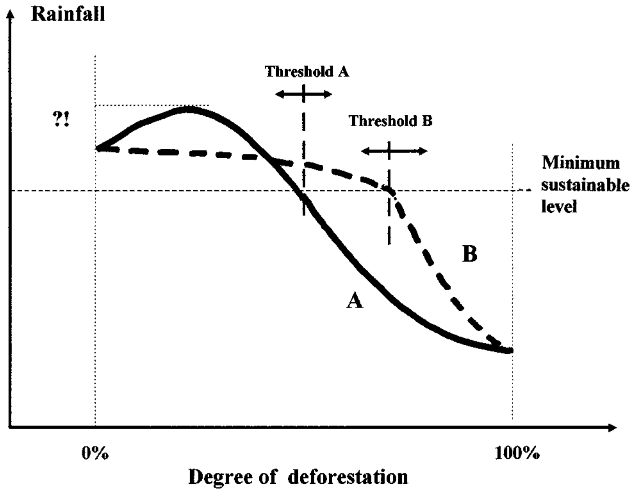

Figure 3. Two versions of the expected decrease of rainfall for an increased degree of deforestation. The dashed curve (B) represents results obtained with general circulation models. The solid curve (A) shows results of recent mesoscale modelling studies which suggest that partial deforestation may locally increase rainfall. The figure also indicates that at some level of deforestation (thresholds A and B), the moisture content of the atmosphere is likely to decrease to a point that rainfall will also decrease. Source: IGBP [16].

Experiments carried out with a complete clearing of the Amazonas's and replacement by pasture indicate that this would lead to temperature increases of up to 2 °C. This in turn will cause rainfall decreases between 6 and 20%. Recent modelling experiments suggest that partial deforestation may locally increase rainfall in comparison with land completely forested (see figure 3). However, at some level of deforestation the moisture content of the atmosphere is likely to decrease to a point that rainfall will decrease [16].

4.2.4. *Soil degradation and loss*

Deforestation implies that the soil becomes more vulnerable to excess rainfall and this can lead to increased risks of run-off changes, erosion and flooding. As pointed out by Norse et al. [33], soil degradation, especially soil erosion, is the most serious consequence of land-use change at present (see table 5).

It should also be recognized that the really irreversible damage following removal of forest occurs when the topsoil is stripped away to a degree that regrowth cannot occur rapidly enough to provide cover. A vicious circle is then initiated, leading to progressively worse degradation [47].

An approximate estimation of the loss of soil can be obtained by using the so-called universal soil loss equation (USLE) based on data from eastern USA [51]:

$$\text{Soil loss} = RKLSCP,$$

where R is an empirically determined expression for rainfall erosivity determined from rainfall amounts and intensity, K a measure of soil erodibility, L and S the length and slope of the area, C the vegetative cover and P is a measure of surface conditions and management. How the

Table 5
Extent of soil degradation classified as moderately to excessively affected (in million ha). Source: ISRIC/UNEP [20].

Region	Water erosion	Wind erosion	Chemical degrad.	Physical degrad.	Total
Africa	170	98	36	17	321
Asia	315	90	41	6	452
South America	77	16	44	1	138
North and Central America	90	37	7	5	139
Europe	93	39	18	8	158
Australasia	3	–	1	2	6
Total	748	280	147	39	1214
Major causes (%)					
Deforestation	43	8	26	2	384
Overgrazing	29	60	6	16	398
Mismanagement of arable land	24	16	58	80	339
Other	4	16	10	2	93
Total	100	100	100	100	1214

tropical soils are affected by these factors has been studied by Lavelle [24] and Renard et al. [37].

However, as emphasized by Rapp [35], despite the extensive data base used in deriving this equation, the correlation between soil loss and the different variables are not universal. He therefore warns against simple acceptance of USLE predictions for regions with characteristics that differ from those of the region for which it was developed.

According to Swaminathan [45], in the tropics the soil erosion exceeds its floor renewal rate by ten to twenty times. Studies in Ghana show that elimination of savanna forests raised soil erosion from less than a ton to more than 100 tons/ha $year^{-1}$ [38].

Less vegetation cover also causes increased leaching and thereby loss of nutrients (phosphorus, potassium, nitrogen, calcium, magnesium, etc.). According to Pettersson [34] the loss of mineral nutrients from agricultural soils is about ten times higher than from forests and grasslands. Such losses of nutrients represent the main limitation for agricultural production using land gained from forests. A detailed list of such soil constraints for crop production in the Amazon Basin has been presented by Nicholaides et al. [32].

4.3. Third and higher order effects

Consider the following indirect impacts:

4.3.1. Change of extent of tropical forests

A change of the climate and an increased atmospheric concentration of carbon dioxide can be expected to affect the extent of tropical forests, and thereby impact on deforestation rates.

Studies carried out with the aid of Global Vegetation Models (GVMs) indicate that a climatic change caused by a doubling of the carbon dioxide concentration would result in a change of the area of the tropical broadleaf area of 70–108%. By also assessing effects of carbon dioxide "fertilization" the change would be 120–138% [31].

Kirschbaum et al. [22] state with a high degree of confidence that tropical forests are likely to be more affected by change in land use than by climatic change as long as deforestation continues at its current high rate. Solomon et al. [44] provide the logic and calculations to support this opinion.

4.3.2. Change of extent of irrigated land

At the same time as demand for irrigation increases, the present shortage of water could become even more pronounced in some regions, for example due to the risk of an increased frequency of droughts. According to Reilly [36], changes in potential irrigation water supply due to climatic change have not generally been integrated into agricultural impact studies, with few exceptions [39].

4.3.3. The risk of salinization

The need for expansion of irrigation to increase food production is often accompanied by an increasing risk of salinization. However, the main direct cause of salinization is usually a consequence of improper irrigation techniques causing poor drainage, and/or inadequate maintenance and inefficient management [10].

According to a report presented by IIASA-ISSS-UNEP [17], more than 50% of the land irrigated at present has been severely damaged by salinization–alkalization as well as by waterlogging. This report also points out that this phenomenon is known from ancient times, for example the deterioration of the Mesopotamian Plain which was transformed from fertile land to desert.

4.3.4. Change of extent of deserts

According to the United Nations Convention to Combat Desertification [5] the problem of land degradation in dryland regions has continued to worsen during the last two decades. The rate of desertification could increase from a possible increase of climate variability and continued mismanagement of drylands. An expansion of deserts implies a modification of the radiation balance and this in turn can accelerate the desertification, i.e., a positive feed-back process.

4.3.5. Impacts of pests, diseases and weeds

Under current climate conditions the losses of the world's four most important crops (maize, rice wheat and potatoes) have been estimated to be 15% by pests, 14% by diseases and 13% by weeds [49].

As a result of a change of climate, implying changes of temperature, precipitation, humidity, radiation and dew, the conditions for survival, growth, and spread of agents causing plant pests and diseases will change [36].

No doubt it can be expected that, as a consequence of a climatic change, the net negative effect of these stresses on food production will be even more severe. However, it has to be recognized that the calculation of the resulting loss of food production is very complex, and must be considered uncertain [26,47]. At the same time it should be pointed out that linked pest-crop models under global change represent an exciting new way to quantify the effects of pests on crop development and yield [46].

4.3.6. Rise of sea-level

The greenhouse gas induced global warming, together with local changes in land elevation could result in a loss of agricultural land in low-lying coastal zones and small islands. This effect is not likely to be too severe within the next few decades.

However, during the second half of the 21st century it is likely that this effect will be important. For example, at that time, the expected rise of the sea level may adversely affect the 7000 km coastal belt of India, comprising 20 million ha [3].

5. Estimation of the impacts of the influencing processes

It can be stated it is possible to estimate fairly accurately the increase of agricultural production that can be immediately achieved following conversion of forest land to agricultural land for cropping and cattle ranching.

It can also be stated we know that this gain is bound to decline due to the many physical, chemical and biological processes induced by the clearing of the forests, and also due to application of more or less unsuitable methods of agricultural practices. At the same time it can be expected that improved management and new technologies can to some extent offset such losses.

However, it has to be recognized there exists limitations in quantifying realistically the impacts of the many factors having an impact on the food production.

5.1. Constraints in quantifying the influencing processes

Basically we are concerned with three types of constraints in estimating the influence of the many processes on the food production following the removal of forests:

- The knowledge about many of the processes having an influence on the agricultural production, and how they interact, are poorly known (see table 6, first column).
- Difficulties abound in quantifying the individual influencing processes due to insufficiency of reliable observational data (see table 6, second column).
- For many of the identified processes initiated by forest clearing too little is known about their influence on the food production (see table 6, third column).

We emphasize here that the information provided in table 6 is based on subjective judgement and must be considered to be very approximate. However, the judgement is based on logic and numbers in the literature cited in previous section.

Table 6

Estimates of: (i) the level of understanding of the processes caused by conversion of tropical forests to agricultural land, (ii) the level of data availability for their determination, (iii) the degree of their impact on food production, and (iv) the accuracy with which direct or indirect impacts may be estimated.

Processes	Level of understanding	Data availability	Impact on food production	
			Level	Accuracy
Increase of CO_2 and other greenhouse gases	good	suffic.		
• Increased photosynthesis	low	poor	medium (+/-)	poor
• Change of global climate and climate variability	low	fair	major (+/-)	low
– their impacts on water availability	low	poor	major (+/-)	low
– their impacts on pests and diseases	low	poor	medium (+/-)	low
– their impacts on global sea level	fair	suffic.	minor (-)	medium
– their impacts on frequency of droughts and desertification	low	poor	medium (-)	low
Soil degradation				
– Water and wind erosion	fair	medium	major (-)	medium
– Physical and chemical degradation	low	poor	major (-)	low
– Risk of desertification	low	poor	medium (-)	low
Changes of surface albedo and wind drag	fair	poor		
– its impact on temperature and rainfall	low	poor	minor (+/-)	low
Mismanagement of agricultural land	fair	medium	medium (-)	medium

5.2. Accuracy of the estimated impacts

As a consequence of the constraints identified above the impacts of many of the processes having an impact on food production cannot be determined with a high degree of confidence (see table 6, fourth column). The various influencing processes will be grouped in the following way:

(a) Processes that have a major influence and can be determined with a high degree of confidence.

(b) Processes that have a major influence but can only be determined with limited confidence.

(c) Processes that may have a significant (medium) influence, but can only be determined with moderate or low confidence.

(d) Processes that may have a medium influence, but cannot be expected to be evaluated with confidence.

(e) Processes that can be assumed to only have a minor influence, and, therefore, can safely be disregarded.

As can be seen in table 6, it is judged that only one of the identified processes can be expected to be evaluated with a comparatively high degree of accuracy, namely the increase of the atmospheric concentration of carbon dioxide caused by the removal of forest.

We may also conclude with a good deal of confidence it is not likely it is possible to simulate and evaluate with good accuracy any one of the processes that have a major influence on the food production as a consequence of the conversion of forest land to agricultural land. Actually, in some cases it is not even possible to judge whether the impacts will be negative or positive.

6. Predicting the net increase of agricultural production

The question of selecting the method for estimating the net increase of agricultural production achieved through removal of forest is not an obvious one.

6.1. Selection of prediction method

A logical approach would undoubtedly be to make use of a comprehensive model that takes into account all the processes that can be judged to have an influence. As an example of the existence of this kind of models can be mentioned the so-called IMAGE model (integrated model to assess the greenhouse effect) as described by Alcamo et al. [1]. It is a model that consists of fully linked models of the relevant sub-systems. Undoubtedly, such models can be powerful tools in providing an insight into the relative importance of the different linkages and feedbacks in the society–biosphere–climate system. They have an important role both for researchers and policymakers.

However, for our purpose, to estimate the net gain of food production through conversion of forest land to agricultural land, it cannot be considered feasible to design a model of this type that is capable of providing realistic results. The main conditions for making this possible:

(a) a fair knowledge of the numerous processes which are at play;

(b) sufficiently complete data for quantifying these processes;

are far from fulfilled. As has been pointed out by Lorenz [27], *it is not always true that the more equations you add to describe a system, the more accurate will be the eventual forecast*.

For these reasons we have adopted an heuristic method to estimate the change with time of the agricultural production. The main source of information made use of are available estimates of the decline of productivity of the land gained through deforestation and the length of time it can be used for agricultural production. Certainly, also this method has obvious limitations. Also here we are confronted with the problem of insufficient data. Nevertheless, it is considered to provide a more useful result (not least because we have greater control over uncertainties).

6.2. Basic assumptions

For the sake of simplification of the computation of the net gain of agricultural production we will assume we know:

- The extent of the present annual removal of forest in the tropics (see table 1). By introducing the notation $\Delta F(t)$ for the area deforested at time t, and that $t = 0$ represents the present time, we can write:

$$\Delta F(0) = 15.4 \times 10^6 \text{ ha per year.}$$

  As has been pointed out above, it is not considered likely that the present rate of deforestation in the tropics will decrease in the near future [10].

- The fractions (μ_i) of the annual removal of forest that will be used for cropping ($i = 1$) and for pasture ($i = 2$). Using these notations we have the following expression for the gain of land for agriculture at year t (to be harvested at time $t + 1$):

$$\Delta A(t) = \Delta A_1(t) + \Delta A_2(t) = (\mu_1 + \mu_2)\Delta F(t) \text{ ha.} \quad (1)$$

  According to Kendall and Pimentel [21] as much as 70–80% of the ongoing deforestation, both tropical and temperate, is associated with the spread of agriculture. Similar figures for expansion of the agriculture frontier have been reported by UNEP [48]. Based on this information we can with some confidence use the value 0.7 for the sum of μ_1 and μ_2.
  However, little is known about the portions of the land gained is used for cropping and for pasture [14]. Attempts to assign realistic values of the two parameters μ_1 and μ_2 by making use of information about the changes of the extent of forests, cropland and permanent pasture during the last two decades [54–58] underscores the validity of this statement. The values chosen for these two parameters: $\mu_1 = \mu_2 = 0.35$ must therefore be considered to be very uncertain.
  Accepting this choice we obtain the following approximate values for the land gained for agriculture at time $t = 0$:

$$\Delta A_1(0) = \Delta A_2(0) = 0.35 \times 15.4 \text{ Mha} = 5.4 \text{ Mha.}$$

- The productivity of the land gained, and the rate at which it is being degraded with time. We assume it can be written in the following form:

$$Y_i(t) = Y_i(0)\nu_\iota^t = k_i Y_i^* \nu_\iota^t \text{ ton/ha} \quad \text{for } t \leqslant \tau_i \quad (2a)$$
$$Y_i(t) = 0 \quad \text{for } t > \tau_i, \quad (2b)$$

  where $Y_i(t)$ is the productivity of the land gained year $t - 1$, and harvested year t.
  Y_i^* is the average productivity of agricultural land in the tropics. The value chosen for Y_1^* is 3.56 ton/ha. It is obtained from values of the supply of cereals and other crops, and the cultivated area in less developed countries published by Leach [25]. The value of the

supply includes human food, animal feed, other uses and losses. The cultivated area is defined as the area of arable land including permanent crops. k_i is a relative measure of how good the quality of the land gained is. Although some areas of tropical forests have soils with good characteristics, the soils in many regions are not sufficiently fertile for sustained agricultural production without application of fertilizers [8]. Due to limited information, the values chosen for this parameter: $k_1 = k_2 = 0.8$, must be considered uncertain. ν_i is a measure of to what extent the productivity of the land gained changes with time, and τ_i is the period of time beyond which the productivity has decreased to an unacceptable low level and has to be abandoned (see figure 4).

There exists considerable uncertainty about how long the deforested land is being used as cropland or pasture. For example, farmers try to convert cleared forest land into alternative uses after crop productivity falls, often after as short time as 1–2 years [8]. Given these limitations, assuming that “shifting” cultivation is practiced, and taking into account the information given in table 2, the following values have been chosen:

$$\nu_1 = \nu_2 = 0.9,$$
$$\tau_1 = \tau_2 = 5 \text{ years}.$$

It is thus assumed that the annual decrease of the productivity is 10%. This implies that in 5 years the productivity has been reduced to $\nu_i^5 Y_i(0) = 0.59 Y_i(0)$, i.e., a reduction by about 40%.

For $k_1 = 0.8$ and $Y_1^* = 3.56$ ton/ha, this would give the following average yield of cropland after 5 years:

$$Y_1(5) = 0.590 \times 0.8 \times 3.56 = 1.68 \text{ ton/ha}.$$

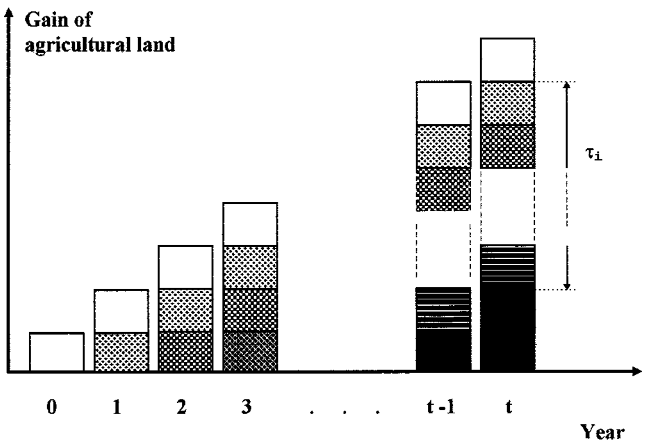

Figure 4. Schematic illustration of the gain and degradation of agricultural land through conversion of forest land. The white areas represent the annual increase of land, and the different shadings indicate the successive decline of the quality with time of the land gained. The parameter τ_i represents the time at which the productivity of the land gained for cropping ($i = 1$), and for cattle ranching ($i = 2$), has declined to an unacceptable low level.

6.3. Expected net gain of agricultural production

We introduce the following notation for the agricultural production in year t using the land gained during the preceding $t-1$ years, and taking into account that the land gained cannot be used for a longer period than τ_i years (cf. figure 4):

$$P_i(t) = \sum_{n=1}^{t} \Delta P_i(n) \text{ ton} \quad \text{for } t \leqslant \tau_i. \tag{3a}$$

In this case the terms $\Delta P_i(n)$ represent the production of the land areas gained at: $t = 0, 1, 2, \ldots, t-1$.

$$P_i(t) = \sum_{n=t-\tau_i+1}^{t} \Delta P_i(n) \text{ ton} \quad \text{for } t > \tau_i. \tag{3b}$$

In this case the terms $\Delta P_i(n)$ represent the production of the land areas gained during the preceding τ_i years: $t = t-\tau_i, t-\tau_i+1, \ldots, t-1$.

Taking into account the change of the yield from year to year, we can write the equations (3a,b) in the following form:

$$\begin{aligned} P_i(t) &= \Delta A_i(0) Y_i(t) + \Delta A_i(1) Y_i(t-1) + \cdots \\ &\quad + \Delta A_i(t-1) Y_i(1) \\ &= \sum_{n=0}^{t-1} \Delta A_i(n) Y_i(t-n) \text{ ton} \quad \text{for } t \leqslant \tau_i, \end{aligned} \tag{4a}$$

$$\begin{aligned} P_i(t) &= \Delta A_i(t-\tau_\iota) Y_i(\tau_\iota) + \Delta A_i(t-\tau_\iota+1) \\ &\quad \times Y_i(\tau_i - 1) + \cdots + \Delta A_i(t-1) Y_i(1) \\ &= \sum_{n=t-\tau_i}^{t-1} \Delta A_\iota(n) Y_i(t-n) \text{ ton} \quad \text{for } t > \tau_i. \end{aligned} \tag{4b}$$

By making use of these expressions for the net gain of agricultural production we will consider two special cases:

Case 1. Constant annual extent of deforestation and gain of agricultural land

To calculate the agricultural production $P_1(t)$ we introduce the following notation for the constant annual gain of agricultural land:

$$\Delta A_i(t) = \Delta A_i(0) = a_i \text{ ha} \quad \text{for } t = 0, 1, 2, \ldots \tag{5}$$

By making use of (2), the expressions (4) for the total agricultural production of the land gained from forest after t years can be written:

$$\begin{aligned} P_i(t) &= a_i Y_i(0) \left[\nu_i^t + \nu_i^{t-1} + \cdots + \nu_i \right] \\ &= a_i Y_i(0) \nu_i \frac{1-\nu_i^t}{1-\nu_i} \text{ ton} \quad \text{for } t \leqslant \tau_i, \end{aligned} \tag{6a}$$

$$\begin{aligned} P_i(t) &= a_i Y_i(0) \left[\nu_i^{\tau_i} + \nu_i^{\tau_i - 1} + \cdots + \nu_i \right] \\ &= a_i Y_i(0) \nu_i \frac{1-\nu_i^{\tau_i}}{1-\nu_i} \text{ ton} \quad \text{for } t > \tau_i. \end{aligned} \tag{6b}$$

We can thus conclude that in this case during the first τ_i years the annual gain of the agricultural production is increasing, and after τ_i years the total gain of the production

Table 7
Calculated increase of agricultural production of cropland for case 1, that is assuming a constant annual gain of agricultural land $\Delta A_i(t) = \Delta A_i(0) = a_i$. The productivity of the land gained is assumed to decrease annually by 10% ($\nu_i = 0.9$), and the maximum length of time the area gained can be used for cropping is five years ($\tau_i = 5$).

Harvest year t	Land deforested after t years	Land harvested after t years	Total production of land harvested after t years	
0	a_i	0	–	
1	$2a_i$	a_i	$a_i\nu_iY_i(0)$	$= 0.9a_iY_i(0)$
2	$3a_i$	$2a_i$	$a_i\nu_i(1+\nu_i)Y_i(0)$	$= 1.71a_iY_i(0)$
3	$4a_i$	$3a_i$	$a_i\nu_i(1+\nu_i+\nu_i^2)Y_i(0)$	$= 2.44a_iY_i(0)$
4	$5a_i$	$4a_i$	$a_i\nu_i(1+\nu_i+\nu_i^2+\nu_i^3)Y_i(0)$	$= 3.10a_iY_i(0)$
5	$6a_i$	$5a_i$	$a_i\nu_i(1+\nu_i+\nu_i^2+\nu_i^3+\nu_i^4)Y_i(0)$	$= 3.69a_iY_i(0)$
6	$7a_i$	$5a_i$	$a_i\nu_i(1+\nu_i+\nu_i^2+\nu_i^3+\nu_i^4)Y_i(0)$	$= 3.69a_iY_i(0)$
7	$8a_i$	$5a_i$	$a_i\nu_i(1+\nu_i+\nu_i^2+\nu_i^3+\nu_i^4)Y_i(0)$	$= 3.69a_iY_i(0)$
...	...	...	...	

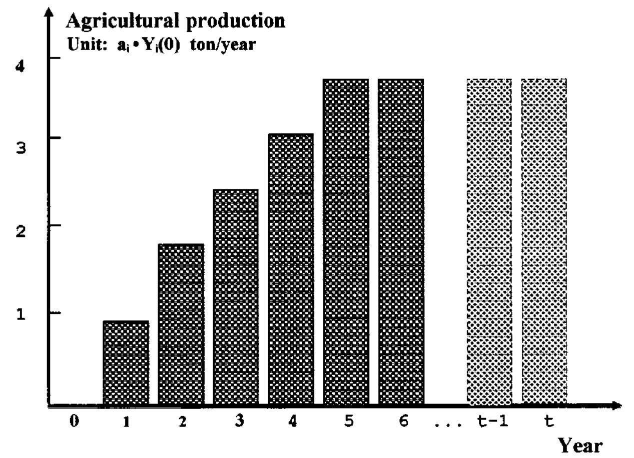

Figure 5. Schematic illustration of the change with time of agricultural production achieved by a constant annual gain of agricultural land by removal of tropical forests (case 1).

remains constant despite a continuing annual conversion of forest land to agricultural land.

This is presented in table 7 and illustrated graphically in figure 5 for $\nu_i = 0.9$ and $\tau_i = 5$ years.

Using this result, we can also derive an estimate of the number of people who can be fed by this annual gain of agricultural land. For this purpose we limit ourselves to consider the need for crop production ($i = 1$). At the first harvest ($t = 1$) it can be written:

$$\Delta P_1(1) = \Delta A_1(0)Y_1(1) = \mu_1 \Delta F(0) k_1 \nu_1 Y_1^* \text{ ton.}$$

Using the assumed values of the present rate of tropical deforestation and the values given to the parameters μ_1, k_1, ν_1 and Y_1^* we obtain:

$$\Delta P_1(1) = 0.35 \times 15.4 \times 10^6 \times 0.8 \times 0.9 \times 3.56 \times 10^6 \text{ ton} = 13.8 \text{ million ton.}$$

Using the values of the supply of crops in the less developed countries (2810.4 million ton), and the number of people in these countries (3943.2 million) we obtain the number of additional people who can be fed by the first year's increased agricultural production

$$\Delta n = \frac{3943.2 \times 10^6}{2810.4 \times 10^6} \times 13.8 \text{ million} = 19.4 \text{ million.}$$

This number represents about one quarter of the annual increase of population in the less developed countries.

We can also conclude that each year the number of additional people who can be fed by the gain of agricultural land is each year decreasing by 10%, and that after 5 years, no additional people can be fed despite the continued gain of cropland.

Case 2. Sufficient annual conversion of forest land to agricultural land to permit a constant annual increase of agricultural production

As in Case 1, we assume the productivity of the land gained is annually decreasing and that it has to be abandoned when its productivity has fallen to an unacceptable low level. This implies that to compensate for the loss of production due to the degradation and abandoning of the agricultural land, it will be necessary to increase the annual expansion of agricultural land $\Delta A_1(t)$ ha each year.

In order to calculate this required increase of land we specify that the constant annual increase of production to be:

$$\Delta P_i(t) = \Delta p_i(0) = a_i Y_i(0) \text{ ton} \quad \text{for } t = 0, 1, 2, \ldots$$

Since this annual increase of production in this case can also be written:

$$\Delta P_i(t) = \Delta P_i(1) = \Delta A_i(0)Y_i(1) = \nu_i \Delta A_i(0) Y_i(0) \text{ ton} \quad (7)$$

we can obtain the following expression for the required initial area increase:

$$\Delta A_i(0) = a_i \nu_i^{-1} \text{ ha.} \quad (8)$$

By using this expression, and the assumed decline with time of the productivity of the land gained (2), we can write (4):

$$P_i(t) = \left[a_i\nu_i^{t-1} + \nu_i^{t-1}\Delta A_i(1) + \cdots + \nu_i \Delta A_i(t-1)\right] Y_i(0) \text{ ton} \quad \text{for } t \leqslant \tau_i, \quad (9a)$$

$$P_i(t) = \left[\nu_i^{\tau_i}\Delta A_i(t-\tau) + \nu_i^{\tau_i - 1}\Delta A_i(t-\tau+1) + \cdots + \nu_i \Delta A_i(t-1)\right] Y_i(0) \text{ ton} \quad \text{for } t > \tau_i. \quad (9b)$$

By also making use of the following expression for the total increase of harvested agricultural production:

$$P_i(t) = \sum_{n=1}^{t} \Delta P_i(n) = t a_i Y_i(0) \text{ ton} \quad (10)$$

we can calculate the required annual increase of harvested agricultural land. This is presented in table 8 and shown in figure 6. It clearly demonstrates the need for increasing the annual gain of agricultural land to maintain a constant annual increase of agricultural production.

Table 8

Case 2. Calculated required annual increase of agricultural area in order to ensure a constant annual increase of agricultural production, $\Delta P_i = a_i Y_i(0)$. The productivity of the land gained is assumed to decrease annually by 10% ($\nu_i = 0.9$), and the maximum length of time it can be used is chosen to be five years ($\tau_i = 5$).

Harvest year t	Deforested area at year t $\Delta A_i(t)$			Extent of defore-station	Extent of harvested area	Produc-tion
0	$a_i\nu_i^{-1}$	=	$1.11a_i$	$1.11a_i$	0	0
1	$a_i(2-\nu_i)\nu_i^{-1}$	=	$1.22a_i$	$2.33a_i$	$1.11a_i$	ΔP_i
2	$a_i(3-2\nu_i)\nu_i^{-1}$	=	$1.33a_i$	$3.67a_i$	$2.33a_i$	$2\Delta P_i$
3	$a_i(4-3\nu_i)\nu_i^{-1}$	=	$1.44a_i$	$5.11a_i$	$3.67a_i$	$3\Delta P_i$
4	$a_i(5-4\nu_i)\nu_i^{-1}$	=	$1.56a_i$	$6.67a_i$	$5.11a_i$	$4\Delta P_i$
5	$a_i(6-5\nu+\nu_i^4)\nu_i^{-1}$	=	$2.32a_i$	$8.99a_i$	$6.67a_i$	$5\Delta P_i$
6	$a_i[(7-6\nu)\nu^{-1}+(2-\nu)\nu^4]$	=	$2.50a_i$	$11.49a_i$	$7.87a_i$	$6\Delta P_i$
7	$a_i[(8-7\nu)\nu^{-1}+(3-2\nu)\nu^5]$	=	$2.60a_i$	$14.09a_i$	$9.15a_i$	$7\Delta P_i$
8	$a_i[(9-8\nu)\nu^{-1}+(4-3\nu)\nu^6]$	=	$2.69a_i$	$16.78a_i$	$10.42a_i$	$8\Delta P_i$
...	...			...	...	...

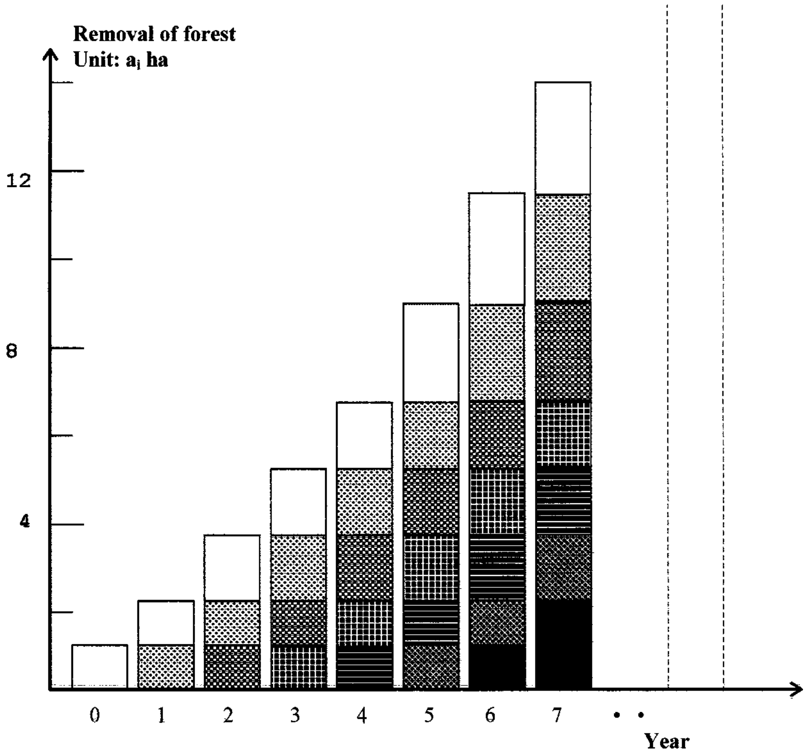

Figure 6. Schematic illustration of the required annual increase of agricultural land in order to ensure a constant annual increase of agricultural production (case 2).

6.4. Sensitivity of the results

In view of the limited data available about the use of forest land to increase agricultural production it is evident that the values selected for the various parameters must be considered very approximate.

For some of these parameters the sensitivity of the results to the values chosen is easy to determine. To this category belong:

$\Delta F(0)$ annual area of deforestation at $t = 0$;
$\mu_{\rm I}$ fractions of deforested area gained for agriculture;
Y^* the average productivity of agricultural land in the tropics;
k expressing the reduced quality of deforested land.

As can be seen from the expressions of food production (or both cases 1 and 2), for a given percentage change of any one of these parameters, it results in a change of the food production by the same percentage.

However, with regard to a change of the following two parameters:

ν_i expressing the decline of productivity of the deforested land,

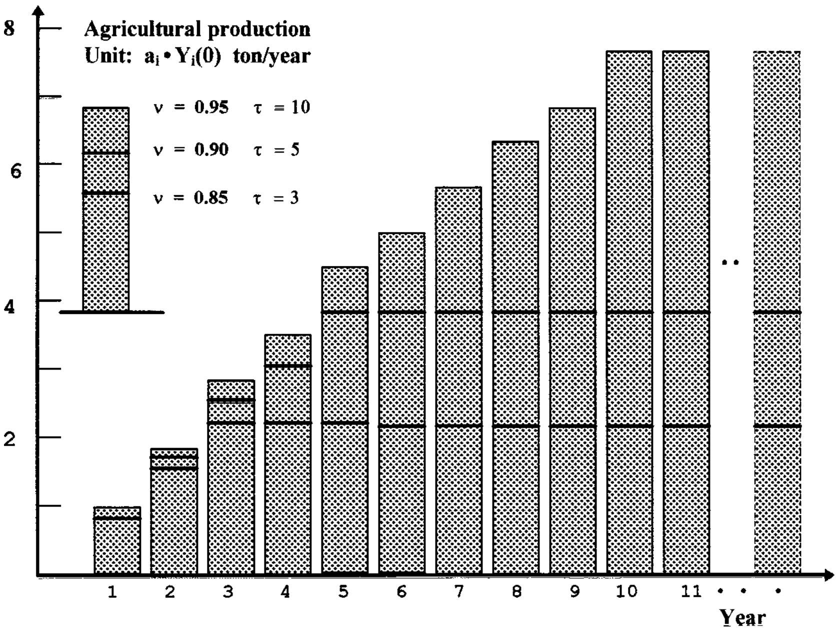

Figure 7. Illustration of the sensitivity of the calculation of the agricultural production for case 1 (i.e., assuming a constant annual gain of agricultural land by removal of tropical forests) to the choice of the parameters ν_i and τ_i. The value of τ_i is chosen so that the land gained for agriculture does not fall below 60% of its initial productivity.

τ_i the period of time the deforested land can be used before the productivity falls below a given low level.

the sensitivity is less straightforward. To illustrate this, we will consider the solution for case 1 for two additional values than $\nu_i = 0.9$ used above. In doing so we will make use of the same acceptable lower limit for the productivity of the deforested land, namely about $0.6Y_i(0)$. This in turn determines the choice of the value for the parameter τ_i as illustrated below:

Case	ν_i	τ_i	$Y(\tau_i)$ (ton/ha)
1(a)	0.95	10	$Y(10) \approx 0.60Y(0)$
1	0.9	5	$Y(5) \approx 0.59Y(0)$
1(b)	0.85	3	$Y(3) \approx 0.61Y(0)$

In figure 7 is shown the variation with time of the agricultural production for case 1, i.e., for a constant annual gain of agricultural land (a_i) for these three pairs of the parameters ν_i and τ_i. It demonstrates clearly the sensitivity of the food production to these parameters.

Although available data do not permit an accurate value for these parameters, it may be judged that the maximum length of time the deforested land can be used for agricultural production is well below 10 years (cf. table 2).

7. Conclusions

Two different approaches have been explored to estimate to what extent it is possible to increase food production by conversion of forest land to agricultural land. The first one represents the possibility of developing a coupled climate-biosphere model capable of taking into account all the processes that can have a significant impact on the food production, including those which are being caused, or modified due to the changing character of the land surface following the forest removal.

Although significant progress have been made in developing such multi-disciplinary, integrated models, it is judged that they are not yet capable of providing reliable estimates of the change of the food production. One reason being that our knowledge about some of the more important processes is still far from satisfactory. Another reason is that sufficiently detailed and reliable data are not available for developing and validating parameterization schemes for simulation of some of the more important processes, and quantifying their impact.

Given this situation, a different approach has been taken, namely the development of a simple, heuristic method. The basic assumption made here is that the net effect of the many processes that are influencing the productivity of the land gained from deforestation can be expressed by a simple function of time.

It is further assumed that the traditional sustainable "shifting" agriculture is practiced. With regard to this assumption it deserves to be pointed out that this does not imply a definite guarantee that the forest eventually will return. It depends on a number of factors. According to IPCC [18] most forest systems will require more than 100 years to return to the level of biomes contained in an undisturbed state. It should also be recognized that "shifting" agriculture is more and more giving way to the non-sustainable "shiftless" type of agriculture [14].

Nevertheless, despite the simplicity of the method used for estimating the future agricultural production that can be achieved by expansion of agricultural land through forest removal, it can be concluded that:

- For any given constant value of the annual conversion of forest land to agricultural land, the food production will not increase after a few years.
- To achieve a constant annual increase of the food production will require that each year the area of forest removal is increased.

Undoubtedly, the calculation of the change of the food production is critically dependent on the assumptions made.

This is particularly true with regard to the value chosen for the decline of the productivity of the land gained, and thereby the length of time this land can be used. However, this does not change the validity of these two conclusions.

As a consequence of the results obtained, and taking into account the expected continued growth of the population in the less developed countries, implying a demand for a substantial annual increase of food production, it can be expected that tropical deforestation will be even more pronounced during the next few decades.

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References

[1] J. Alcamo, E. Kreileman, M. Krol, R. Leemans, J. Bollen, J. van Minnen, M. Schaefer, S. Toet and B. de Vries, Global modelling of environmental change: an overview of IMAGE 2.1, in: *Global Change Scenarios of the 21st Century*, eds. J. Alcamo, R. Leemans and E. Kreileman (Elsevier, Oxford, 1998) pp. 3–94.

[2] F.A. Bazzaz, S.L. Bassow, G.M. Berntson and S.C. Thomas, Elevated CO_2 and terrestrial vegetation: implications for and beyond the global carbon budget, in: *Global Change and Terrestrial Ecosystems*, eds. B. Walker and W. Steffen (Cambridge Univ. Express, Cambridge, 1996) pp. 43–76.

[3] P. Bullock and H. Le Houérou, Land degradation and desertification, in: *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Contribution of Working Group 1I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, eds. R. Watson, M.C. Zinyowera and R.H. Moss (Cambridge Univ. Press, 1996) pp. 171–189.

[4] D.J. Carson, Current parameterizations of land surface processes in atmospheric general circulation models, in: *Land Surface Processes in Atmospheric General Circulation Models*, ed. P.S. Eagleson (Cambridge Univ. Press, 1981) pp. 67–108.

[5] CCD, An introduction to the United Nations Convention to Combat Desertification, The Interim Secretariat for the UN Convention to Combat Desertification, Geneva, Switzerland (1995);
CCD, Down to Earth – a simplified guide to the Convention to Combat Desertification, why it is necessary and what is important and different about it, The Centre for Our Common Future (1995) p. 32.

[6] M.W. Downton, Measuring tropical deforestation: development of the methods, Environmental Conservation 22 (1995) 229–240.

[7] D.L. Dufour, Use of tropical rainforests by native Amazonians, Bioscience 40 (1990) 652–659.

[8] M.D. Faminow, *Cattle, Deforestation and Development in the Amazon* (CAB International, Oxford, 1998) p. 253.

[9] FAO, Global forest resources 1990, Forestry Paper 112, Food and Agriculture Organization of the United Nations, Rome, Italy (1993).

[10] FAO, *World Agriculture: Towards 2010*, An FAO study, ed. N. Alexandratos (Food and Agriculture Organization of the United Nations/Wiley, Chichester, 1995) p. 488.

[11] P.M. Fearnside, Causes of deforestation in the Brazilian Amazon, in: *The Geophysiology of Amazonia: Vegetation and Climatic Interactions*, ed. R.E. Dickinson (Wiley, New York, 1987) pp. 637–653.

[12] P.M. Fearnside, Forest management in Amazonia: the need for new criteria in evaluating development options, Forest Ecology and Management 27 (April 1989) 61–79;
P.M. Fearnside, Deforestation and agricultural development in Brazilian Amazonia, Interciencia 14 (November/December 1989) pp. 291–297.

[13] R.J.A. Goodland and H.S. Irwin, *Amazon Jungle: Green Hell to Red Forest* (Elsevier, Amsterdam, 1975).

[14] L.S. Hamilton, Current human impacts on forests, in: *The Global Environment*, Vol. 1, eds. D. Brune, D.V. Chapman, M.D. Gwynne and J.M. Pacyna (Scandinavian Science Publisher/VCH, Oslo/Weinheim, 1997) pp. 225–252.

[15] J.E. Hansen, M. Sato, A. Lacis, R. Ruedy, I. Tegen and E. Mathews, Climate forcings in the industrial era, in: *Proc. Nat. Acad. Sci.*, Vol. 95 (1998) pp. 12753–12758.

[16] IGBP, Large-Scale Biosphere-Atmosphere Experiment in Amazon (LBA): Effects on Rainfall, Weather and Climate, The International Geosphere-Biosphere Programme (IGBP), Global Change Newsletter, No. 33 (March 1998) pp. 3–4.

[17] A.W. Arnold, I. Szabolcs and V.O. Targulian, eds., IIASA-ISSS-UNEP, Anthropogenic effects on soils, in: Global Soil Change, Report by International Institute of Applied Systems Analysis (IIASA), International Society on Soil Science (ISSS) and United Nations Environment Programmme (UNEP), IIASA CR-90-2, Laxenburg (1990) pp. 69–86.

[18] IPCC, *Greenhouse Gas Inventory – Reference Manual*, Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, Vol. 3, Revised 1996 (IPCC WG Technical Support Unit, British Meteorological Office, Bracknell, 1995) p. 5.34.

[19] IPCC, *Climate Change 1995, The Science of Climate Change*, Contribution of Working Group 1 to the Second Assessment Report of the Intergovernmental Panel on Climate Change, eds. J.T. Houghton, L.G. Meira Filho, R.A. Callander, N.A. Harris, A. Kattenberg and K. Maskell (Cambridge Univ. Press, 1996) p. 572.

[20] ISRIC/UNEP, World map of the status of human induced soil degradation, Global assessment of soil degradation, United Nations Environment Programme, Nairobi (1991).

[21] H.W. Kendall and D. Pimentel, Constraints on the expansion of the global food supply, Ambio 23 (1994) 198–205.

[22] M.U.F. Kirschbaum, A. Fischlin, M.G.R. Cannell, R.V.O. Cruz, W. Galinsky and W.P. Cramer, Climate change impacts on Forests, in: *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Contribution of Working Group 1I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), eds. R. Watson, M.C. Zinyowera and R.H. Moss (Cambridge Univ. Press, 1996) pp. 95–129.

[23] Ch. Körner, The response of multispecies systems to elevated CO_2, in: *Global Change and Terrestrial Ecosystems*, eds. B. Walker and W. Steffen (Cambridge Univ. Press, Cambridge, 1996) pp. 20–42.

[24] P. Lavelle, Biological processes and productivity of soils in the humid tropics, in: *The Geophysiology of Amazonia: Vegetation and Climate Interactions*, ed. R.E. Dickinson (Wiley, New York, 1987) pp. 175–214.

[25] G. Leach, Global land use & food in the 21st century – trends and issues for sustainibility, Polestar Series Report no. 5, Stockholm Environment Institute (1995) p. 90.

[26] R. Leemans, Impacts of greenhouse gases and climatic change, in: *The Global Environment*, Vol. 1, eds. D. Brune, D.V. Chapman, M.D. Gwynne and J.M. Pacyna (Scandinavian Science Publisher/VCH, Oslo/Weinheim, 1997) pp. 352–368.

[27] E.N. Lorenz, *The Essence of Chaos* (University of Washington Press, Seattle, 1995) p. 227.

[28] G.P. Marsh, *The Earth as Modified by Human Actions* (Sampson Low, London/New York, 1874).

[29] E. Mathews, Global vegetation and land use: new high resolution data bases for climatic studies, J. of Climate and Applied Meteorology 42 (1983) 474–487.

[30] J.M. Melillo, I.C. Prentice, G.D. Farquhar, E.-D. Schulze and O.E. Sala, Terrestrial biotic responses to change and feedbacks to climate, in: *Climate Change 1995, The Science of Climate Change*, Contribution of Working Group 1 to the Second Assessment Report of the Intergovernmental Panel on Climate Change, eds. J.T. Houghton, L.G. Meira Filho, R.A. Callander, N.A. Harris, A. Kattenberg and K. Maskell (Cambridge Univ. Press, 1996) pp. 445–481.

[31] R.P. Neilson, Simulated changes in vegetation distribution under global warming, in: The Regional Impacts of Climate Change – An Assessment of Vulnerability, A Special Report of Intergovernmental Panel on Climate Change (IPCC) Working Group 1I, eds. R. Watson, M.C. Zinyowera and R.H. Moss (Cambridge Univ. Press, 1998) pp. 439–456.

[32] J.J. Nicholaidos, D.E. Bandy, P.A. Sanchez, J.R. Benites, J.H. Villachica, A.J. Coutuad and C.S. Valverde, Agricultural alternatives for the Amazon Basin, BioScience 35 (1985) 279–285.

[33] D. Norse, C. James, B.J. Skinner and Q. Zhao, Agriculture, land use and degradation, in: *An Agenda of Science for Environment and Development into the 21st Century*, eds. J.C.T. Dooge, G.T. Goodman, J.W.M. la Rivière, Marton-Lefvèvre, T. O'Riordan and F. Praderie (Cambridge Univ. Press, Cambridge, 1992) pp. 79–101.

[34] O. Pettersson, Impact and sustainibility of agriculture, in: *The Global Environment*, Vol. 1, eds. D. Brune, D.V. Chapman, M.D. Gwynne and J.M. Pacyna (Scandinavian Science Publisher/VCH, Oslo/Weinheim, 1997) pp. 186–206.

[35] A. Rappp, Erosion and land degradation in drylands and mountains, in: *The Global Environment*, Vol. 1, eds. D. Brune, D.V. Chapman, M.D. Gwynne and J.M. Pacyna, (Scandinavian Science Publisher/VCH, Oslo/Weinheim, 1997) p. 224.

[36] J. Reilly, Agriculture in changing climate: impacts and adaptation, in: *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Contribution of Working Group 1I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), eds. R. Watson, M.C. Zinyowera and R.H. Moss (Cambridge Univ. Press, 1996) pp. 427–467.

[37] K.G. Renard, G.R. Foster, G.A. Weesies and P. Porter, RUSLE – Revised Universal Soil Loss Equation, J. Soil and Water Conservation 46 (1991) 30–33.

[38] R. Repetto, Deforestation in the tropics, Scientific American 262 (1990) 18–24.

[39] N.J. Rosenberg, *To an Integrated Assessment of Climate Change – The MINK Study* (Kluwer Academic, Boston, MA, 1993) p. 173.

[40] C.E. Rosenzweig and M.L. Parry, Potential impact of climate change on food supply, Nature 367 (13 January 1994) 133–138.

[41] K.P. Shine, R.G. Derwent, D.J. Wuebbles and J.J. Morcrette, Radiative forcing of climate, in: Climate Change, The IPCC Scientific Assessment, Report prepared for the Intergovernmental Panel on Climate Change (IPCC) by Working Group 1, eds. J.T. Houghton, G.J. Jenkins and J.J. Ephraums (Cambridge Univ. Press, Cambridge, 1990) pp. 41–68.

[42] A. Siiriäinen, Man's role in the ecological processes in Africa towards a long-term historical model, in: *Deforestation or Development in the Third World?*, Metsäntutkimuslaitoksen 272, eds. M. Palo and J. Salmi (The Finish Forest Research Inst., Helsinki, Finland, 1987) pp. 15–51.

[43] K.D. Singh, Tropical forest resources. An analysis of the 1990 assessment, J. Forestry 92 (1994) 27–31.

[44] A.M. Solomon, N.H. Rabindranath, R.B. Stewart, M. Weber and S. Nilsson, Wood production under changing climate and land use, in: *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Contribution of Working Group 1I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), eds. R. Watson, M.C. Zinyowera and R.H. Moss (Cambridge Univ. Press, Cambridge, 1996) pp. 487–510.

[45] M.S. Swaminathan, Agriculture and food systems, in: *Proceedings of the Second Climate Conference*, eds. J. Jäger and H.L. Ferguson (Cambridge Univ. Press, Cambridge, 1991) pp. 265–277.

[46] P.S. Teng, K.L. Heong, M.J. Kropff, F.W. Nutter and R.W. Sutherst, Linked pest-crop models under global change, in: *Global Change and Terrestrial Ecosystems*, eds. B. Walker and W. Steffen (Cambridge Univ. Express, Cambridge, 1996) pp. 291–316.

[47] P.B. Tinker and J.S.I. Ingram, The work of Focus 3, in: *Global Change and Terrestrial Ecosystems*, eds. B. Walker and W. Steffen (Cambridge Univ. Express, Cambridge, 1996) pp. 207–228.

[48] *UNEP, Global Environment Outlook* (Oxford University Press, 1997) p. 264.

[49] B. Walker and W. Steffen, eds., The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems, A Synthesis of GCTE and Related Research, IGBP Science No. 1, IGBP Secretariat, Stockholm (1997) p. 32.

[50] R. Winterbottom, *Taking Stock: The Tropical Forestry Action Plan after Five Years* (The World Resources Institute, WA, 1990).

[51] W.H. Wischmeier and D.D. Smith, Predicting rainfall erosion losses – a guide to conservation planning, in: *Agricultural Handbook*, No. 537 (WA, 1978).

[52] W.H. Wan Azli, K. Chan Ali, T. Holt and M. Kelly, Modelling the impact of forest conversion on climate: a review, in: *Conversion, Management and Development of Forest Resources*, Proceedings of the Malaysia – United Kingdom Programme Workshop, October 1996, Kuala Lumpur, eds. Lee Su See., Dan Yit May, I.D. Gauld and J. Bishop (1996) pp. 332–348.

[53] D.W. Wolfe and J.D. Erickson, Carbon dioxide effects on plants: uncertainties and implications for modeling of crop response to climate change, in: *Agricultural Dimensions of Global Climate Change*, eds. H.M. Kaiser and T.E. Drennen (St. Lucie Press, Delrey Beach, Florida, 1993) pp. 153–178.

[54] WRI, World Resources 1990–91 (World Resources Institute, Oxford University Press, Oxford, 1990) p. 383.

[55] WRI, World Resources 1992–93 (World Resources Institute, Oxford University Press, Oxford, 1992) p. 383.

[56] WRI, World Resources 1994–95 (World Resources Institute, Oxford University Press, Oxford, 1994) p. 400.

[57] WRI, World Resources 1996–1997 (World Resources Institute, Oxford University Press, Oxford, 1996) p. 365.

[58] WRI, World Resources 1998–1999 (World Resources Institute, Oxford University Press, Oxford, 1998) p. 369.

[59] H. Zhang, A. Henderson-Sellers and K. NcGuffie, Impacts of tropical deforestation, Part I: Process analysis of local climatic change, J. Climate 9 (1996) 1497–1517;
H. Zhang, K. NcGuffie and A. Henderson-Sellers, Impacts of tropical deforestation, Part II: The role of large-scale dynamics, J. Climate 9 (1996) 2498–2521.